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The effects of climate change on the robustness of the urban drainage system of the Soesterkwartier.

A study about the main challenges of the urban drainage system of the Soesterkwartier and the best (sustainable) solutions for this district.

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Abstract

Many urban areas are facing pluvial flooding problems due to extreme rainfall events that are too intensive for the local drainage network. One of these urban areas is the Soesterkwartier, a district in the city of Amersfoort which is located in the central part of the Netherlands. A large part of the sewer system of this district is a so-called combined sewer system, discharging wastewater as well as rainwater. In 2014, two extreme rainfall events on respectively the 11th and 28th of July caused water nuisance in this district whereby also sewage came out of the sewer system. This resulted inter alia in increased health risks and odour problems. The KNMI expects that the frequency and intensity of these extreme rainfall events will increase in the future. If nothing is done with the current urban drainage system of the Soesterkwartier, this will lead to more water nuisance, increased health risks and more economic damage in the future.

The main objective of this research project is to investigate how the current drainage system of the Soesterkwartier could be made more robust to prevent the effects of extreme rainfall events. Hereby, climate change is taken into account. The aim is to find practical, sustainable and area specific solutions that are in line with the vision of the municipality of Amersfoort and increase the robustness of the drainage system of the Soesterkwartier. To achieve this objective, information about the extent and degree of the water nuisance due to the heavy rainfall events in July 2014 is obtained via a district survey and an investigation in the municipal archives. Besides, a rainfall runoff model of the Soesterkwartier is made using the openLISEM model, whereby the sewer system is modelled as a buffer with an inflow (runoff water) and outflow (pumpovercapacity and overflow). With the help of the results of the district survey it is tested if this model corresponds well with reality. Subsequently, the best measures to reduce the consequences of extreme rainfall events are analysed using the model.

The district survey identified two vulnerable areas in relation to pluvial flooding in the Soesterkwartier. These areas were flooded during both heavy rainfall events in July 2014 and are respectively the Soesterweg, Hulststraat and Palmstraat (1) and the Spaarnestraat and Dollardstraat (2). The nuisance consisted mainly of streets that were flooded with rainwater that also contained sewage. The events caused no significant economic damage because the district is in general well-designed. The maximum water levels on the surface seems to have approximately been the same during both rainfall events, even though the return periods of the events on the 11th and 28th were quite different, respectively 5 and 70 years. The high water levels on the 11th of July were in contrast to the 28th of July largely because of the failure of the functioning of the sewer system.

Increasing the robustness of the drainage system of the Soesterkwartier is not a short-term straightforward process, as it takes time and requires cooperation between the different stakeholders. Because of this, it is important to have a flexible long term vision whereby necessary measures are adapted to other developments in the district. This way, projects to improve the drainage system will be integrated and costs of the measures could be reduced when their proceedings are combined with other work.

On the short term, it is important to increase the awareness of the civilians of the Soesterkwartier in relation to pluvial flooding. In the course of time more water retention areas and infiltration systems should be constructed to increase the robustness of the drainage system. Besides, more use should be made of the potential buffering capacity and infiltration capacity of green areas if the groundwater levels are favourable. Furthermore drainwave (permeable pavement) could be constructed in both problem areas. On the long term the combined sewer system must be replaced by a separated system. If this replacement is considered it should be analysed if an expensive rainwater sewer is really

necessary everywhere in the district or that the money could better be invested in a dry weather system only and the remaining funds be used for retention and infiltration measures that increase the robustness of the system.

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1. Introduction

Many cities in Europe are currently facing pluvial flooding problems due to extreme rainfall events that are too intensive for the local drainage network to cope with (Sušnik et al., 2014). It is expected that pluvial flooding will become more frequent in Europe because of urbanisation and climate change (ibid.; IPCC, 2007; Parry et al., 2007; Madsen et al., 2009; Mailhot and Duchesne, 2010). Climate change will increase frequency and intensity of rainfall events which could potentially lead to more flooding damage. Besides, urbanisation causes more impermeable surface area and increases pressure on the existing drainage network (Sušnik et al., 2014).

In the Netherlands, municipalities are responsible for the drainage of rainwater and processing of the collected water. Besides rainwater, municipalities are responsible for collecting and purification of wastewater. The relevant laws for municipalities in the Netherlands in terms of collecting, transporting and processing waste- and rainwater are given in appendix A (GRP, 2012). Despite these laws, many urban drainage systems in the Netherlands are vulnerable for water nuisance due to heavy rainfall events.

The Royal Netherlands Metrological Institute (Dutch: Koninklijk Nederlands Meteorologisch Instituut: KNMI) predicted that the rainfall intensity will increase in the Netherlands in the coming decades (KNMI, 2014). This will increase the pressure on the performance of the urban drainage system. As a result, many municipalities in the Netherlands want to increase the robustness of their drainage system to prevent water nuisance in the future due to pluvial flooding.

One of these municipalities is the municipality of Amersfoort, which is located in the Gelderse Vallei in the central part of the Netherlands (figure 1.1). In the summer of 2014 two heavy rainfall events took place in Amersfoort within several weeks. These events caused severe and less severe water nuisance in different places in the city of Amersfoort. This nuisance varied from flooded streets (figure 1.2), bicycle lanes and sidewalks to flooded tunnels, houses, parking garages and shops. Because of climate change, the heavy rainfall events of the summer of 2014 are expected to become a more common occurrence in the future.

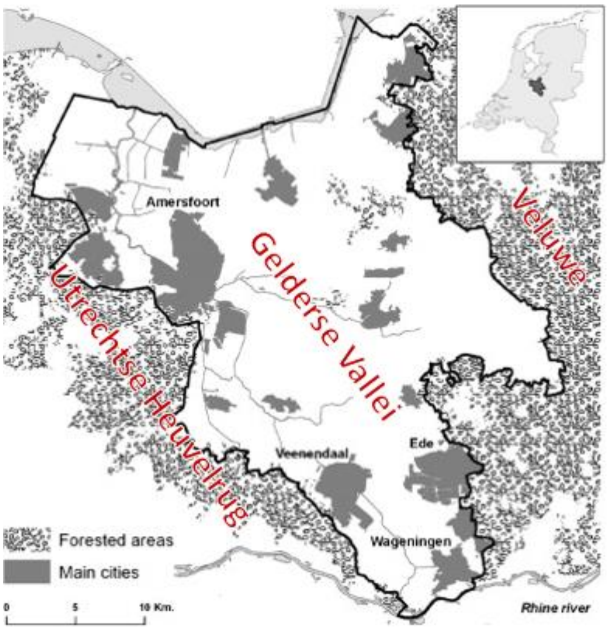


Figure 1.1: Geographical position of Amersfoort in the Gelderse Vallei (Willemen et al., 2010).

Figure 1.2: Water nuisance in Amersfoort in the summer of 2014. (photo taken by a resident).

This thesis will focus on water nuisance in the Soesterkwartier, which is a district in the city of Amersfoort (figure 1.3). Information about water nuisance in the Soesterkwartier due to the heavy rainfall events in July 2014 has been collected via a district survey. This way the vulnerable places of the drainage system of the Soesterkwartier have been mapped. Furthermore, the consequences of climate change on the robustness of the system are investigated and solutions are determined that contribute to a more robust drainage system fitting within the policy of the municipality of Amersfoort. Besides that, the effectiveness of the solutions are tested by using an urban drainage model. A freely available urban drainage model is used because this research has not the financial possibilities to use commercial software programs which are often seen as more accurate and complex.

One of the free available software programs is openLISEM which is developed by the University of Twente. This is a spatial hydrological model that could simulate sediment dynamics, runoff and shallow floods in rural and urban catchments (ITC, 2013). It is an event-based model designed to simulate the effects of conservation measures during heavy rainfall events (ibid.). With the help of this model, the drainage system of the Soesterkwartier is modelled for the heavy rainfall events in July 2014. Model results are checked for correspondence with the information about the water nuisance that is collected via the district survey. If these correspond, openLISEM is used to test the effectiveness of the proposed solutions against pluvial flooding. Finally, recommendations are given how to improve the robustness of the current drainage system of the Soesterkwartier.

1.1 Area description

This research focusses on the Soesterkwartier district which is located in Amersfoort. Amersfoort is situated in the Gelderse Vallei (figure 1.1) which is roughly bounded by the Lower Rhine (NL: Nederrijn) in the south and the ice-pushed ridges Utrechtse Heuvelrug and Veluwe in respectively the west and the east. The Gelderse Vallei distinguishes three types of landscape. These are respectively the sandy moraine ridges (Veluwe and Utrechtse Heuvelrug) in the east and west, the brooks in the south and the polder landscape in the north. The city of Amersfoort is located on the intersection of these landscapes where approximately 150.000 people live (Buurtmonitor, 2016). The Soesterkwartier district, where almost 12.000 people live, lies on the transition zone between the Utrechtse Heuvelrug and the polders. It lies north of the central station of Amersfoort and is largely built, apart from the Puntenburg area in the east (figure 1.3), between 1925 and 1962 (Eem Archief, 2016). In the

Figure 1.3: Location of the 'Soesterkwartier' (Modified from google maps, 2016). Blue areas represent surface waters and the blue dotted lines (in the north) represent ditches.

streetscape of that time little place was reserved for green infrastructure which makes the neighbourhoods densely built. The green areas were concentrated on the edge of the district. Since the construction in 1962, the Amsterdamseweg forms the northern boundary of the district (figure 1.3). Pluvial flooding occurred in the past on different locations in this district after heavy rainfall events.

1.1.1 Impression of the Soesterkwartier

Figure 1.4 gives an impression of a typical road in the Soesterkwartier. The most roads have several speedbumps across the entire width and consists generally out of bricks with on both sides of the road sidewalks. The sidewalks are separated from the roads by curbs which are usually 6-12 centimetres high. There are predominantly terraced houses in the Soesterkwartier. The sills of the front doors of the houses are in most places high (>6cm). Further, in front of the houses there is mostly room for small 'gardens' which slant upwards from the streets towards the houses. In large parts of the district these gardens are completely paved whereby less rainwater could be infiltrated and more water will runoff via the surface.

Large green areas of the Soesterkwartier are in the north of the district between the Amsterdamseweg and Dollardstraat. These large green areas together are called the 'Groengordel'. Small green areas are spread over different neighbourhoods. East of the Bloemenbuurt there is a green area that functions as a sanctuary. It is striking that all green areas are positioned above street level (figure 1.5) causing runoff water entering the sewer system instead of flowing towards the green areas.

Figure 1.4: Impression of a typical road in the Soesterkwartier. Photo taken from the Palmstraat which was flooded two times in July 2014.

Figure 1.5: One of the green areas (Palmstraat) in the Soesterkwartier that is located above street level and is surrounded by curbs. Rainwater that falls on the street enters the sewer system instead of runoff to the green areas.

1.2 Background of the drainage system of the Soesterkwartier

This section covers the groundwater levels, surface drainage and sewer system of the current Soesterkwartier. These factors have a large influence on the functioning of the drainage system and it is essential to understand their influence on the functioning of the system. Only by understanding the drainage system of Soesterkwartier, valid solutions to improve its robustness can be deduced.

1.2.1 Drainage, groundwater and surface water

The Soesterkwartier area lays on the transition zone between the higher grounds of the 'Amersfoortse Berg' in the south and the polders in the north resulting in a considerable elevation difference between the northern and southern part of the district (figure 1.6). This elevation difference is predominantly noticeable north of the Noordewierweg (figure 1.6) where the surface level decreases with 1-3 meter towards the Groengordel. In contrast, south of the Noorderwierweg the elevation differences are considerably less (0-1 m).

Nowadays, there is not much surface water in the Soesterkwartier and there are only a few ditches in the Groengordel (figure 1.3). These ditches are connected via culverts with each other and with the ponds in the northwest of the area. The drainage direction of the ditches is in the direction of the ponds. In the rest of the area the drainage goes mainly via the streets.

The drainage direction is determined by the highest surface gradient which is dependent on elevation differences. In general, this drainage direction in the Soesterkwartier is in such a way adapted that the rainwater runs off towards the sewer inlets. In case a sewer inlet is clogged or filled the runoff water will follow the highest surface gradient in the street. Hereby, the speedbumps stagnate the flow whereby accumulation of water occurs on the upstream side. This could result in more water nuisance upstream of the speedbump but on the other hand it could also result in less water nuisance downstream of the speedbump. Through this mechanism, speedbumps could play an important role in relation to pluvial flooding.

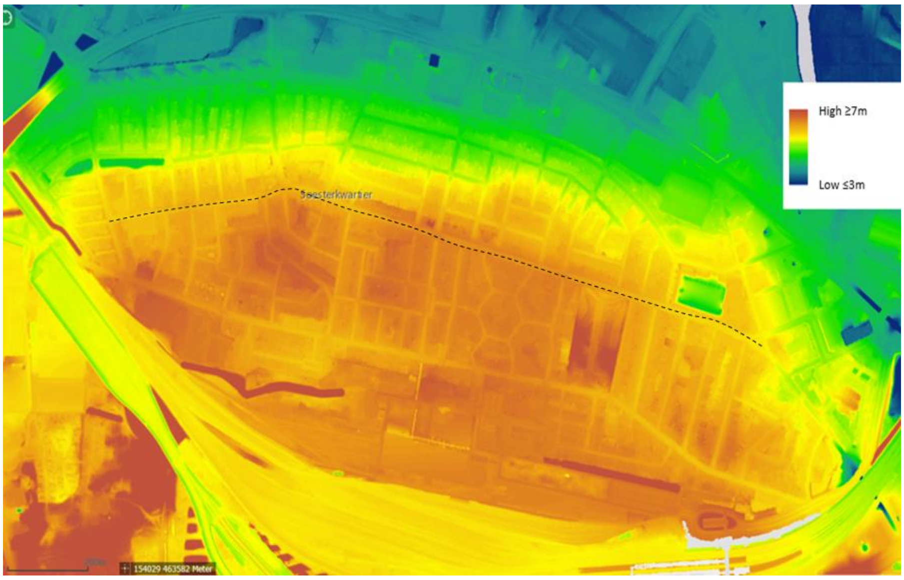


Figure 1.6: Elevation map of the Soesterkwartier (AHN,2016). Dotted line represents the Noordewierweg.

The subsoil of the Soesterkwartier exists mainly out of a thin anthropogenic layer at the surface (max one meter depth) followed by a thicker layer of fine sand (Formatie van Boxtel). There are no local values known of the hydraulic conductivity but in general this formation has a hydraulic conductivity between 0.5-10 m/day (Cohen et al., 2009). The formation of Boxtel is continuous till a marine clay layer which belongs to the 'Eemformatie' and has a very low hydraulic conductivity (Klooster and Wuite, 2006; Dinoloket, 2016). This clay layer starts between eight and ten meters below the surface and is relatively thin in the south (<1 meter) of the research area and it increases towards the north where it is more than three meters thick (Dinoloket, 2016).

The highest groundwater levels relative to Dutch Ordnance Level (Normaal Amsterdam Peil: NAP) are found in the south which corresponds with the highest elevation. However, the groundwater gradient is smaller than the gradient of the land surface resulting in shallower groundwater levels in the north and deeper groundwater levels in the south (Appendix K). The groundwater level varies in the north of the neighbourhood over the year between 0.5 and 1.5 meters below the surface and in the south between 1.5 and 3 meters below the surface (Dinoloket, 2016).

Several residents in the north of the district experience groundwater nuisance due to the high groundwater levels in this part of the district. Many residents complain that the nuisance has increased in the recent years. According to some residents, the origin of this groundwater nuisance lies with the construction of the Amsterdamseweg. Several ditches, which were mainly orientated from the Groengordel towards the north, were filled up (Grontmij, 2014). However, the consequences of this filling up for the water system of the Soesterkwartier have never been properly investigated, so it remain uncertain if there is a relation between the construction of the Amsterdamseweg and the groundwater nuisance. A more recent cause of the increased groundwater problems in the Soesterkwartier could be the reduced abstraction of drinking water on the Amersfoortse Berg in 2004, in order to diminish desiccation of the Utrechtse Heuvelrug (Blaakmeer-Kruidhof, 2011). Since then, the water abstraction has been reduced from 3 to 1.5 million cubic meters a year (ibid.). To prevent excessive groundwater levels in the urban area of Amersfoort because of the diminished abstraction, the province of Utrecht financed additional measures like drainage (Province of Utrecht, 2012). However, it is not known if these additional measures have compensated in the north of the Soesterkwartier the consequences of the reduced abstraction. This is because there are not enough monitoring wells with groundwater levels observed well before the reduction took place.

1.2.2 The sewer system of the Soesterkwartier

The sewer system of Amersfoort has a total length of 1034 km and there is one sewage treatment plant (STP) that is located northwest of the Soesterkwartier (Waterschap Vallei & Eem, 2004). The total length of the sewer system in the Soesterkwartier is 30 kilometres and there are three different types present. These are separated, combined and, improved separated sewer system. The largest part of the system could be attributed to a combined sewer system (figure 1.7; appendix C). A small part of the sewer system in the northwest of the district is improved separated and in the east it is separated (figure 1.7). The combined system of the Soesterkwartier transports waste- and stormwater via a sewer pumping station and an internal overflow (in case it rains hard enough) out of the system (figure 1.7) where it will ultimately end in the sewage treatment plant (STP). The separated and improved separated system consists both of a dry weather system (DWS) and a rain water system (RWS). The DWS transports domestic and industrial wastewater towards the STP and in case of an improved DWS it also transports the 'first flush' which is the rainwater at the start of a rainfall event with a relatively high concentration of pollutants (Stowa, 2014). The improved separated system in the northwest will be changed to a separated system when the incorrect connections between the DWS and RWS are recovered (Lensink, 2016). This is because it will reduce the amount of water at the sewage treatment plant and thereby also the treatment costs (ibid.). The transformation from improved separated to separated system will happen in the next two years (ibid.)

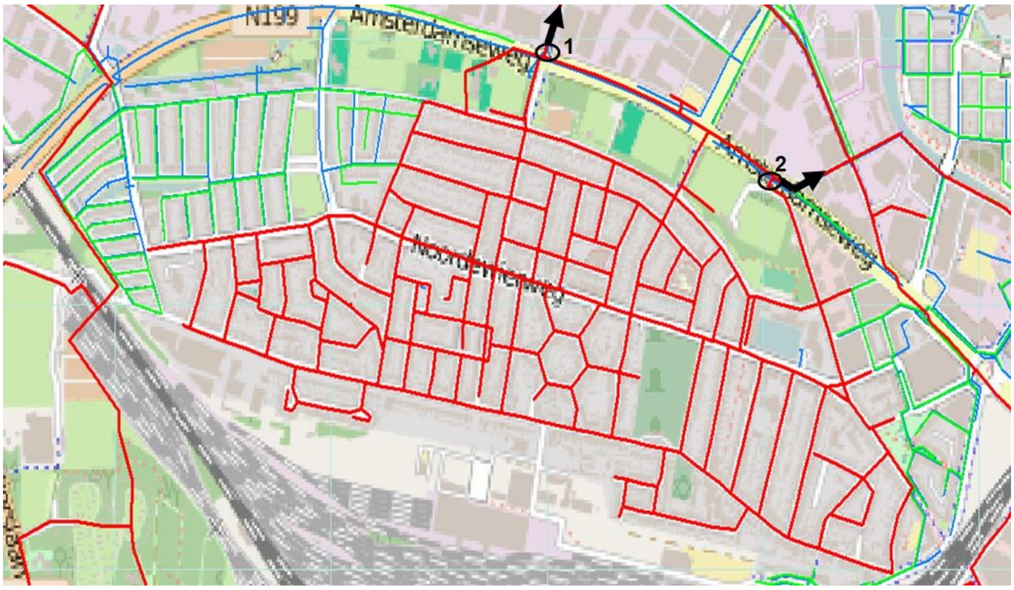


Figure 1.7: type of sewer pipes in the Soesterkwartier. Red = combined; green = dry weather system; blue = rain water system (Kikker, 2016). 1) internal overflow; 2) sewer pumping station.

The most commonly used material for the sewer system in the Soesterkwartier is concrete but also PVC pipes are present (appendix C). The municipality of Amersfoort has predominantly used concrete because it is easier to recycle and PVC is seen as less sustainable because of the chloride that is added to the material during the production (Lensink, 2016). For both concrete and PVC sewer pipes, it is difficult to predict the technical lifespan because it is dependent on many things like maintenance, and time of construction (VPB, 2008; VPB, 2016). However, the municipality of Amersfoort assumes a lifespan of PVC pipes of at least 50 to 60 years but it could also be as high as 80 years (Lensink, 2016). Besides, the municipality assumes a lifespan for the concrete sewer of approximately 80 years if the system is constructed during or after the 1960s, which is the case for almost the whole sewer system in the Soesterkwartier (appendix C) (ibid.). With the help of relining the lifespan of concrete sewers could be extended with at least 50 years if the diameter of the sewer is large enough (ibid.). Because of the long lifespan of the sewer pipes and the high replacement costs it is unlikely that the sewer system will be replaced on the short term (ibid.).

1.3 Vision and ambition of the municipality of Amersfoort

In 2013 the municipality of Amersfoort presented their environmental policy ambitions for 2030 (Municipality of Amersfoort, 2013). An important ambition of the municipality is to create a ‘climate proof city’ meaning that it is waterproof, heat proof and green. Hereby, it emphasizes the advantages of an integrated approach in relation to the realization of this climate proof city (ibid.). In relation to heat, the municipality has the ambition to reduce the heat island effect of Amersfoort (appendix E) as much as possible. They think to achieve this in particularly by implementing more green in the city.

The central concepts of the climate proof city: water, heat and green are also important in the ‘natuurlijke alliantie’ (natural alliance), where the key themes are soil, water and green. The ‘natuurlijke alliantie’ is a new method for spatial planning that is not finished yet and must be further developed in practice. However, the basic principle is simple: soil, water and green are strongly interwoven with each other and belong together in the spatial planning process and execution. An integrated approach of soil, water and green will result in an effective spatial plan against climate change. The ‘natuurlijke alliantie’ is for the municipality of Amersfoort a guideline for better cooperation between soil, water and green professionals. It is a basis for the structural development vision of the municipality. Hereby, it is important that for example water related problems, like pluvial flooding, are tackled with an integrated approach in which also soil and green are considered.

With respect to water, the municipality of Amersfoort has an ambitious vision. Central in this vision are ten ‘sustainable principles’ (appendix B). The ten sustainable principles are policy principles that serve inter alia as support of the vision, ambition and goals of the municipality of Amersfoort and are based on the natural behaviour of water (ibid.). The water vision for 2030 contains four main topics which are respectively surface water, groundwater, rainwater and waste water (Schuurman, 2009). These topics are strongly interwoven with each other but also with other urban aspects like soil (e.g. infiltration) and (life) environment.

Concerning rainwater, the municipality has several ambitions for 2030. Rainwater should be retained and infiltrated locally to delay and decrease the discharge (Schuurman, 2009). In 2030, 50 percent of the paved surface area in Amersfoort must be disconnected from the wastewater system (Municipality of Amersfoort, 2013). The rainwater that falls on this disconnected area is preferably infiltrated into the ground. When infiltration is not possible it is transported towards the surface waters (ibid.). This transportation (storm water) system must be located as much as possible aboveground because it enhances the awareness and experience value of water (Schuurman, 2009). Polluted rainwater from inter alia busy roads, car washing bays and parking lots should be filtered before it can infiltrate into the ground or it is transported to the surface waters (ibid.). Only on places where there is no other alternative, polluted rainwater may be transported to the sewage treatment plant (ibid.). With the replacement of combined sewers into separated sewers the technical lifespan of the existing sewer is taken into account (ibid.). Besides, the costs could be reduced when the proceedings are combined with other work like the replacement of roads.

Further, in relation to groundwater the municipality stated that the use of groundwater should be reduced. This must be achieved by implementing water-saving techniques or using other water sources like surface- and rainwater. For example rainwater could be used instead of drinking water for purposes that do not need the highest quality of water like car washing, toilet flushing and irrigation of gardens (ibid.).

The municipality expects from civilians and companies in relation to rainwater that they take actions to keep the rainwater clean (GRP, 2012). This means inter alia that they do not dispose grey water on the rainwater system and do not wash their vehicles on the street (ibid.). Furthermore, it is expected that they contribute to the disconnection of rainwater by means of the separate delivery of waste- and rainwater on the property border when the combined system is replaced for a separated system (ibid.). Besides, the municipality has the right to draw up a regulation whereby civilians and companies are obliged to process rainwater on their own property within a certain time, or to deliver waste- and rainwater separately to the separated sewer system (Appendix A, Wet Milieubeheer, artikel 10.32a). Nowadays, this is done on voluntary basis and because of the large participation of civilians and companies so far and from the viewpoint of the desired reduction of rules and obligations is yet no regulation established (GRP, 2012).

Current projects of the municipality
In 2015 a project that is called ‘Meet je stad’ (measure your city) started with inter alia temperature and humidity measurements. The first year was used to determine the best measuring method (Meet je stad, 2016). In 2016 and the coming years this method will be used to measure temperature and humidity in different places in the city (ibid.). Besides ‘Meet je stad’, the municipality is also involved in another project called ‘Operatie Steenbreek’, which has the goal to reduce the amount of paved area in the city and to increase the amount of green. This project predominantly focusses on increasing the awareness and changing the mind-set of civilians (Operatie Steenbreek, 2016). The main goal of this project is to increase the biodiversity in the city and the resilience against extreme rainfall (ibid.).

1.4 Problem description

During the last decade, parts of the Soesterkwartier were flooded several times. In July 2014, two heavy rainfall events even caused two pluvial floods within three weeks in Amersfoort. The structures of both rainfall events are very different and are shown in figure 1.8. The rainfall event of July 11th was relatively short and intense while the event of July 28th was much longer with several intense peaks. The nuisance in the Soesterkwartier consisted mainly of flooded streets. The water contained sewage in the areas with a combined sewer system. In case the combined sewer system is filled during extreme rainfall events, the proportion of sewage in relation to rainwater in the sewer water is very small. As a result, the contribution of the sewage flow to the magnitude of pluvial flooding is small. However, the contribution to the degree of nuisance is large because it increases the risk of diseases and it creates a very unpleasant smell when the water level recedes.

Besides the health and odor problems in the parts of Soesterkwartier with a combined sewer system, the extent of the flooding during the heavy rainfall events in July 2014 worried inhabitants. Water entered houses at certain locations in the district and the municipality received a lot of reports of concerned residents that the water reached levels that were just below the sills of the houses.

Although, the total amount of rain during the heavy rainfall events of the 11th of July and the 28th of July were respectively 21.3 and 44.7 mm and high rainfall intensities occurred during both events, these values are not uncommon in the Netherlands. Many other places in the Netherlands suffered the 28th of July 2014 from more extreme rainfall events. In lots of places the daily precipitation exceeded 100 mm (Weeronline, 2014). On the Veluwe, 130 mm of rain was recorded in 90 minutes time (ibid.). The KNMI expects that the probability of these extreme rainfall events will increase. This will lead to more water nuisance and more economic damage if nothing is done with the urban drainage system in Amersfoort.

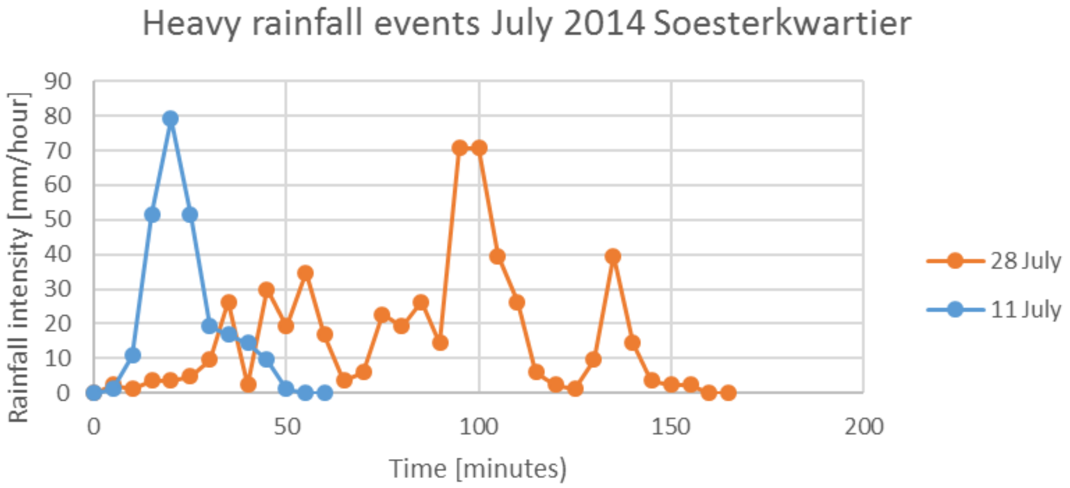


Figure 1.8: Rainfall events in the Soesterkwartier in July 2014 (Data from HydroNET, 2016).

1.5 Objectives of this research

The main objective of this research is to find practical, sustainable and area specific solutions to increase the robustness of the drainage system of the Soesterkwartier against pluvial flooding. Hereby, it is very important that these solutions are in line with the vision of the municipality of Amersfoort. To reach this goal, it is firstly important to completely understand the current drainage system and to determine the vulnerable places in relation to pluvial flooding. Secondly, the effects of climate change on heavy rainfall events and the consequences of this for the functioning of the drainage system of the Soesterkwartier must be investigated and understood. After the solutions are found, the goal is to assess the effectiveness of these solutions with the help of the openLISEM software and give recommendations to improve the robustness of the drainage system.

1.6 Research questions

How could the current drainage system of the Soesterkwartier be made more robust to prevent the consequences of extreme rainfall events?

1. What are the current vulnerable locations of the drainage system of the Soesterkwartier when extreme rainfall occurs?
2. How will climate change affect the frequency and intensity of extreme rainfall events and what are the consequences of this for the drainage system of the Soesterkwartier?
3. Could the current drainage system of the Soesterkwartier be modelled for extreme rainfall events with the help of openLISEM and do the results correspond with reality?
4. Which solutions are in line with the vision of the municipality of Amersfoort and could be implemented to increase the robustness of the drainage system?
5. What are the effects of the solutions on the pluvial flooding problem when they are tested in the openLISEM model?**

***Question 5 is only answered if question 3 is answered with yes.*

1.7 Research focus

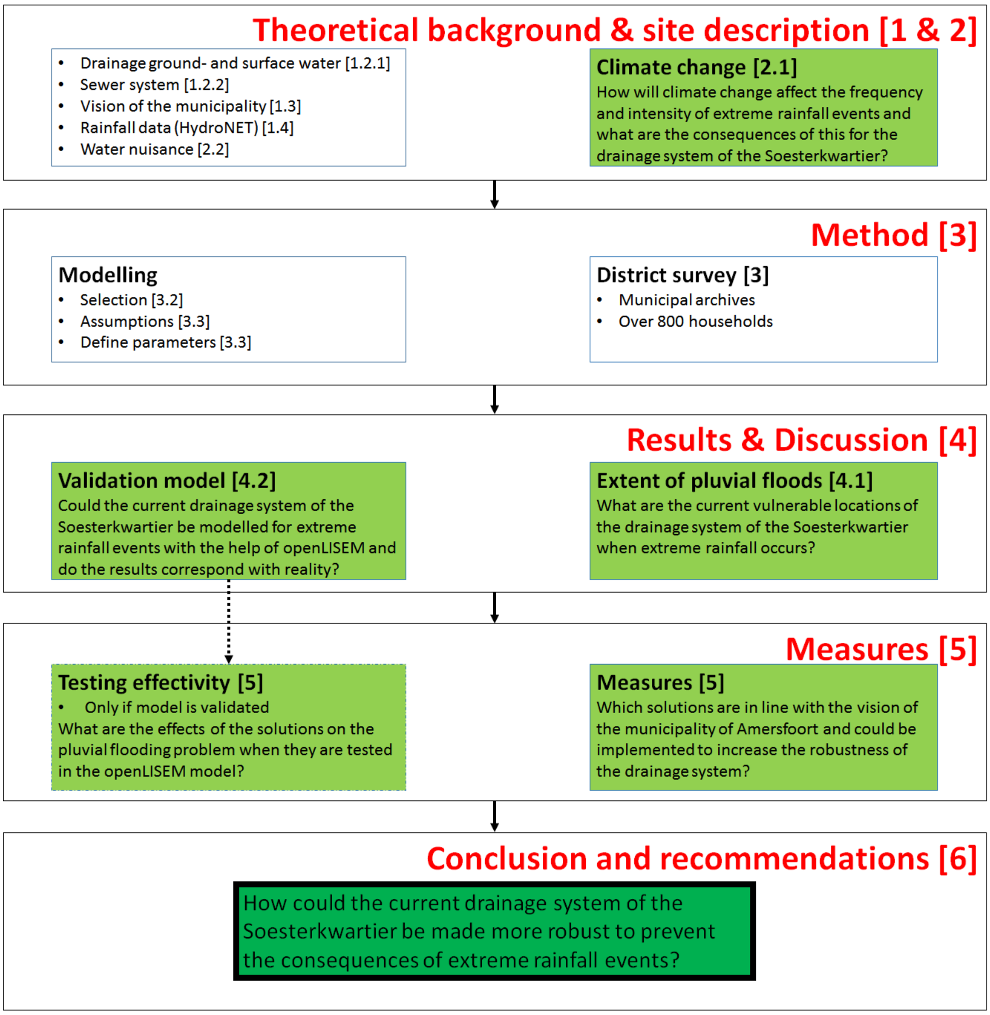
This research will focus on the area in the Soesterkwartier that has a combined sewer system (figure 1.7) which will be called from now on “the research area”. In the research area, the nuisance due to pluvial flooding will be mapped and area specific solutions will be given. Hereby, the criteria are:

1) The degree of effectiveness of the solution on the robustness of the drainage system;
2) The vision of the municipality of Amersfoort;
3) The costs of the solution.

Further the focus will lay on developing a model with the help of openLISEM that gives a realistic simulation of pluvial flooding in the research area in order to test the effectivity of the solution in relation to reduce water nuisance in the Soesterkwartier.

1.8 Outline of the report

In figure 1.9 an overview is given of the research structure. This thesis continues with a description of climate change and water nuisance in chapter two. Subsequently, the research method and the input parameters are described in chapter three. Further, the results of respectively the district survey and the openLISEM model are given and discussed in chapter four. Chapter five gives solutions to improve the robustness of the drainage system of the research area and in chapter six conclusions and recommendations are given for the realization of a robust drainage system of the Soesterkwartier. Besides, the main research question is answered in this chapter.



How will climate change affect the frequency and intensity of extreme rainfall events and what are the consequences of this for the drainage system of the Soesterkwartier?

Could the current drainage system of the Soesterkwartier be modelled for extreme rainfall events with the help of openLISEM and do the results correspond with reality?

What are the current vulnerable locations of the drainage system of the Soesterkwartier when extreme rainfall occurs?

What are the effects of the solutions on the pluvial flooding problem when they are tested in the openLISEM model?

Which solutions are in line with the vision of the municipality of Amersfoort and could be implemented to increase the robustness of the drainage system?

How could the current drainage system of the Soesterkwartier be made more robust to prevent the consequences of extreme rainfall events?

Figure 1.9: Overview of the research structure. The green boxes represent the five sub questions of chapter 1.6 and the dark green box is the main research question.

2. Theory

This chapter describes the effects of climate change in the Netherlands on the temperature and precipitation. Hereby, the second research question will be answered:

> *How will climate change affect the frequency and intensity of extreme rainfall events and what are the consequences of this for the drainage system of the Soesterkwartier?*

Besides that, the definition of water nuisance is given in chapter 2.2.

2.1 Climate change in the Netherlands

Nowadays, climate change is an important aspect of urban development and urban water management and could no longer be denied. The Royal Netherlands Meteorological Institute made four climate scenarios (KNMI'14 scenarios) for the Netherlands based on the climate during the reference period from 1981 till 2010. The KNMI'14 scenarios are the four combinations of two divergent values for temperature rise, 'moderate and warm', and two possible changes in air flow patterns, 'low value and high value' (figure 2.1). Together they describe the boundaries in which climate change is likely to take place in the Netherlands. Figure 2.2 shows the boundaries for two emission scenarios of greenhouse gasses. The blue line shows the average result of different climate models for a stabilization of the emissions and the red line shows the average result of an increase of greenhouse gas emissions. The four black points in figure 2.2 show that the moderate (G-scenario) and warm (W-scenario) coincide with respectively the stabilization and exaltation of greenhouse gasses. The KNMI did not use a scenario which assumes a decrease in greenhouse gas emissions.

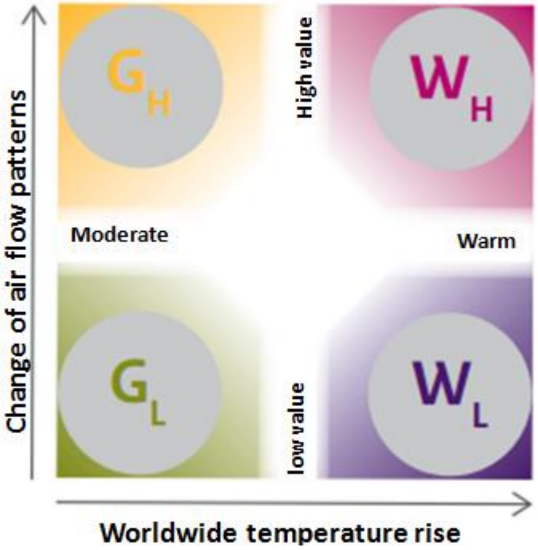


Figure 2.1: KNMI'14 Climate Scenarios for the Netherlands (Modified from KNMI, 2014).

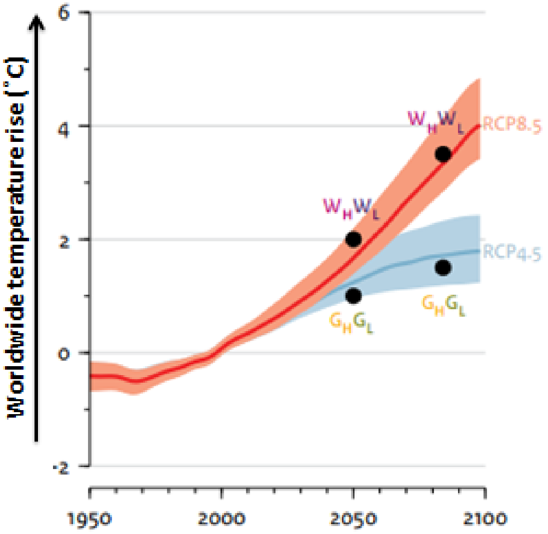


Figure 2.2: Worldwide temperature rise compared to 1981-2010 for two emission scenarios. Red = high emission; blue = stabilization of current emission. RCP= Representative concentration Pathways (Copied from KNMI, 2014).

Following the KNMI'14 scenarios the average temperature in the Netherlands will increase in this century between 1.5 ˚C and 4.4 ˚C. In line with the average temperature, the number of summer days per year will increase in this century as well compared with the reference period 1981 and 2010 (KNMI, 2014). The reference period counted on average 21 summer days per year which will increase with minimal 22 and maximal 70 percent by 2050 following the different scenarios (ibid.). This will increase the probability of heat waves and heat stress (ibid.). In particularly urban areas are vulnerable because air and surface temperatures in urban areas are usually higher than in the neighbouring rural areas (van Hove et al., 2011). This is the so-called Urban Heat Island (UHI) effect which is further explained in appendix E.

Besides the temperature rise, the airflow pattern has also influence on climate change in the Netherlands (KNMI, 2014). In the low or L-scenarios the change of airflow pattern is small and in the high or H-scenarios the change is large. In the H-scenarios the wind will come more often from the west which means a milder and wetter climate. However in summer, high pressure areas will have a bigger influence on the weather system whereby easterly winds will increase which will result in drier summers in the Netherlands. Despite of the drier summers, extreme rainfall in the summer season will probably increase. This is because warmer air in summer could contain more water vapour which could lead to more extreme rainfall. Besides, extreme rainfall events are to a large extent dependent on regional and local processes and not on large-scale airflow patterns that are used in the KNMI'14 scenarios. The models used for the KNMI'14 scenarios cannot show the regional and local processes because the uncertainty and sensitivity is too high to give a reliable prediction (KNMI, 2014). This means that one can expect huge regional differences in the Netherlands concerning the amount of rainfall. Nevertheless, in all the four scenarios for 2050 and 2085, the maximum precipitation in one hour will increase. From observations, it appears that for the most extreme shower events, the amount of rainfall per hour increases with approximately 14 percent per increased degree of Celsius (ibid.). This means that in 2050 the amount of rainfall during an extreme event for the L- and W-scenario will be increased by respectively 14 and 28 percent (figure 2.3). Hereby, extreme rainfall events will occur more frequently and the intensity will increase as well. This will increase the pressure on for example the drainage system of the Soesterkwartier. If nothing is done with the current drainage system, there is a large change that in the future the Soesterkwartier will be flooded more often and the extent of the floods will aggravate as well.

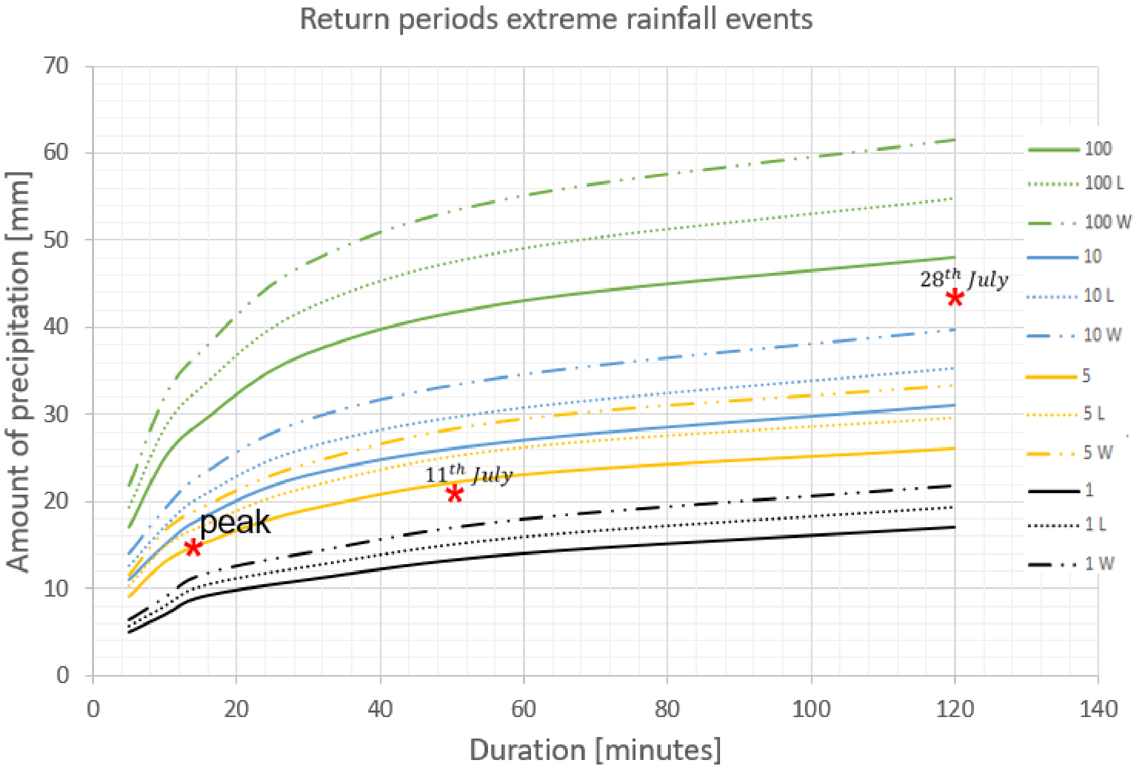


Figure 2.3: Return period of different rainfall events. The fixed lines represent the current return periods [T=1,5,10,100] (copied from Buishand A. and Wijngaard, 2007); the dotted line shows the return period for the L-scenario in 2050 and; the dots alternated with dashes represents the return period for the W-scenerio in 2050. Further the rainfall events of 11th and 28th July are represented in the graph just as the peak of approximately 15 mm in 15 minutes of both events

2.2 Water nuisance

There is not an exact definition of water nuisance. A as result water nuisance is often defined differently by several agencies. In the sewer plan of the municipality (Gemeentelijk rioleringsplan: GRP) of Amersfoort for 2012-2021 three different categories of water nuisance were distinguished. These are respectively:

1. **Hindrance:** This concerns water on street in limited amounts (less than 5 cm) and short duration (less than one hour) in residential and industrial areas. This may happen on average once every two years.
2. **Material or economical damage:** This implies water on street in limited amounts and short duration in shopping areas and major roads, flooded tunnels, dislodged manhole covers, or water on street in significant amounts (more than 5 cm) and long duration (more than one hour) in residential and industrial areas. This may happen once every 10-25 years on the same location.
3. **Severe material or economical damage:** This concerns water in shops, firms, houses, basements and serious obstruction of the traffic. Hereby, the vulnerable infrastructure like transformer stations and telephone exchanges should be considered as well. The chance that this may happen is once every 100 years.

It is not always easy to classify water nuisance into one of these three categories because they do not contain all the possible practical situations. Besides that, it is striking that sewage outflow from the sewer to the street is not directly mentioned into a water nuisance category in the GRP (2012) of Amersfoort. Instead of that, it is only mentioned that the municipality has the ambition to further separate the sewage and rainwater flows.

3. Research Methodology

Figure 3.1 gives an overview of the research set up. The numbers between the brackets correspond to the (sub) chapters the different topics are discussed. The research started with a site description and a literature study about the research area that provide the theoretical background. In this chapter the methodologies that are used to collect the required data to answer the main research question and sub questions are described.

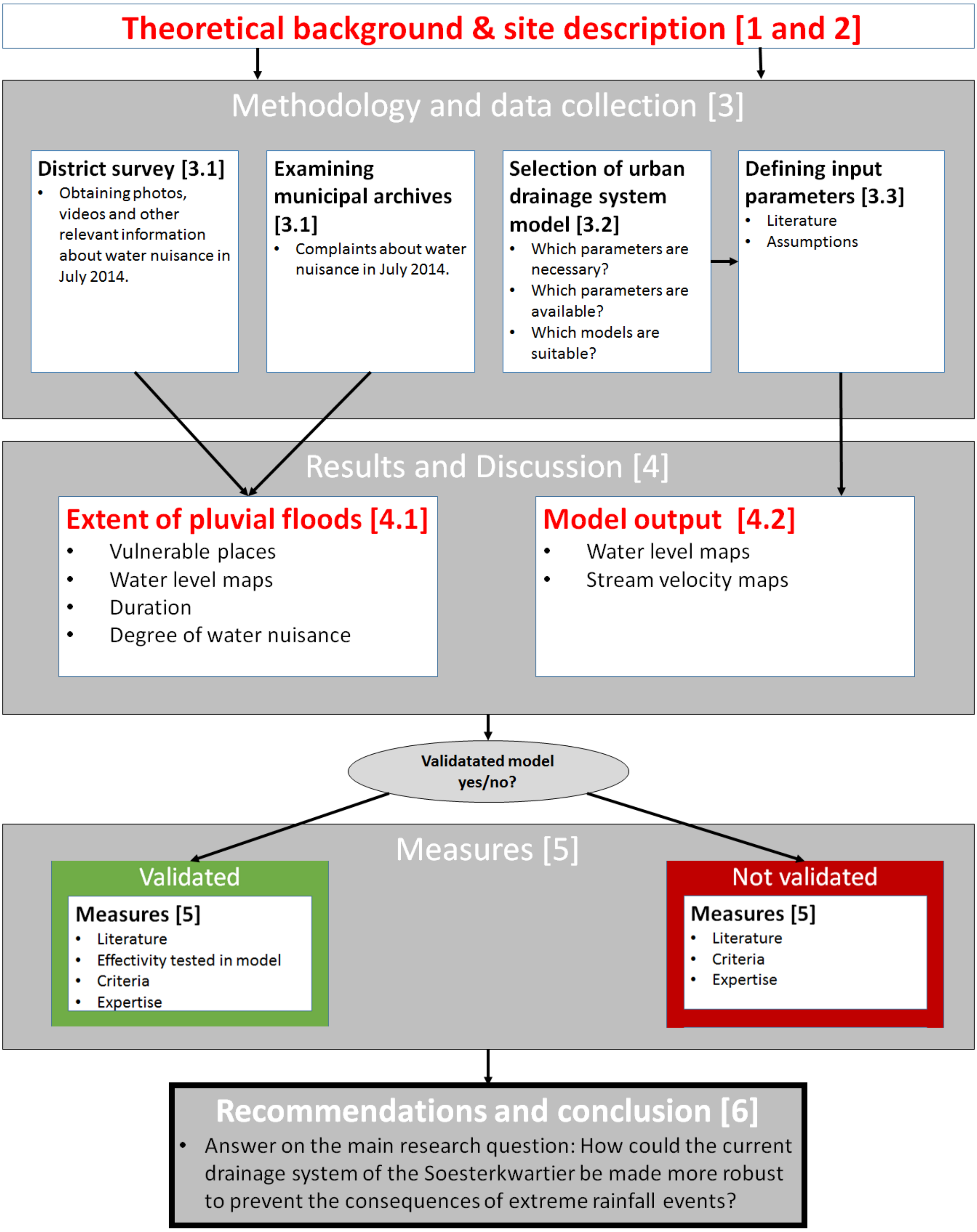


Figure 3.1: Overview of the research set up. The numbers between the brackets refer to the corresponding chapters in which the topics are discussed.

With the help of a district survey and the archive of the municipality the extent of the pluvial floods in July 2014 were described. Parallel to this, a model of the drainage system of the research area was made. This model is based on the heavy rainfall events that occurred in July 2014 and was calibrated and validated with the aid of the results of the district survey and the research in the municipal archives. Subsequently, the best measures to reduce the consequences of extreme rainfall events were given based on the criteria defined in chapter 1.7 and dependent on the validation of the model, the effectiveness of the proposed measures were tested with the model.

3.1 District survey and investigation in the municipal archive

Information about the extent of the two flooding events is obtained via a district survey and from the municipal archives. The municipality's archives contains a file wherein complaints of residents about water nuisance in Amersfoort in 2014 are recorded. This concerns complaints about groundwater, surface water, rainwater and wastewater that the municipality received in 2014. It was examined if this file contains complaints about the water nuisance in the Soesterkwartier due to the extreme rainfall events in July 2014.

Further, more information about the extent of the two pluvial flooding events was obtained by a district survey. By means of a letter, shown in appendix J, the residents were asked to give all the relevant information they have about the two pluvial flooding events in July 2014. This letter was posted on the district website and in the local newspaper. Besides that, more than 800 households received it in their post-box. With the help of the responses and the archives of the municipality the extent of the pluvial floods and the degree of nuisance during and after the heavy rainfall events in July 2014, were mapped.

3.2 Selection of an urban drainage system model

A model was selected which is suitable for modelling the urban drainage system of the Soesterkwartier. There is a great variety of urban drainage system models available, each which its own input requirements needing more or less extensive inputs. The three most important aspects of an urban drainage model are respectively the precipitation input, sewer system (underground) and the surface drainage system. In order to save time on the model setup and parameterization and having more time for a qualitative analyses of the model results it was decided to keep the model simple. Hereby, the sewer system was simplified to a reservoir consisting of a buffer with an inflow and outflow (chapter 3.3.4). As a result, the simplified sewer system and the surface drainage system could be modelled with the help of a rainfall runoff model. Table 3.1 shows the input that is mostly used in rainfall runoff models. To choose the correct model, it was first examined, if all the input could be obtained. The corresponding sources of the input are shown in table 3.1 as well and are further explained in chapter 3.3.

Table 3-1: Commonly used input for urban drainage system models and the origin of this input.

Input of rainfall runoff models	Source
• Sewer system (buffer)	
○ Dimensions (buffer capacity)	KIKKER, 2016 (software of the municipality)
○ Inflow	-
○ Outflow	
▪ Overflow	Results of a Sobek model in 2007
▪ Pump overcapacity	Sewage flow (ROVA) pumping capacity (municipality)
• Surface drainage	
○ Land use	Municipality
○ Infiltration coefficients	RIONED, 2004
○ Elevation map	AHN, 2016
• Precipitation	
○ Rainfall events (11th and 28th July)	HydroNET, 2016

There are many rainfall runoff models on the market with a variety of specifications. There are models that focus predominantly on larger areas like complete river basins or sub basins (RIBASIM: River BASin SIMulation) and models that focus on smaller areas like cities or neighbourhoods (Cityflood). Further there are models like InfoWorks ICM that are both suitable for modelling river and urban catchments (innovyze, 2016). Most of these models are commercially available programs. However, there are also free available software programs like PCRaster Python and OpenLISEM in which universities play often an important role. These software programs are often seen as less complex and less accurate. Nevertheless, in this research is chosen for the free available software because of the lack of access to the commercial programs. It is tested how reliable the openLISEM software is in relation to pluvial flooding in the Soesterkwartier area.

OpenLISEM 3.7 is a spatial hydrological model that is able to simulate sediment dynamics, runoff and shallow floods in rural and urban catchments (ITC, 2013). It is an event-based model that is designed to simulate the effects of detailed land changes or conservation measures during heavy rainfall events (ibid.). It is suitable for small research areas like the Soesterkwartier to research areas of several 100 square kilometres (ibid.). LISEM (the Limburg Soil Erosion Model) is an event based model used in disaster risk management and generally not used for long-term estimates (ibid.). Hereby, it does not include long term processes like evaporation. All input (Appendix I) and output maps in openLISEM are in PCRaster format and are made in this research with the help of PCRaster Python.

PCRaster is a Geographical Information System (GIS) that is raster based. It is suitable for analysing, manipulating and retrieving geographic information (PCRaster, 2016). PCRaster has a relatively open database that permits integration of environmental modelling functions with GIS functions like screen display, database maintenance and hard copy output (ibid.). The map algebra package allows users to build models by means of scripts. *"The central concept of PCRaster is a discretization of the landscape in space, resulting in cells of information (PCRaster, 2016)".* The state of each cell is determined by its neighbouring cells of which it receives and transmits information to and from. With the help of the dynamic modelling language in PCRaster spatial-temporal models can be built. This varies from very simple (point) models up to conceptually complex models like physically-based models for environmental modelling (ibid.).

With the aid of the PCRaster Python extension it is possible to write PCRaster models in Python. In this way, there are two languages that could be used to express the model: the Python programming language and the PCRaster environmental modelling language. In this research, the PCRaster Python extension was used to make all the required input maps (appendix I) in PCRaster format for openLISEM. The most important input maps and assumptions are further explained in chapter 3.3. Subsequently, the maps were loaded in openLISEM which simulated the water level on the surface. OpenLISEM uses bilinear interpolation to simulate overland flow and it could represent the water level in each cell per timestep.

3.3 Modelling input

This section discusses the origin of the data that was used as input for the model and the different steps and assumptions that were taken to realize the rainfall-runoff model. The resolution of the input maps for openLISEM in this research was set to one square metre (1 m^2). This was never done before in openLISEM so it was first tested if it would work. The smallest resolution that was used before is 5x5 = 25 m^2 but in that case too much important detail would have been be lost such as elevation differences between the sidewalks and the street.

3.3.1 Land use classes

The research area is divided into different land use classes that have different rates of infiltration. The subdivision of land use classes made in this research is based on the four main types of draining surface used in the Leidraad Riolering C2100 (RIONED, 2004). These are respectively:

1. Closed paved area;
2. Open paved area;
3. Roof surface;
4. Unpaved area.

In the Leidraad Riolering C2100 these four main types of draining surfaces are all divided into three subclasses based on the slope of the surface. The minimum and maximum infiltration capacities are the same for the different slopes of the four main types of draining surface (RIONED, 2004).

In this research the four main types of draining surfaces are subdivided into seven different land use classes based on their infiltration capacity and the available maps (water, buildings, pavement and property of the municipality of Amersfoort). The pavement map distinguishes three types of pavement: Asphalt, open pavement (e.g. bricks and tiles) and a third type that exists of unclassified pavement (<1% of the surface area). Approximately 80 percent of the pavement in the research area is open (e.g. bricks and tiles) and 20 percent is made of Asphalt. The seven land use classes distinguished in this research are:

- a) Closed paved area;
    1. Asphalt
- b) Open paved area;
    2. Open Pavement
    3. Remaining pavement
- c) Roof surface;
    4. Buildings
- d) Unpaved area.
    5. Green areas of the municipality
    6. Water
    7. Private areas (partly unpaved)

The roof surface class in the Leidraad Riolering C2100 distinguishes between flat and sloping roof surface. However, in this research only one class (buildings) which represents the sloping roof surface, is used for the roof surface class because the proportion of flat roof surface is very low in the Soesterkwartier. Further, the seven different land use classes are represented in figure 3.1. The 'private areas' class exist of both paved (driveway, terrace, e.g.) and unpaved areas and do not include buildings. In general, the degree of impermeable surface area of private property in the Soesterkwartier is high. This is inter alia the consequence of too few parking spaces in the district whereby house owners pave their own property to ensure a parking spot. In 2015, the lack of parking places was part of the problem top three of the Soesterkwartier which was compiled by residents (stadspeiling O & S, 2015). Besides, the private areas are relatively small whereby often a relatively high percentage of the garden is paved. The fraction paved area of private property in this research is estimated at 0.7 and is based on observations in the district and on aerial images. The value is based on the places in the district which have the highest percentage of paved area. This is done to prevent an underestimation of the pluvial flooding problem in the district.

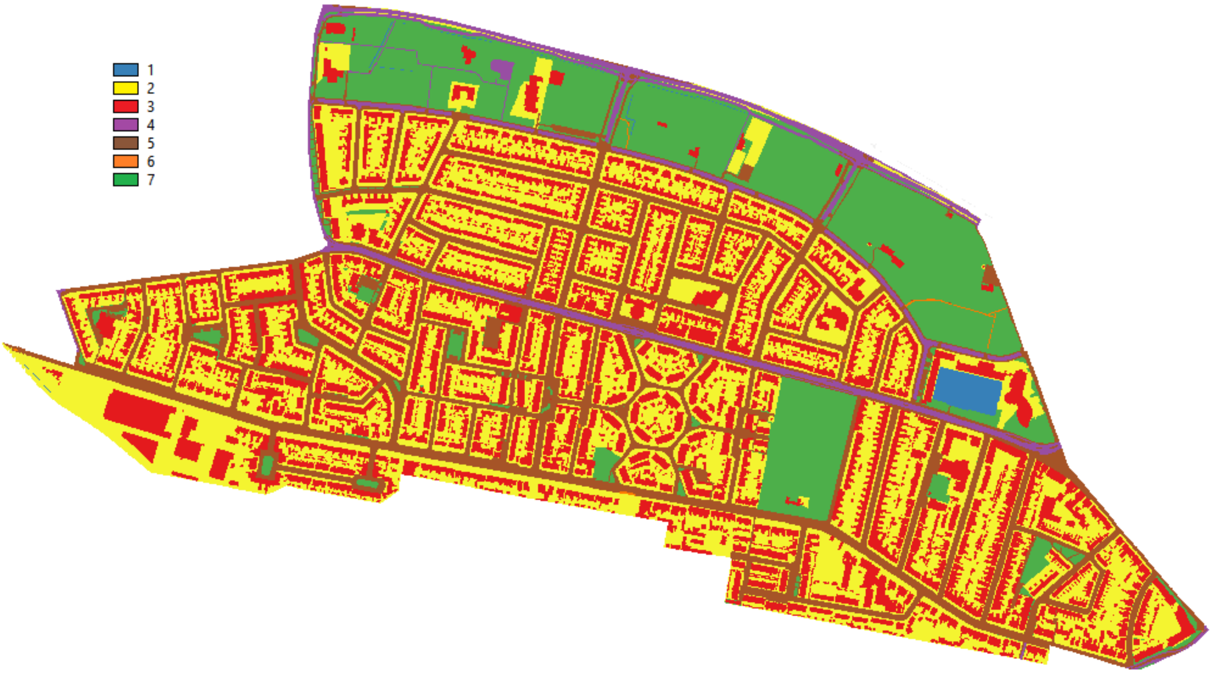


Figure 3.2: Land use classes that are used in the model. 1) Water, 2) Private areas, 3) Building, 4) Asphalt, 5) Open pavement, 6) Remaining pavement, 7) Green areas of the municipality.

3.3.2 Infiltration rate

An infiltration rate is assigned to all land use classes that are distinguished in chapter 3.2.1. Most of the infiltration rates are derived from the Leidraad Riolering C2100 and are shown in table 3.1. Buildings have just as asphalt surfaces (closed roads) an infiltration rate of zero. The open roads exist of pavement which has joints such as bricks and tiles whereby a small amount of rain could infiltrate. This infiltration rate is dependent on the size of the joints, the age, the type of use, the extent of use and maintenance. In the model, the infiltration rate of open pavements is also used for the land use class 'remaining pavement'. For the green areas of the municipality, the infiltration rate in the model is determined on four mm/hour. This is based on the infiltration rate value of unpaved surface in the Leidraad Riolering C2100 and the soil conditions of the green areas in the Soesterkwartier.

Table 3-2: Infiltration rate of different types of surfaces. The min and max values are derived from RIONED, 2004.

Surface type (RIONED, 2004)	Infiltration rate [mm/hour]		Land use class in model	Infiltration rate used in model
	min	max		
Roof	0.0	0.0	Building	0.0
Closed road	0.0	0.0	Asphalt	0.0
Open road	0.5	2.0	Open pavement	1.0
			Remaining pavement	1.0
unpaved surface	1.0	5.0	Green areas of the municipality	4.0

The infiltration rate of the land use class 'private areas' is calculated based on the infiltration rates of the surface types 'open road' and 'unpaved surface area' given in the Leidraad Riolering C2100 and the ratio paved/unpaved area of private property given in chapter 3.2.1. It is calculated as follows:

Fraction paved area of private area = 0.7, infiltration rate of paved area = 1.0 mm/hour
Fraction unpaved area of private area = 0.3, infiltration rate of unpaved area = 4.0 mm/hour
Infiltration rate private area in research area = (0.7*1.0) + (0.3*4.0) = 1.9 mm/hour

The last land use class is water which corresponds with a pond in the northeast of the district and has an infinite infiltration rate in the model. This means that there will not be any runoff from this class during a heavy rainfall event.

3.3.3 Local drainage direction map and digital elevation map

The local drainage direction (ldd) map is made with the help of the elevation map of the research area and the PCRaster software. The elevation map is downloaded from the website of AHN (Actueel Hoogtebestand Nederland) and has a raster of 0.5 meter. It contains cells without value (missing values) that had to be corrected (Appendix F). Further the map is smoothed with the help of the *windowaverage(dem.map,5)* function in PCRaster. This was done because otherwise the stream velocities calculated with 2D interpolation were very low (~10^-5 m/s)) whereby the water on the street would barely move between cells (Jetten, 2016). With a smoothed elevation map, the stream velocities in the model increased to more realistic values (~dm/s). After that a ldd map of the research area was made with the help of the *lddcreate(dem.map, 1e31,1e31,1e31,1e31)* function in PCRaster. With the four high values (1e31) the pit cells, which are the cells that do not have a drainage direction because these are surrounded by cells with a higher elevation, were removed. This needed to be done to run openLISEM correctly.

3.3.4 The sewer system

In this research, the sewer system is simplified to a reservoir consisting of a buffer with an inflow and outflow (figure 3.3). As said before in chapter 3.2, this is done to save time to spent more time on analysis of the results. The inflow of the sewer system exists of rainwater runoff and sewage. The sewage flow is taken constant and is derived from data of the sewer pumping station (NL:rioolgemaal) during a dry period. The sewer pumping station is managed by the ROVA and processes on average about 95 m^3 of sewage each hour (Goedhart, 2016).

The combined sewer system of the Soesterkwartier has two outflow points which are the sewer pumping station and the internal sewer overflow near the Amsterdamseweg (figure 1.7). The pumping capacity of the sewer pumping station is derived from an internal file of the municipality and is about 550 m^3/hour. Hereby the pump-overcapacity which is the pumping capacity minus the sewage flow is set on 455 m^3/hour. The internal overflow is not used in dry weather circumstances. However, when the system is filled, the largest part of the sewer water is transported via the sewer overflow. With the aid of a SOBEK model from 2007 the sewer system of the research area was tested for a rainfall event of 20 mm/hour (Bui 8) and the maximum value of the discharge was approximately 1,7 m^3/s. This coincided with the time that the storage capacity of the system was reached.

In 2014, two holes with a diameter of 300 mm were made in the internal overflow with the idea to discharge earlier and more water out of the system. However when these holes were implemented in the SOBEK model, it appeared that the holes only reduced the water level on the overflow (NL: overstortende straal) whereby less sewer water was transported over the overflow. Instead, this water was transported via the holes. The discharge in the sewer pipe downstream of the sewer overflow stayed practically the same. From this could be concluded that the discharge over the internal overflow is limited by the supply of water via the sewer pipes. Hereby the same discharge as the SOBEK model from 2007 of 1.7 m^3/s will be used in this research.

The amount of runoff for each cell in the model is calculated by subtracting respectivily the corresponding infiltration rate and pump-overcapacity (appendix D) from the absolute precipitation of five minutes (Appendix G). The runoff will follow the ldd map and will accumulate on the lowest points of the map or will enter the sewer system.

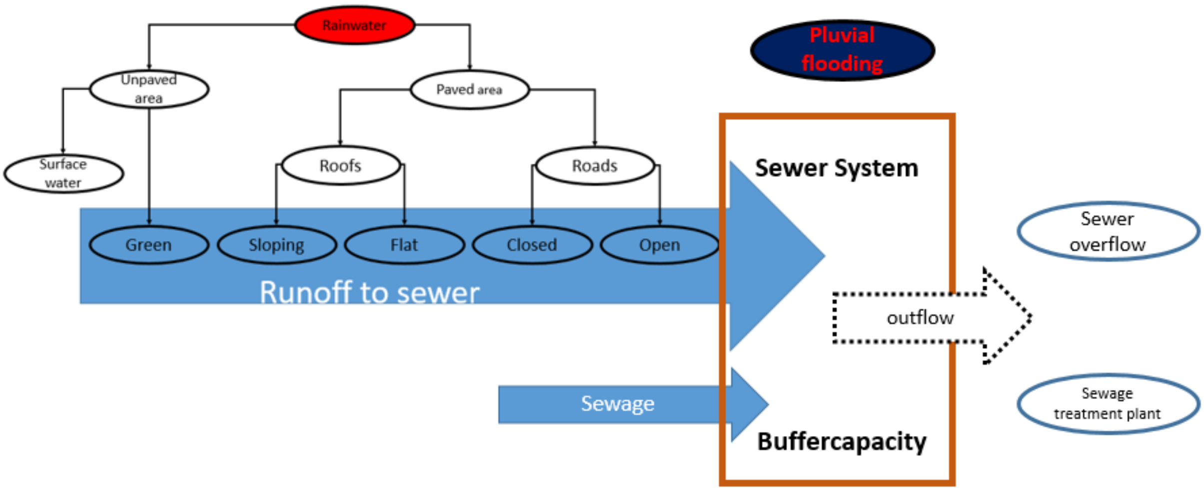


Figure 3.3: Schematic representation of the parameters that define the in- and outflow of the sewer system. Pluvial flooding occurs when the sewer system is filled and the inflow exceeds the outflow.

In this model a few assumptions are made in relation to the runoff and the sewer system:

- All the runoff will enter the sewer system untill the storage capacity of the sewer system is reached. This is done because no PCRaster map is available with detailed information about the sewer system. Hereby, the software could not read data such as the exact places of the sewer inlets, velocities/resistances within the system and, about the local capacity of the sewer system.
- The internal overflow will start to function in the same timestep as the storage capacity is reached. This corresponds with the SOBEK model (2007) where in less than ten minutes (two timesteps), the discharge over the internal overflow went from zero to its maximum value of approximately 1,7 m^3/s.
- The amount of water that is discharged over or trough the internal overflow is kept constant. As long as the system is completely filled there will be no big changes in pressure whereby the discharge over or through the internal overflow will stay constant.
- The pumpovercapacity (mm/5min) and internal overflow (mm/5min) are homogeneous distributed over the whole research area. This means that these parameters are the same for each cell whereby they can be deducted from the precipitation which is also the same for every cell.

3.3.5 Net Precipitation map

In the model two historical rainfall events that respectively took place on the 11th and 28th of July 2014 are modelled. The precipitation values of these two historical events in the Soesterkwartier are derived from HydroNET. These absolute precipitation values are given for an area of one square kilometre for every five minutes and are shown in figure 3.4. The same duration of a single timestep is used in the model to limit runtimes. It makes no sense to reduce the duration of a single timestep because it will increase the runtime and the other time dependant input variables that are used as input for the model are also given for durations of at least five minutes.

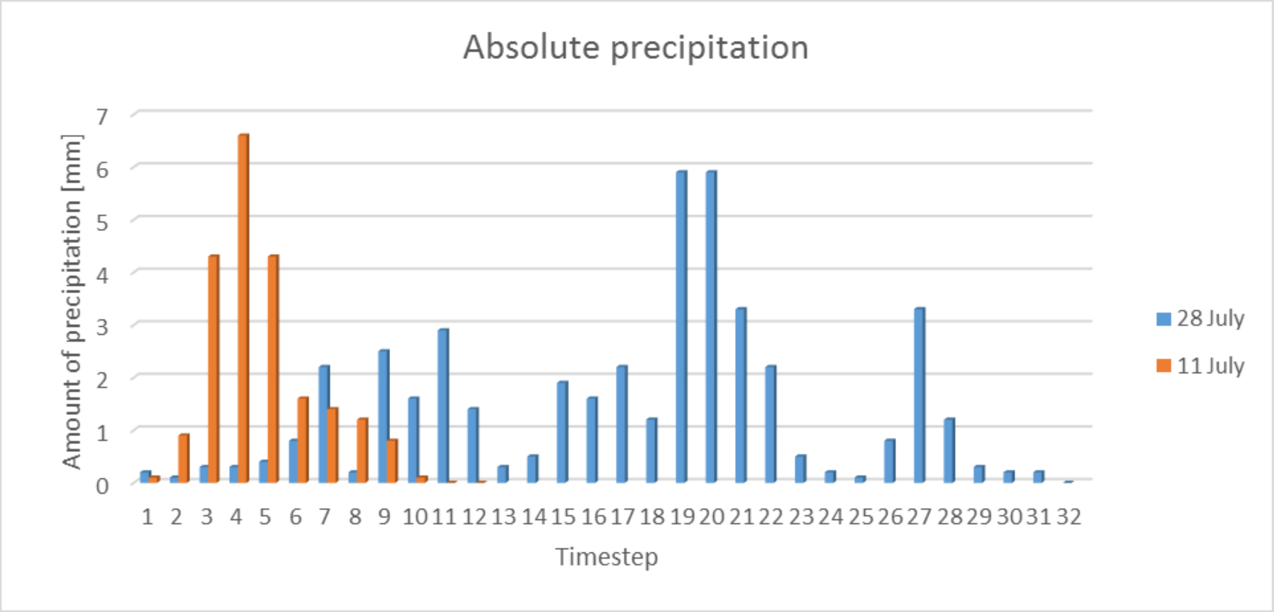


Figure 3.4: Absolute precipitation amounts for the rainfall events of 11 and 28 July 2014. Every timestep corresponds with a period of five minutes (Data from HydroNET, 2016)

In Appendix G is shown in which way the net precipitation values are calculated. The net precipitation value is calculated because openLISEM does not include the sewer system parameters and has an option to simulate a research area without infiltration. The net precipitation value is the amount of rain that does not enter the sewer system or infiltrate into the ground. It will stay at the surface and runoff following the ldd map. The net precipitation maps that are loaded in openLISEM are made with the help of PCRaster Python for all time steps in which the sewer system is filled. Herein, it is assumed that all the water that falls on the buildings is equally distributed over the three pavement classes based on the ratio building/pavement of each of the five districts. Besides that, the infiltration values of each cell are subtracted from the Net P on the basis of the land use classes (figure 3.1).

4. Results

In this chapter the results of the district survey will be discussed first in subchapter 4.1. After that, the results of the rainfall runoff model will be given and discussed in subchapter 4.2. Central in these subchapters are respectively the following sub questions of this thesis (chapter 1.6):

- *What are the current vulnerable locations of the drainage system of the Soesterkwartier when extreme rainfall occurs? [chapter 4.1]*
- *Could the current drainage system of the Soesterkwartier be modelled for extreme rainfall events with the help of openLISEM and does this correspond with reality? [chapter 4.2]*

4.1 Vulnerable places of the current drainage system of the research area

The message on the district website, the local newspaper and the letter for the households in the research area resulted in approximately 60 reactions and more than 75 photos and videos of the rain water nuisance that was caused by heavy rainfall events. The reactions were predominantly about water nuisance in certain areas of the district but also some residents mentioned that they never had suffered from water nuisance. Further, seven complaints of residents about the water nuisance during and after the rainfall events in July 2014 were found in the archive of the municipality.

In total, respectively 49 and 24 photos and videos about the heavy rainfall events of the 11th and 28th of July 2014 were received. Appendix L is shows how many photos and videos were received from both problem areas for each rainfall event. It is not possible to give an exact duration of the water on street because for all videos and for a substantial portion of the photos the exact time is unknown (Appendix L). Moreover, the photos for which the time they were taken was known, were taken with different cameras. As a result the time settings could vary which could result in a large insecurity. Furthermore, there are no photos or videos of the start or end of the water on street.

In figure 4.1 an overview is given of the photos received from the residents. These photos are from both rainfall events because not for every place photos were available of both dates. Based on the photos, videos and stories received from the residents and the complaints that the municipality received after the rainfall events in July 2014, roughly two vulnerable locations could be distinguished in the research area (figure 4.1):

1. Soesterweg, Hulststraat and Palmstraat
2. Spaarnestraat and Dollardstraat

Almost all the information about pluvial flooding received from the residents felt within these two areas. Based on this information and the elevation maps of both vulnerable areas, a description of the extent of the water nuisance is given in chapter 4.1.1 and the water level maps shown in figures 4.2B and 4.3B are made for the 11th of July. These maps give an indication of the minimum water levels on the street that are reached due to the heavy rainfall event.

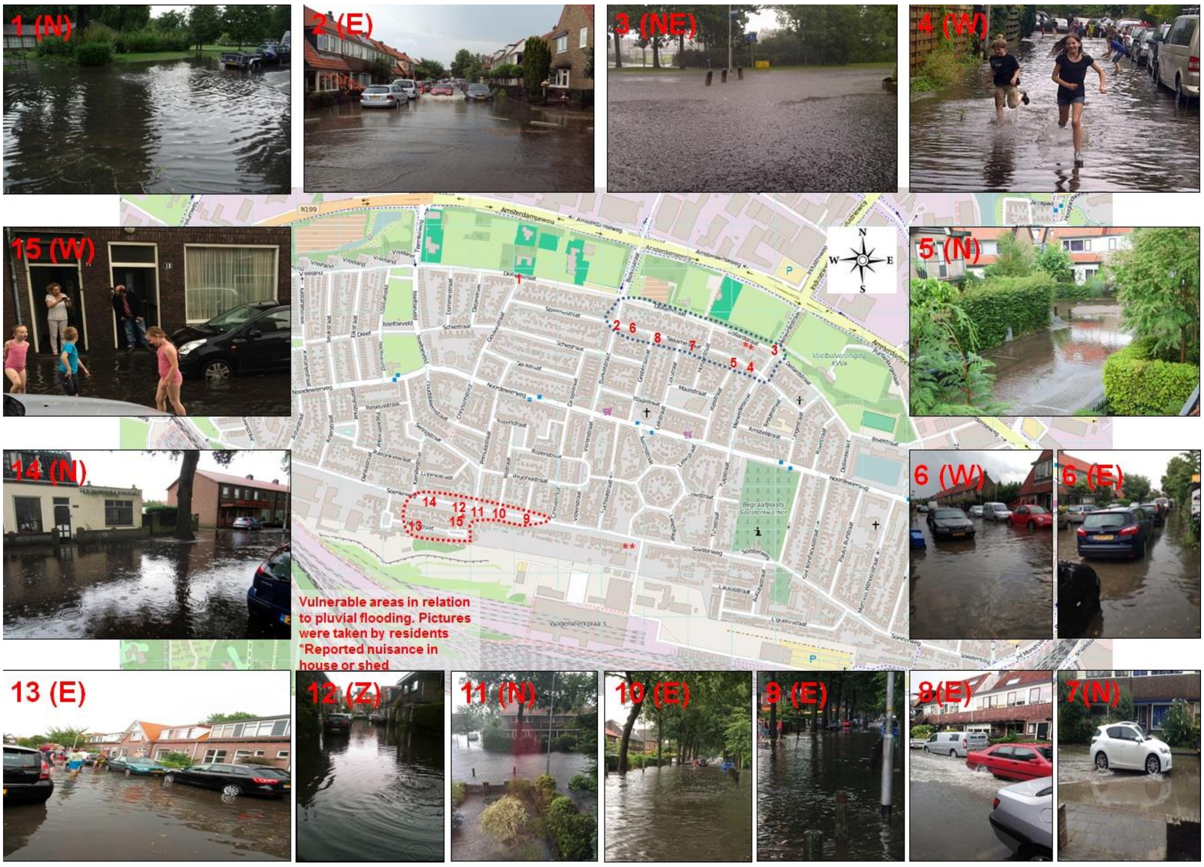


Figure 4.1:Overview of a part of the pictures received from the residents. The red dotted line indicates area 1 and the blue dotted line represents area 2. Magnification of this figure is shown in appendix L.

4.1.1 Description of the flooding event in both problem areas on the 11th July 2014

In problem area 1 is the junction between the Hulststraat and Palmstraat the lowest area (figure 4.2A). Water flowed from both the east and west of the Soesterweg in the direction of the Hulststraat. Hereby, a speedbump that is located over the entire T-junction of the Soesterweg with the Primulastraat (figure 4.2A) forms an obstacle for the water from the east. As a result, a large part of the Soesterweg and the sidewalks on the eastern side of this speedbump and a few front gardens nearby the speedbump were flooded before the speedbump was (partly) inundated and water would flow from this area towards the Hulststraat. From the western side, there are no obstacles on the Soesterweg and water could flow directly towards the Hulststraat. The difference between the street level of the Soesterweg and the sills of the front doors of the houses is considerable so there was no direct danger the water would enter the houses in this street.

On the other hand, the water stood in the Hulststraat just a few centimeters below the front door sills which are directly connected to the sidewalks. The situation at the time of maximum water level was so critical that water would enter the houses if a car would drive through the street. One resident in this street has, as a result of several pluvial floods in the recent years, even made a barrier that could be placed in front of the door to prevent water from entering his house.

In the Palmstraat the water reached also high levels around the green area. However, there was no direct danger from the pluvial flooding because of the high sills of the houses south of the green area. The green area itself was barely flooded because it is approximately 15-20 centimeters higher than the lowest parts of the surrounding street. The Palmstraat between the speedbumps was also flooded but the to prevent water from entering his house. water did not come further than the sidewalks or halfway the front gardens.

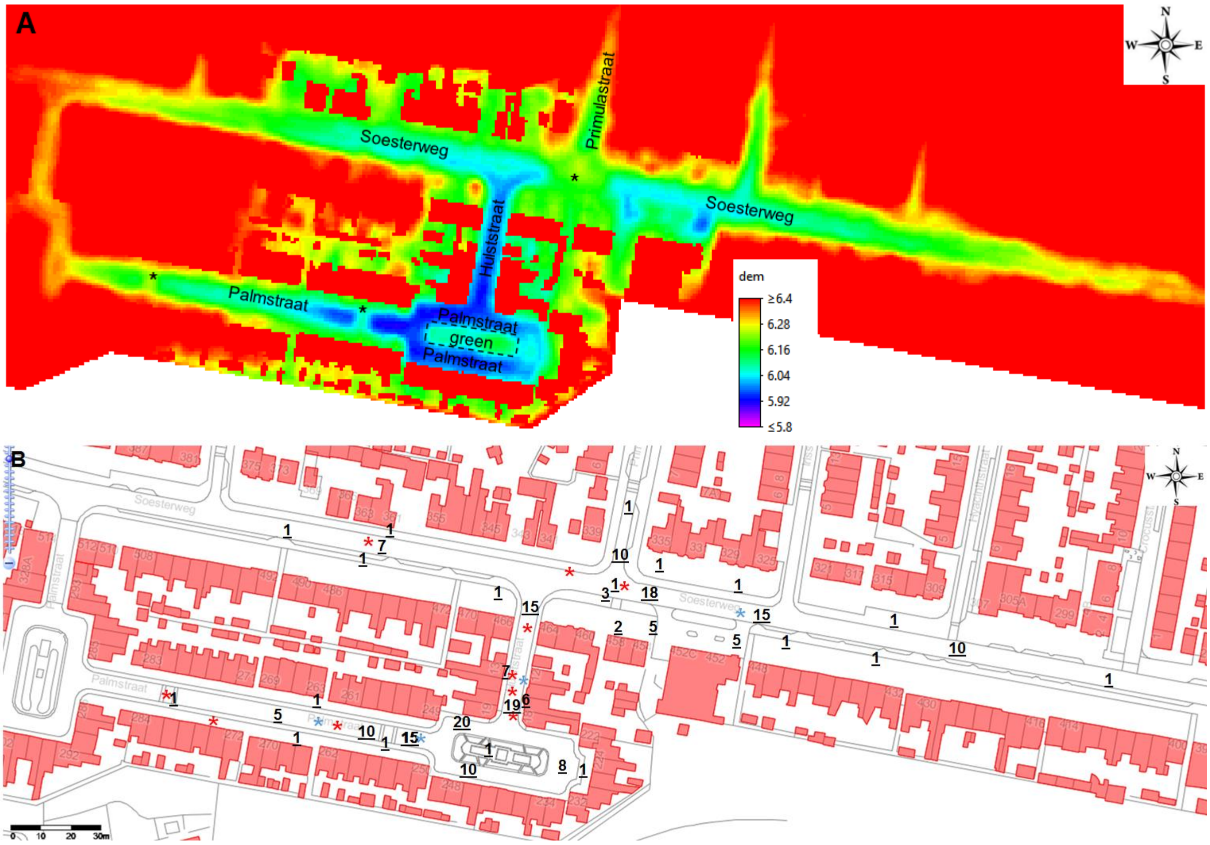


*Figure 4.2: A) Elevation map [m] of problem area 1. The black * indicate speed bumps. B) An approximation of the water levels that are minimally reached in area 1 on the 11th of July 2014. These numbers are based on analysing the photos, videos and reactions of the residents and the elevation map. Blue stars are places of which videos of the flooding are available and red stars indicate places with photos of the flooding.*

In problem area 2 the surface level globally decreases from the Noordewierweg in the direction of the Dollardstraat. The streets with a north-south orientation have, for Dutch terms, a relatively steep gradient of approximately 0.01 whereby rainwater will flow relatively fast over the surface from south to north. Multiple residents of these streets described their street as ‘small rivers’ during extreme rainfall events. The water from these ‘rivers’ accumulated in the Spaarnestraat and Dollardstraat which are east-west orientated. At all the junctions between these streets with the north-south orientated streets are speedbumps positioned except of the junction between the Dollardstraat and Hunzestraat (figure 4.3A). Hereby the flow stagnated and large puddles arose south of the speedbumps before these were inundated. The Spaarnestraat and most of the sidewalks were completely flooded between the Berkelstraat and Merwedestraat. The water level in this street was strongly dependent of the height of the speedbumps that were (partly) inundated (0-3 cm). The water flowed from the junctions with the Berkelstraat, Hunzestraat and Merwedestraat in the direction of the Dollardstraat were also large parts were flooded. Here the water level in the street was strongly dependent of the height of the northern sidewalk and the adjacent part of the Groengordel. When the water reached this level, it flowed towards the lower situated part of the Groengordel lying behind. The sills of the houses on the south side of the street are located sufficiently high whereby water did not enter the houses via the surface.

The rainfall event of 11th July resulted in 21,4 mm in 50 minutes time. Although this amount in such a time is surely not uncommon (return period T = 5 years; figure 2.3), this event caused high water levels on the street in the problem areas. This is probably largely due to the peak of 15.2 mm in only fifteen minutes (T=5; figure 2.3) at the start of the rainfall event (t3-t5). As a result, air was trapped in the sewer pipes (figure 4.4) such that the flow velocity decreased drastically and the sewer system did not function as the way it should be functioning. This resulted in high hydrostatic pressures upstream of the trapped air such that the water flowed out of the sewer system in these areas. This was confirmed by the reactions of the residents who stated that sewer water came out of several manhole covers in the Hulststraat, Spaarnestraat and Dollardstraat. This could also be seen in the photos 1 and 12 in figure 4.1 and in figure 4.4 on the right photo.

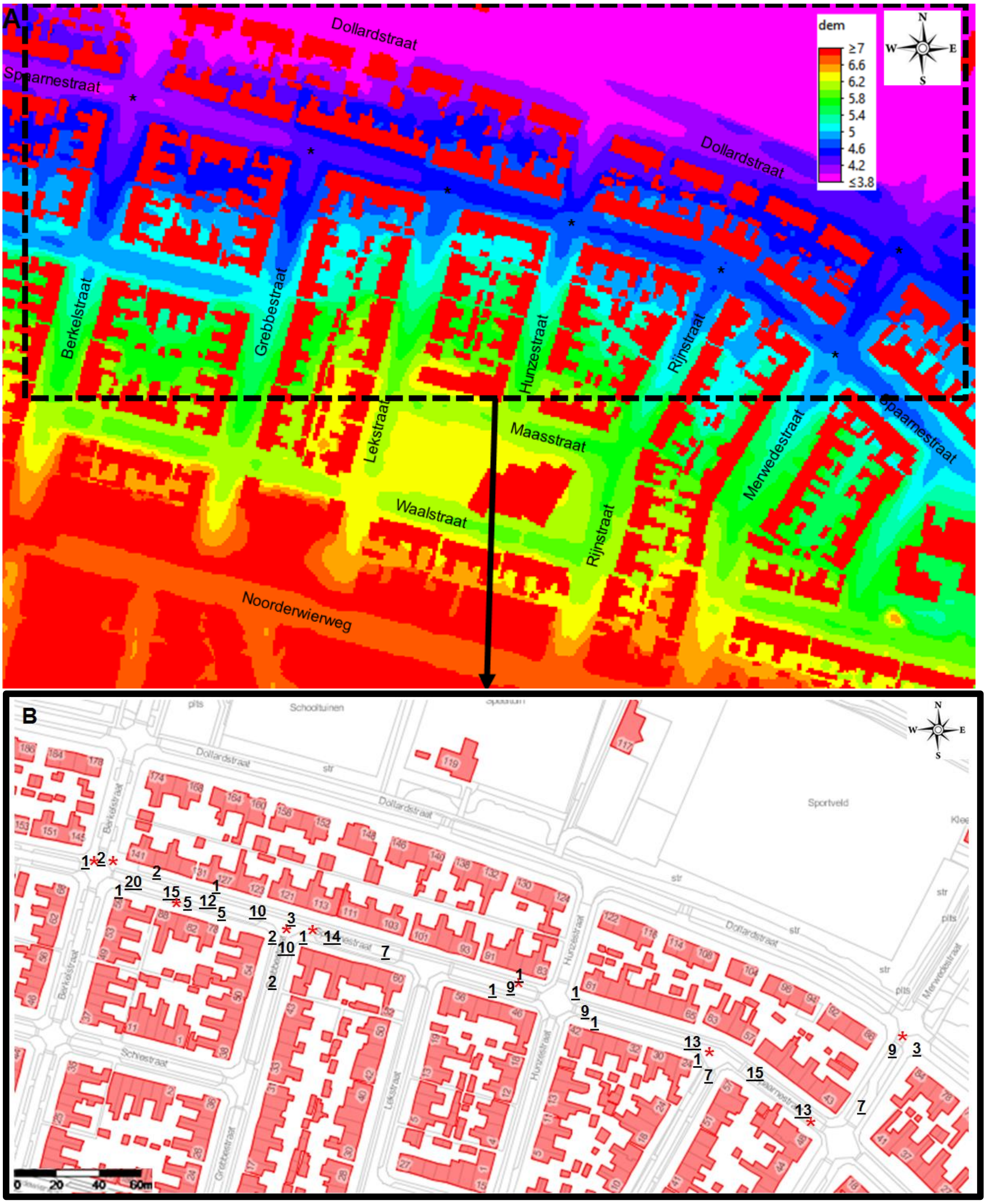


*Figure 4.3: A) Elevation map [m] of problem area 2. The black * indicate speed bumps. B) An approximation of the water levels that are minimally reached in area 1 on the 11th of July 2014. These numbers are based on analysing the photos, videos and reactions of the residents and the elevation map. Red stars indicate places with photos of the flooding.*

All in all, the flooded streets resulted not into considerable economical damage. The water on the street did not flow via the surface into houses because the streets are laying low with elevated sidewalks on both sides. In case there is a front garden, this rises towards the front door, which has a sill sufficiently higher than the street for the rainfall event of the 11th of July. However, it should be noted that in especially the Hulststraat the situation was critical because the water could not flow away from this area. This means that during rainfall events with more rain in the same amount of time the water on the street will probably reach a higher level than on the 11th of July 2014. This is not the case in problem area 2 because during the rainfall events in July 2014 the water level in the street rose to respectively the level of the speedbumps in the Spaarnestraat and northern sidewalk in the Dollardstraat. In first instance these objects blocked the water but when these were inundated, water flowed further downstream and finally ended in the Groengordel. A larger amount of rain in the future will lead to approximately the same water levels in the Dollardstraat and Spaarnestraat and in more overland flow towards the Groengordel.

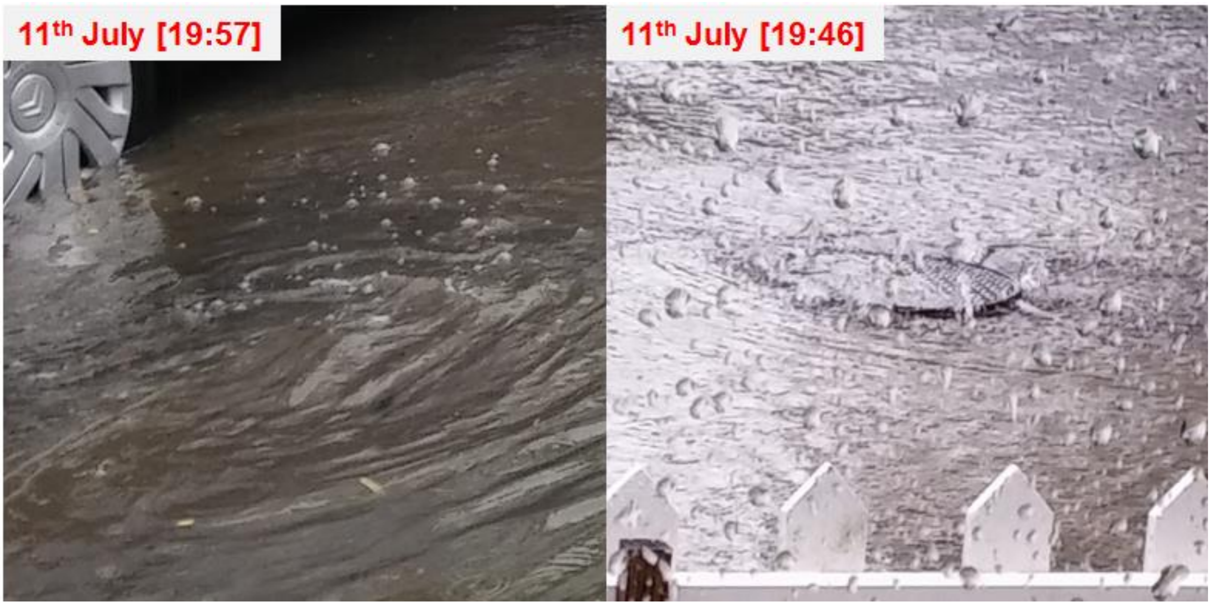


Figure 4.4: Left) Air bubbles above a storm drain located 15 meters to the west from the second picture. Right) Sewer water flows out of a manhole cover on the T-junction between the Spaarnestraat and Grebbestraat. Both pictures are taken with the same camera.

4.1.2 Comparing the rainfall events of the 11th and 28th of July 2014

For the 28th of July, there was not enough information available to produce the same water level maps as for the 11th of July. Besides that, there is only one exact spot of which information is available of both rainfall events. This place is located east of the Primulastraat on the Soesterweg. In the first instance, it seems that the water levels in this place during both rainfall events did not differ much from each other which is quiet surprising because the return periods of both events differ significantly (figure 2.3). Also if other pictures and videos made in other places in the problem areas on the 28th of July are compared with the water level maps of the 11th of July in chapter 4.1.1 and the elevation map, the water level does not seem to deviate much from each other. However, it should be noted that comparing the photos and videos from both rainfall events is very unreliable because the videos do not have an exact recording time, the structure of the rainfall events are completely different and the most places do not have information about the water levels of both events whereby it is almost impossible to take any conclusions.

The total amount of rainfall during the 155 minute rainfall event on the 28th of July was 44.7 mm. The event started and ended with low rainfall intensities. Between 20 and 140 minutes after the start of the event 43.1 mm fell, which has a return period of approximately 70 years (figure 2.3) which is much higher as the return period of the rainfall event of 11 July (T=5). However, the peak of the rainfall event of the 28th of July (15.1 mm) fell between 90 and 105 minutes after the start of the event. In contrast to 11 July probably no air was trapped because before the peak already 20.6 mm was fallen whereby the sewer system was presumably largely filled. When subsequently, the peak intensities occurred this resulted in large quantities of water on the street. Following observations also during this event water flowed out of the sewer system in the Spaarnestraat, Dollardstraat and Hulststraat.

4.1.3 The degree of water nuisance

The municipality distinguished three types of water nuisance which are described in the introduction:

1. Hindrance
2. Material or economical damage
3. Severe material or economical damage

Hereby, there are some grey areas in between the categories whereby it is difficult to place the water nuisance during the rainfall events in July 2014 in a certain type of category that is distinguished by the municipality.

First, no distinction is made between the type of water nuisance. In both problem areas sewer water came out of the sewer system during both rainfall events whereby odor nuisance occurred. Some parts were littered with toilet paper and faeces after the water was withdrawn. This resulted in additional cleaning costs. Besides, the sewer water on the street caused increased health risks. Largely because many residents, whose especially children, ventured in strolling through the polluted water on the street during or just after the rainfall event.

Secondly, reactions confirmed that on the most places the water was withdrawn within one hour (short duration). However, the water level on the street was significant (>5cm) in large parts of the problem areas. This situation falls in between the first two types of water nuisance. Further, only four houses in the research area responded that sewer water had entered their house via domestic sewer pipes (appendix D). This was caused by the high pressure in the sewer system and the lack of check valves in the domestic sewer pipes. However, since the event check valves have been constructed at these locations.

In conclusion, the nuisance of the rainfall events in July 2014 can not be categorized in one of the types distinguished by the municipality in the GRP (2012). It falls somewhere between the first two categories. The actual damage due to the rainfall events seems to be low because the district is well designed. However, the sewer water on the street caused increased health risks.

4.2 Results of the rainfall runoff model

Here the outcomes of the openLISEM rainfall runoff model are compared with the outcomes of chapter 4.1. The results are further discussed based in light of the general assumptions of the model and the input parameters that are used in this research. The goal of this chapter is to answer the fourth sub question (chapter 1.6) of this research:

> *Could the current drainage system of the Soesterkwartier be modelled for extreme rainfall events with the help of openLISEM and do the results correspond with reality?*

Figures 4.5 and 4.6 show the simulated water level maps directly after the end of the rainfall events on respectively the 11th and 28th of July. In figure 4.7 four maps are shown which represent respectively the velocity, water height (relative to surface level), water surface height (relative to Dutch Ordnance Level: DOL), and elevation of a certain spot in the research area. The findings made for this spot are representative for the whole model.

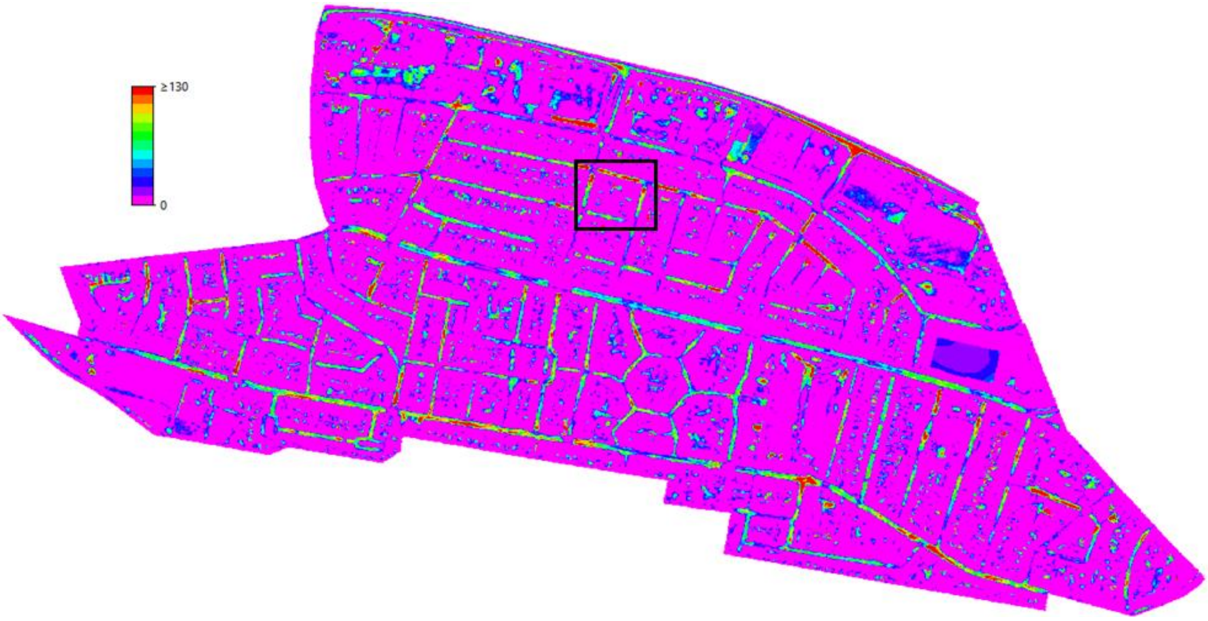


Figure 4.5: Water levels [mm] directly after the end of the rainfall event on the 11th of July. Black square indicates the location of figure 4.7.

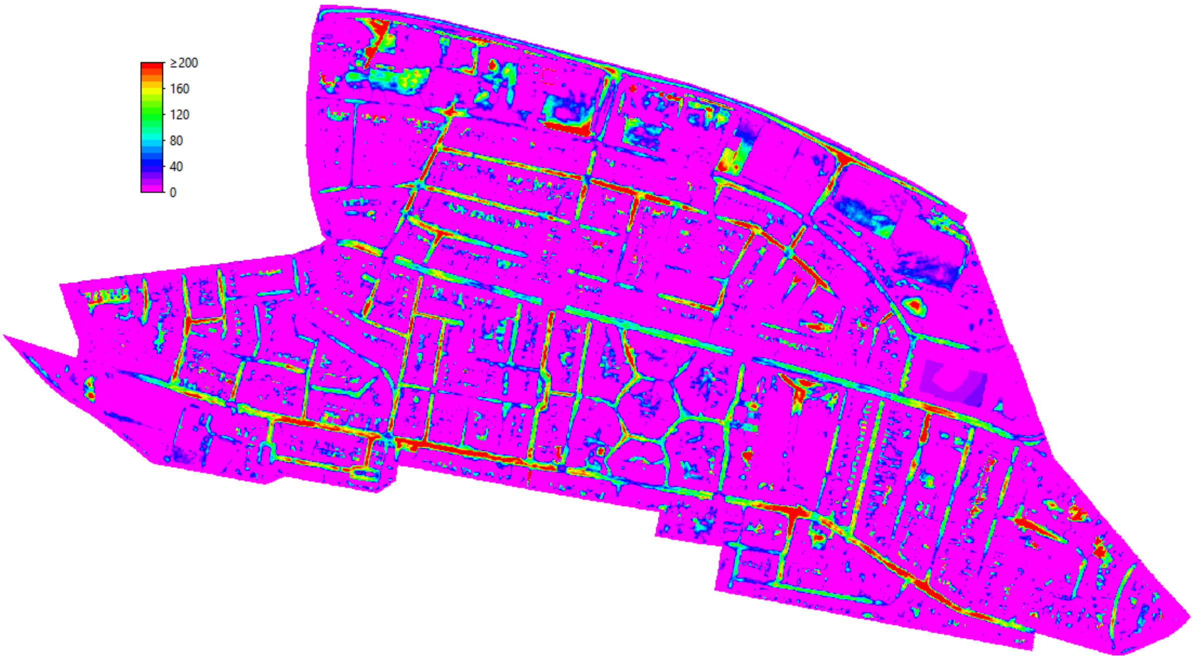


Figure 4.6: Water levels [mm] directly after the end of the rainfall event on the 28th of July

The first thing that stands out is that almost all streets are completely flooded and have water levels of three centimetres or more which does not correspond with the information received from the residents. This is probably caused by the fact the sewer parameters are homogeneously distributed over the research area. Hereby, every cell and thus also every land use class in the model has the same sewer inflow capacity which makes that this parameter is (strongly) underestimated in some parts. This is particularly true for the areas for which the hydraulic gradient of the sewer is in reality located underneath the surface levels of the sewer inlets (figure 4.8). Also, if the hydraulic gradient is higher than the surface level of the sewer inlet, water will flow out of the sewer system. These return flows is also not simulated by the model.

The second thing that stands out is that the flow velocities are very low on the places a certain water level is found while there is a is a certain elevation difference (dem figure 4.7). On the first sight this is logical because when puddles are formed the flow velocities would drop to (almost) zero. However, in that case the water surface level (wsh) which is the sum of the water height and the elevation, of these puddles must be practically flat which is not the case here (figure 4.8). In the model the water surface level has a relatively steep gradient while the velocities are very low (order of mm/s) at the places with water on the street. Hereby the water on the streets barely moves. Changing the input parameters of the model has no influence on this process so it depends on the functioning of the model.

OpenLISEM use 2D bilinear interpolation to divide, the water flux over the downstream cells based on the elevation map and the water height from the timestep before. This way, the new water height is calculated. Subsequently, the new water height is used to calculate velocity and discharge, which is routed with the kinematic wave. Hereby, openLISEM does not include pressure differences (3D) or acceleration. The model calculates velocities, discharges and water height on a cell-to cell basis and does not look at a larger scale. Thus, the small local differences could disturb the bigger picture. However, on the other side the small resolution is also important for the accuracy of modelling pluvial flooding because otherwise factors that influences the flow direction like curbs and speedbumps are faded.

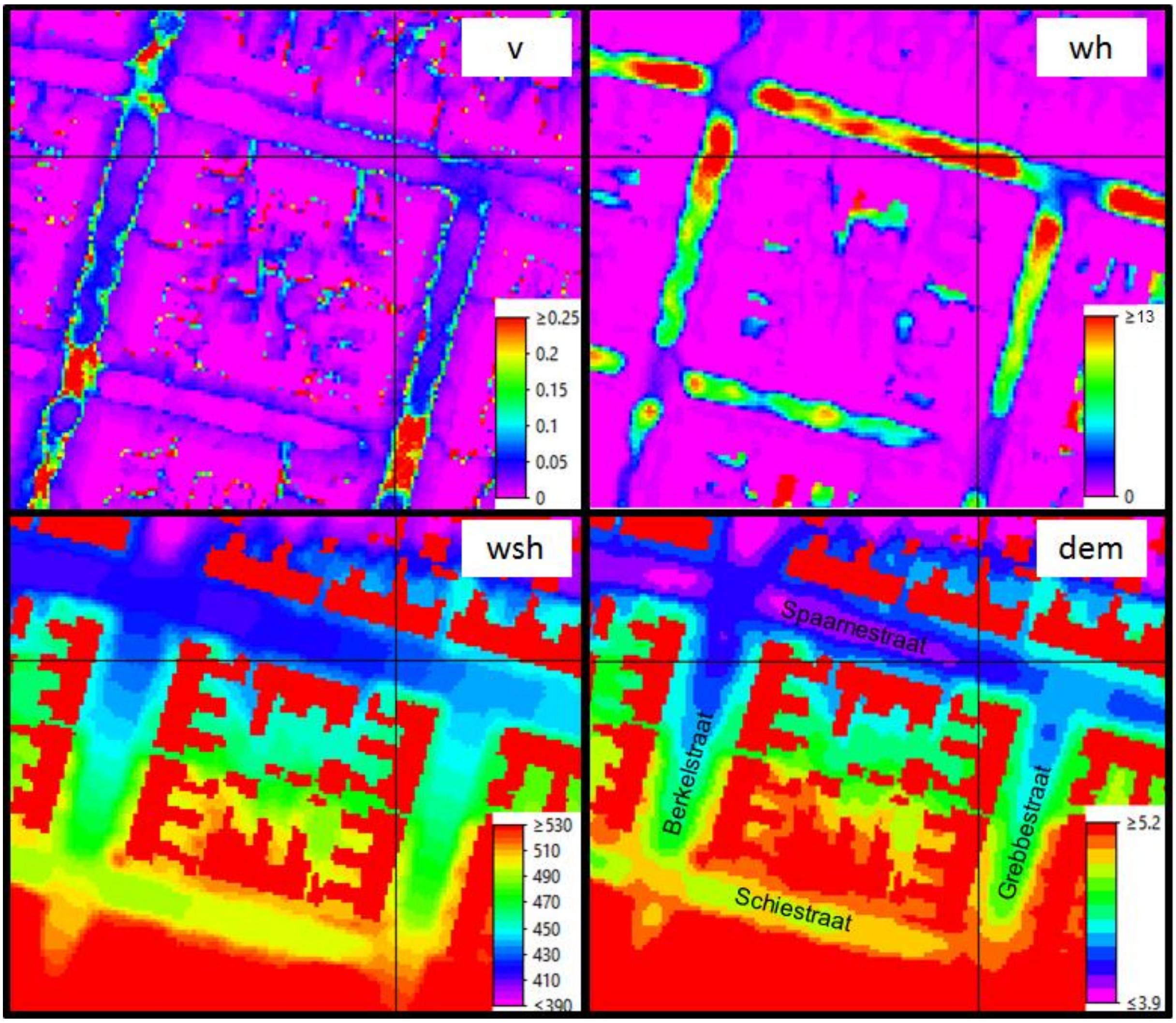


Figure 4.7: Resulting maps of openLISEM for a specific area (see figure 4.5). V= velocity [m/s]; wh= water height [cm]; wsh= water surface level in relation to DOL [cm]; dem= digital elevation map in relation to DOL [m].

In conclusion, to answer the question at the begin of this subchapter, the drainage system of the Soesterkwartier could be modelled with the help of PCRaster Python and openLISEM software packages. However, it does not correspond with reality because almost all streets are flooded and the stream velocities are very low on the places with water on the street. Calibration of the input parameters had no influence on these factors. Thus it can be concluded that openLISEM in combination with the set-up used in this research is not suitable for modelling the drainage system of the Soesterkwartier. It should be noted that currently a new version of openLISEM is being developed in which overland flow can be calculated with the full Saint-Venant equations which also includes pressure differences. Using this setup is it might be possible in the future to successful model the drainage system of the Soesterkwartier in the openLISEM model.

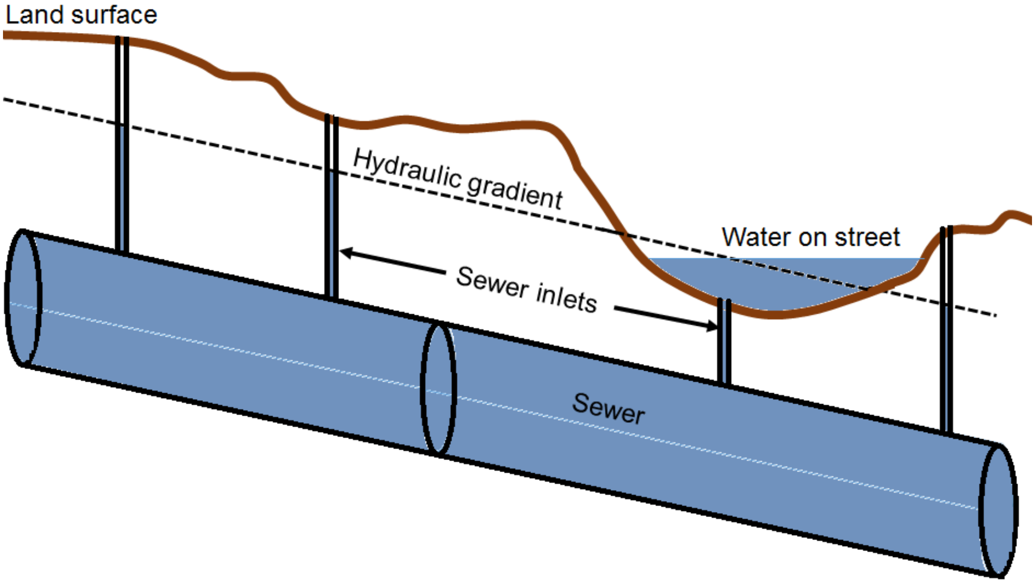


Figure 4.8: Schematic overview of the hydraulic gradient in the sewer system when it is filled. If the sewer inlet is located underneath the hydraulic gradient water will flow out of the sewer until it reaches the level of the hydraulic gradient.

5. Measures

There are many measures known that increase the robustness of urban drainage systems. This chapter gives a number of measures that are feasible to implement in the current drainage system of the Soesterkwartier and are also in line with the vision of the municipality (chapter 1.3). The central question in this chapter is:

> *Which solutions are in line with the vision of the municipality of Amersfoort and could be implemented to increase the robustness of the drainage system?*

The measures are given one by one and for each measure the general functioning is described first, followed by a description of the best locations and best opportunities in the Soesterkwartier for implementing these solutions. Besides that, the unit costs for implementing the solution are given where possible. These unit costs are based on the sewer unit costs described by RIONED (2015) and appendix M shows how the unit costs are made up. Finally this chapter will end with a comparison about the effectivity and costs of the different measures.

5.1 Water retention areas

In general, water retention areas are lower lying areas that function as a buffer for storm water. Water retention areas slow down the peak discharge and increase the storm water storage capacity of urban areas. A good example of a water retention area is a wadi (figure 5.1). Wadis are lower lying green areas where rainwater could in generally easily infiltrate. Mostly ground improvement has taken place in the top layer of the wadi and underneath this layer a box filled with high permeable material like gravel or lavastones is placed (Groenblauwe netwerken, 2016). This box is surrounded by geotextile to prevent congestion and root penetration and includes a drain (ibid.). To prevent flooding of the wadi during extreme rainfall events, it has an overflow possibility. This could be directly to an infiltration sewer or to a rainwater sewer (figure 5.1). The height of this overflow is dependent of the infiltration capacity of the wadi and is usually designed such, that the water is standing in the wadi less than 24 hours. A typical depth for a wadi is 0.3 meter which corresponds to an infiltration rate of 0.3 meter per day (12.5 mm/hour). Experiences in Twente revealed that the slope of the wadi must be at least less than 1:3 to allow mowing the grass on it (ibid.).

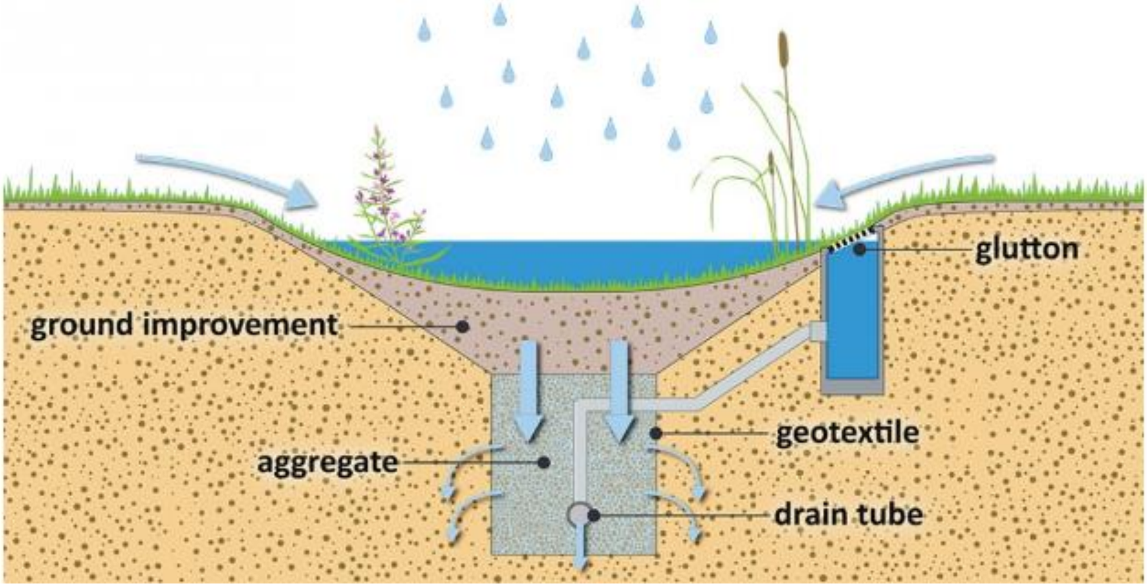


Figure 5.1: Schematic cross section of a wadi (Groenblauwe netwerken, 2016; based on Boogaard et al., 2006)

The recommendations to construct the bottom of the high permeable box at least above the average highest groundwater level, are not met in large parts of the Netherlands (Boogaard et al., 2006). With a minimal cover of 0,8 meter and an average cross section for an infiltration sewer of 300 mm, the groundwater level must lay at least 1,1 meter below the surface of the wadi (ibid.). Add to this that the wadi is located lower than the surrounded area, which makes that the maximum groundwater level before construction of the wadi should be about 1.5 meter below the surface, preferably even more (Groenblauwe netwerken, 2016).

In some areas with high groundwater levels and low permeability the wadis function more as buffers during extreme rainfall events (Birch et al., 2008). Besides wadis, other areas in cities like parks, sport fields and playing grounds can function as a temporary storage and infiltration place during extreme rainfall events. However, in these cases the water must be clean so that this does not form a risk for the public health (Birch et al., 2008). Rainwater that is collected on the roofs of the buildings is generally relatively clean water and could be discharged to these multifunctional water retention areas (Ibid.). Besides that, rainwater that falls on roads with a low traffic intensity (<less than 1000 cars a day) is also mostly relatively clean (Groenblauwe netwerken, 2016). The majority of the roads in the Soesterkwartier have a low traffic intensity, so that the rainwater which falls on these roads is suitable for transport to water retention areas.

The unit costs for the construction of a wadi are approximately 120 euros per meter wadi with a width of two meters (RIONED, 2015; appendix M). In addition, extra costs could be made by adapting the surface drainage system to make sure the rainwater will runoff towards the wadi. Besides that, the maintenance costs are approximately 6 euros per square meter per year. This is based on biweekly mowing and removing of litter, and twice a year verticutting (NL: verticuteren) and removal of leaves (ibid.). Further, corrective maintenance is necessary which costs on average approximately 1.4 euro per square meter per year (ibid.).

In general, green areas are the easiest and cost-effective places to implement water retention areas because the green function could be retained if a water retention function is added to the area and the maintenance costs remain nearly the same. The largest green area of the Soesterkwartier is in the north of the district between the Dollardstraat and Amsterdamseweg (figure 1.3). However, this green area, which is called the Groengordel, is located downstream of the areas where flooding occurs and has a relatively high groundwater level whereby wadis are less suitable (Appendix K). In contrast, the smaller green areas south of the Noordewierweg are more suitable for the construction of wadis because here the groundwater levels are much lower during the year (Appendix K). However, the type of vegetation and the quality of the vegetation play an important role as well. Changing green areas of high quality into wadis could lead to resistance of inhabitants.

Green areas that could potentially be changed easily into wadis to increase the robustness of the drainage system are respectively located at the corner of the Soesterweg and Narcisstraat, and at the junction of the Palmstraat and Hulststraat (figures 5.2). The latter is located near the lowest point of problem area one (figure 4.2) whereby constructing a wadi here could be a good solution to reduce the extent of pluvial flooding in this area and increase the robustness of the drainage system. This green area is separated from the road by curbs and a schematic overview is given in figure 5.2. In total, it is approximately ten meters width and 33 meters long. If a wadi with a depth of 30 centimeters is constructed here including sloping sides (1:3), it could buffer almost 90 cubic meters of water.

Figure 5.2: An impression (left side) and a schematic overview (right side) of the green area which is located on the junction between the Palmstraat and Hulststraat. The red star indicates the place where the photo on the left side is taken; pink indicate a hornbeam surrounding the area; the 8 little circles are small trees; the squares indicate paved areas with two picnic tables on it and; the green colour represents the grass.

5.2 Infiltration systems

A large part of the surface area of the Soesterkwartier has a low infiltration capacity because it is built or paved whereby comparatively much rainwater does runoff to the sewer system. There are different measures that could increase the infiltration and therefore reduce the runoff to the sewer system. A wadi could be categorized as well under the infiltration systems. However, this has already been discussed in chapter 5.1 whereby this chapter focusses on the characteristics of infiltration boxes and permeable pavement.

5.2.1 Infiltration boxes

An infiltration box is an underground box that temporarily stores rainwater and at the same time infiltrates the water gradually to the subsoil. An infiltration box, which has been mostly made of plastics, has a storage capacity up to 95 percent of the original size (Rainproof, 2016). It is very easy to connect individual boxes with each other to make a larger structure with more storage capacity (figure 5.3). Hereby, the infiltration structures could be adopted to almost every size. The structure is surrounded by geotextile to prevent it from clogging (Groenblauwe netwerken, 2016). Infiltration boxes could be inter alia constructed underneath roads, parking spaces and sport fields whereby it could be very useful in areas with little space (ibid.).

The construction depth of the infiltration boxes is dependent of the surface load. For roads and parking spaces a depth of 70 centimeters is recommended between the top of the boxes and the surface level (Rainproof, 2016). For squares and sidewalks 30-40 centimeters is enough. However, to minimize the risk of freezing a depth of 60 centimeters is recommended (Raineo, 2012). Besides that, the bottom of the infiltration system must be at least 0.5 meters above the groundwater level (ibid.). Further the dimensions of the infiltration boxes are dependent of the hydraulic conductivity of the soil, the connected and type surface area and, the intended infiltration and buffer capacities of the system. The dimensioning is typically based on a certain return period of a certain rainfall event (ibid.). It is common practice to use a return period of T=2, which indicates that the system may overflow once every two years (ibid.).

A disadvantage of the infiltration boxes is the maintenance (Rainproof, 2016). This is because it is an underground structure that is not always provided with an inspection tunnel and even if there are one or more present it is not always easy to clean the whole structure (ibid.). This could lead to reduced infiltration- and storage capacity of the infiltration boxes over the years or higher maintenance costs.

Figure 5.3: Infiltration structure that is built up from many separate infiltration boxes. Image copied from Indra, 2016.

The unit cost for the construction of an infiltration box is approximately 512 euro per cubic meter (RIONED, 2015; appendix M). Hereby it is advisable to combine the construction of infiltration boxes with other construction or maintenance work like replacements of road/parking places or the construction of artificial turf fields (NL: kunstgrasvelden). This could reduce the labor costs. However, following the last road inspections in the Soesterkwartier in 2015, it is expected that no large-scale roadworks need to be done in at least the coming ten years (Boelhouwers, 2016). This also applies to the sewer system (Lensink, 2016). However, if this unexpectedly does happen it is good to check if there are possibilities to construct infiltration boxes or other infiltration facilities.

On the short term, there are maybe possibilities for infiltration boxes under the schoolyard of 'obs De Magneet' which is located between the Maasstraat and Waalstraat (figure 4.3A). At this moment, the schoolyard is completely paved but there are plans for greening the schoolyard. This is also a great opportunity to increase the water robustness of the area for example by the construction of infiltration boxes. It is dependent of the dimensions of the infiltration system and the exact groundwater level if the infiltration box system is achievable here because the average highest groundwater level lays somewhere between 1.5 and 2.37 meter in that area (appendix K). It is therefore advisable to enable the help of a water specialist for the new design of the schoolyard who looks at the potential for an infiltration box system and other water robust measures. This way, water and green could be well-integrated in this project which is an important part of the vision of the municipality.

5.2.2 Permeable pavement

Permeable pavement is a road construction wherein water infiltrates through or along the stones into the underlying foundation. This type of pavement has been developed and applied in the Netherlands approximately since the year 2000 (Tauw, 2014). Since then, there are varying reactions about the functioning of the pavement. The most common problem of all kinds of permeable pavement is clogging due to different types of pollution and the use hereof. As a result, the infiltration capacity decreases drastically whereby the lifetime of most permeable pavement is less than twenty years (ibid.). However, since the first types of permeable pavement appeared on the market, the product got gradually better.

In the recent years, a new type of permeable pavement appeared which is called Drainvoeg (figure 5.4). This is a water passing infiltrating joint made of fibrebonded PP (85%) and PE (15%) (Drainvast, 2016). A great advantage of this joint is that it could be applied in between many kinds of bricks, so that it could also be used in case of repaving old bricks. Besides that, Drainvoeg does not need extra maintenance in comparison with normal pavement. Further, the joint does not hold any water so that it does not expand when it freezes. In addition, the lifetime is estimated to be at least 25 years and it is reusable in the case of repaving.

Figure 5.4: Impression of the Drainvoeg (Drainvast, 2016)

The infiltration capacity of the Drainvoeg is dependent on the number of joints that are filled with it. One Drainvoeg of 100*8*76 (l*b*h) millimeter has an infiltration rate of at least 30 liter/hour. The Drainvoeg could be laid out mechanically in a certain structure of which every square meter has six bricks with on both short sides a Drainvoeg. This structure is called drainwave and can handle a rainfall event of 360 mm/hour. Naturally, it is also important that the foundation of the pavement has a high hydraulic conductivity and a high porosity which determine the buffer capacity.

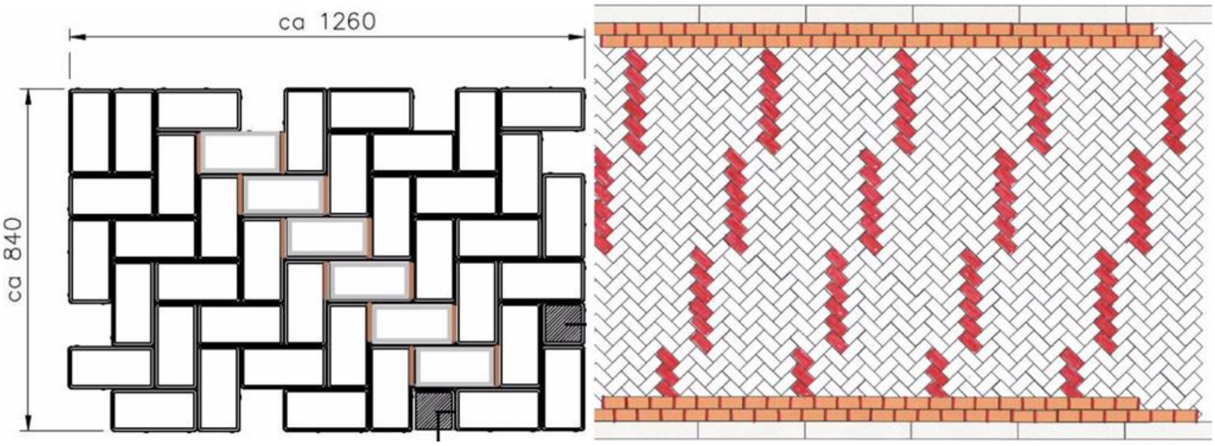


Figure 5.5: One square meter of pavement with drainwave (left) and a drainwave package with Drainvoeg on the sides (right). Copied from Drainvast, 2016.

The unit cost for the construction of pavement with drainwave and a foundation of 30 cm is 37.65 per square meter (Appendix M). This includes the costs for delivery of drainwave in the machinable package as well. This shows that the construction costs of drainwave are higher than other permeable pavements. However, the maintenance costs are much lower which makes drainwave cheaper on the long run (appendix M).

Drainwave could be applied in almost all roads in the Soesterkwartier because it could still function properly with relatively high groundwater levels. Therefore, it is useful to apply drainwave in both problem areas and in the streets that runoff to these problem areas. However, it is not sure in what kind of degree drainwave will affect the groundwater level. This is predominantly important in problem area two where groundwater problems are in the Spaarnestraat and Dollardstraat. The municipality received already many complaints about groundwater nuisance from this area. Therefore, it is advisable to do first research about this groundwater nuisance before implementing drainwave.

5.3 Rain water sewer

The largest part of the nuisance in the research area is caused by the fact the flood water contained sewage. This resulted in extra cleaning costs and odor nuisance. Changing the combined sewer system into a separated sewer system is an effective measure to reduce the largest part of the nuisance. As a result, the flood water will not contain sewage anymore. However, the unit prices for only replacing sewer pipes are considerable (figure 5.6; Appendix M). Changing the whole system is even more expensive because inter alia connections to the sewer system must be changed (sewage or rainwater) and an extra system of sewer pipes must be constructed. This certainly is the case for Soesterkwartier as almost nineteen kilometers of its sewer system is combined (appendix C).

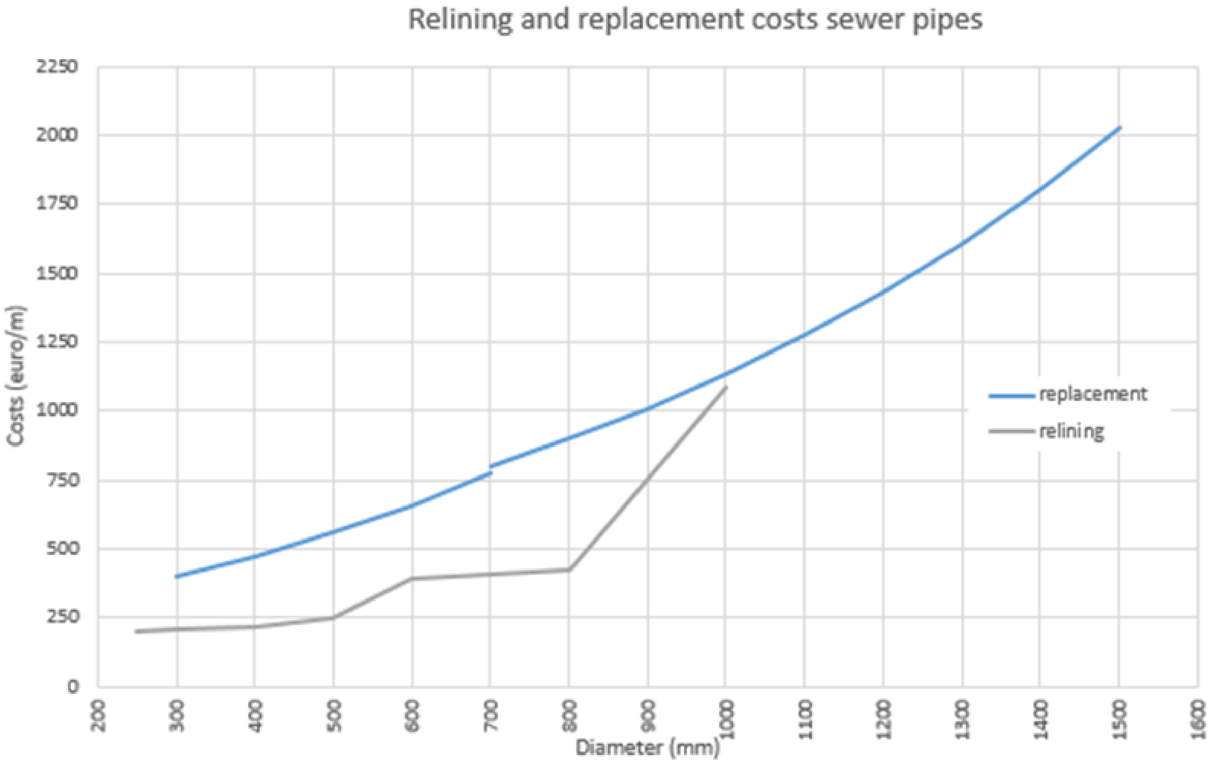


Figure 5.6: Unit cost for replacement or relining of the sewer pipes for different diameters (Values from RIONED, 2015).

In the water vision of Amersfoort for 2030 is stated that with the replacement of combined sewers into separate sewers, the municipality will take the technical lifespan of the existing sewer into account. The municipality assumes a lifespan for concrete sewer pipes of approximately 80 years. Because the current sewer system is constructed after 1960 and the largest part even after 1975 (appendix C), it is unlikely that the sewer system will be replaced on the short term. Besides, the sewer system could be relined as well, which is cheaper for the pipe diameters that are present in the Soesterkwartier (appendix C; figure 5.6). If the whole combined system will be replaced it will cost approximately 8 million euros and if it will be relined it costs 3.8 million.

Changing the sewer system has no priority because the technical lifespan of the system is provisionally not reached and the actual damage caused by historical rainfall events is low. In addition, it should be wondered in the case the combined sewer system must be replaced if a rainwater sewer is necessary or that the money could be invested into a DWS and other rainwater related measures that increase the robustness of the system.

5.4 Private property

Approximately 62 percent of the research area belongs to private property. Given the surface area of this class and the high number of paved gardens there is much to gain by water retention on private land. Besides that, almost all the rainwater that falls on the roofs is transported directly to the sewer system. About 26 percent of the research area is occupied by roofs whereby there is much to gain with respect to decoupling of roof surfaces.

First, it is important that the residents are aware of the flooding in their district. Recognition of the problem is the first step toward prevention. In general, the people who live further away from the problem area are less aware about the factors that aggravate pluvial flooding. However, these people are also part of the same drainage system. So it is reasonable to expect that they too could take measures in order to decrease the runoff to the sewer such that the pressure on the system decreases. The municipality could increase the awareness inter alia by informing the residents.

When people are aware of the vulnerable urban drainage system, there are many ways residents could contribute to a more robust system in the Soesterkwartier. Measures could focus on increasing the buffer capacity and infiltration capacity of their property. Besides that, it is important to increase the amount of green on private properties. This has not only a positive effect with respect to pluvial flooding but also in relation to the urban climate. More green also reduces the UHI effect and increases biodiversity.

A nice example of an easy measure that residents could take to increase the buffer capacity is the purchase of a rain barrel. Hereby, it is important that the rain barrel is empty before the heavy rainfall event starts. This way, the water from the roof could be (partly) buffered. A simple plastic rain barrel of 150 to 200 litre costs approximately 40 to 60 euros (RIONED, 2015). Wooden rain barrels are more expensive and cost about 70 to 100 euros (ibid.). The purchase of rain barrels could be organised and stimulated for example by a district association, so that the rain barrels could be bought in larger amounts which reduces the cost per barrel. Further, parts of the garden like the grass or terrace could be constructed lower as the rest of the garden whereby more water could be retained in the garden which reduces the peak flow. Besides, the water on the grass could slowly infiltrate. Hereby it is advisable to enable the help of a professional who could help with the design of a waterproof garden.

At this moment, there is a very active district association which is called 'Duurzaam Soesterkwartier' which means sustainable Soesterkwartier. This association has a good network within the Soesterkwartier and could therefore be a good platform to reach the residents and to address the problem centrally. Via this platform also the use of other measures could be stimulated. Perhaps it is possible to set up a working group of concerned residents who deal with the promotion and execution of measures against pluvial flooding. Comparable working groups of residents are active in Deventer (De Hoven) and Utrecht (Zeeheldenbuurt). The municipality should investigate whether how this working group could be stimulated, for example by financial support.

5.5 Comparing effectivity and costs of the measures

Appendix N shows a spreadsheet about the effectivity and costs of four different measures discussed in this chapter which are respectively wadis, drainwave, rain barrels and infiltration boxes. The costs are based on the unit costs described by RIONED (2015) which are shown in appendix M. It is important to realize the spreadsheet does not show maintenance costs. For each measure is the potential surface area that could be decoupled calculated. Besides, it shows for three different rainfall events the amount of euros that should approximately be invested to decouple one square meter of drainage system of the Soesterkwartier. On this way the different measures are compared from economic perspective which does not mean that the cheapest measure is certainly the best measure.

Appendix N shows that the construction costs (unit prices) of the four measures are the lowest for drainwave and the highest for the infiltration box. Approximately seventeen percent of the surface area of the Soesterkwartier is open pavement. This open pavement has in most places low traffic intensity whereby drainwave could be an effective measures to reduce water nuisance in the Soesterkwartier. However, it is still important to implement measures on the right moment because for example it is a waste of money to repave a certain street with drainwave while the old pavement can last for years. There should be indented on local developments in the district. The plan for greening the schoolyard of 'obs De Magneet' is a nice opportunity to indent on local developments and to increase at the same time the robustness of the drainage system of the Soesterkwartier.

6. Conclusions and recommendations

This chapter answers the research questions and give recommendations to transform the current drainage system of the Soesterkwartier into a more robust drainage system in the future. The central question in this chapter is the main research question:

> *How could the current drainage system of the Soesterkwartier be made more robust to prevent the consequences of extreme rainfall events?*

The research started with a literature study wherein inter alia the background of the drainage system of the Soesterkwartier and the effects of climate change were described. Subsequently, via a district survey, information was collected about the extent of the two pluvial flooding events in order to determine the vulnerable areas of the drainage system of the Soesterkwartier. Besides, the drainage system of the Soesterkwartier was modelled with the help of openLISEM. With the aid of the results of the district survey it was checked if the model corresponded with reality. Thereafter, was examined which measures are most suitable for increasing the robustness of the drainage system of the Soesterkwartier. Unfortunately, the model did not correspond well with the results of the district survey. As a result, the effects of these measures on the extent of flood could not be tested in the model.

Following the district survey, two areas vulnerable two flooding were identified in the Soesterkwartier. These are respectively the Soesterweg, Hulststraat and Palmstraat (1) and the Spaarnestraat and Dollardstraat (2). These areas were flooded during both rainfall events that occurred in July 2014. The nuisance consisted mainly of streets that were flooded with rainwater that also contained sewage. The amount of water on the streets resulted not into considerable economical damage because the district is in general well-designed, where the sills of the front doors are located considerably higher than the street level.

The maximum water levels on the surface seems to have approximately been the same during both rainfall events, which is striking because the return periods of the rainfall events on the 11th and 28th of July 2014 were respectively 5 and 70 years. The high water levels on the 11th of July were probably largely due to the failure of the sewer system. Because of the peak (15 mm in 15 minutes) at the start of the event, air was trapped in the sewer pipes so that the sewer system did not function properly. In contrast to 11 July, no air was trapped on the 28th because before the peak already 20.6 mm had fallen in 90 minutes which presumably largely filled the sewer system. Under climate change, the probability of extreme rainfall events like the two events that happened in July 2014 increases. Furthermore, from observations it appears that for the most extreme showers, the amount of rainfall per hour increases with approximately 14 percent per increased degree of Celsius (KNMI,2014). This will increase the pressure on the drainage system of the Soesterkwartier and if nothing will be done, there is a large chance that in the future the Soesterkwartier will be flooded more often and the extent of the floods will aggravate as well.

Increasing the robustness of the drainage system of the Soesterkwartier is not a short-term unilateral process. It takes time and requires cooperation between the different stakeholders. Because of this it is important to have a flexible long term vision aligned with autonomous developments in de district. This way, projects become more integrated and the district management is more efficient. Besides, the costs of the measures could be reduced when the proceedings are combined with other work.

On the short term, it is important to increase the awareness of the civilians of the Soesterkwartier in relation to pluvial flooding. The municipality could do this inter alia by informing the residents or to emphasize on the surface part of the drainage system, so that people can see what is happening with the rainwater. As a result, the residents will have a greater understanding of the work that is done by the municipality on the urban drainage system in the district. Besides that, it increases the chance that residents are willing to cooperate to increase the robustness of the drainage system. A working group of concerned residents could possibly promote and execute measures on private properties against pluvial flooding. Here, the focus must be on measures that are relatively easy to implement and are not too expansive, because otherwise residents will not cooperate with suggested initiatives. Besides, there are possibilities on the short term for implementing water retention and infiltration systems at the schoolyard of 'obs De Magneet' because this schoolyard will be greened within a few years.

In the course of time more water retention areas and infiltration systems should be constructed to increase the robustness of the drainage system. In particular, the southern part of the district where the groundwater levels are low (GHG > 1.5m), measures like wadis or infiltration boxes could be implemented. More use should be made of the potential buffering capacity and infiltration capacity of green areas if the groundwater levels are favourable. Currently, almost all green areas in the Soesterkwartier are located above street level and as a result water cannot runoff into the green areas. Near the lowest point of problem area one a wadi could be constructed with a potential buffer of approximately 90 cubic meters. Furthermore drainwave (permeable pavement) could be constructed in both problem areas. Drainwave could process a rainfall event of 360 mm/hour and could still function properly with fairly high groundwater levels. However, it is advisable for problem area two to do first research about the effects of drainwave on the groundwater level because the municipality has received several complaints about groundwater nuisance in this area.

On the long term the combined sewer system must be replaced by a separated system. This has no priority because the technical lifespan of the system is provisionally not reached and the actual damage caused by historical rainfall events is low. In addition, it should be wondered if, in case the combined sewer system does have to be replaced, a rainwater sewer is needed everywhere in the district or that the money could be invested into a DWS and other retention and infiltration measures that increase the robustness of the system.

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8. Appendices

Appendix A Relevant laws and Regulations

Waterwet, artikel 3.4 (GRP, 2012)

1. Zuivering van stedelijk afvalwater gebracht in een openbaar vuilwaterriool geschiedt in een daartoe bestemde inrichting onder de zorg van een waterschap. Een zodanige inrichting kan worden geëxploiteerd door het waterschap zelf dan wel door een rechtspersoon die door het bestuur van het waterschap met die zuivering is belast.

2. In afwijking van het eerste lid kunnen het bestuur van het betrokken waterschap en de raad van een betrokken gemeente op voorstel van één van beide partijen besluiten, dat de zuivering van daarbij aangewezen stedelijk afvalwater in die gemeente, vanaf een daarbij te bepalen tijdstip, geschiedt in een daartoe bestemde inrichting onder de zorg van die gemeente. Een besluit als bedoeld in de vorige volzin kan slechts worden genomen op grond dat zulks aantoonbaar doelmatiger is voor de zuivering van stedelijk afvalwater.

3. Het bestuur van het waterschap en de raad van de betrokken gemeente beslissen op een voorstel als bedoeld in het tweede lid, binnen één jaar na de dag waarop het door de raad van de betrokken gemeente dan wel door het bestuur van het waterschap is ontvangen. Bij gebreke van overeenstemming binnen die termijn beslissen, de beide partijen gehoord, gedeputeerde staten

Waterwet, Artikel 3.5 (GRP, 2012)

1. De gemeenteraad en het college van burgemeester en wethouders dragen zorg voor een doelmatige inzameling van het afvloeiend hemelwater, voor zover van degene die zich daarvan ontdoet, voornemens is zich te ontdoen of zich moet ontdoen, redelijkerwijs niet kan worden gevergd het afvloeiend hemelwater op of in de bodem of in het oppervlaktewater te brengen.

2. De gemeenteraad en het college van burgemeester en wethouders dragen tevens zorg voor een doelmatige verwerking van het ingezamelde hemelwater. Onder het verwerken van hemelwater kunnen in ieder geval de volgende maatregelen worden begrepen: de berging, het transport, de nuttige toepassing, het, al dan niet na zuivering, terugbrengen op of in de bodem of in het oppervlaktewater van ingezameld hemelwater, en het afvoeren naar een zuiveringtechnisch werk.

Waterwet, Artikel 3.8 (GRP, 2012)

Waterschappen en gemeenten dragen zorg voor de met het oog op een doelmatig en samenhangend waterbeheer benodigde afstemming van taken en bevoegdheden waaronder het zelfstandige beheer van inname, inzameling en zuivering van afvalwater

Wet milieubeheer, Artikel 10.32a (GRP, 2012)

1. De gemeenteraad kan bij verordening bepalen dat:

a) Bij het brengen van afvloeiend hemelwater of van grondwater op of in de bodem of in een voorziening voor de inzameling en het transport van afvalwater, wordt voldaan aan de in die verordening gestelde regels, en
b) Het brengen van afvloeiend hemelwater of van grondwater in een voorziening voor de inzameling en het transport van stedelijk afvalwater binnen een in die verordening aangegeven termijn wordt beëindigd.

2. Van de mogelijkheid, bedoeld in het eerste lid, onderdeel b, wordt geen gebruikgemaakt, indien van degene bij wie afvloeiend hemelwater of grondwater vrijkomt redelijkerwijs geen andere wijze van afvoer van dat water kan worden gevergd.

Wet milieubeheer, Artikel 10.33 (GRP, 2012)

1. De gemeenteraad of burgemeester en wethouders dragen zorg voor de inzameling en het transport van stedelijk afvalwater dat vrijkomt bij de binnen het grondgebied van de gemeente gelegen percelen, door middel van een openbaar vuilwaterriool naar een inrichting als bedoeld in artikel 3.4 van de Waterwet.

2. In plaats van een openbaar vuilwaterriool en een inrichting als bedoeld in het eerste lid kunnen afzonderlijke systemen of andere passende systemen in beheer bij een gemeente, waterschap of een rechtspersoon die door een gemeente of waterschap met het beheer is belast, worden toegepast, indien met die systemen blijkens het gemeentelijk rioleringsplan eenzelfde graad van bescherming van het milieu wordt bereikt.

3. Op verzoek van burgemeester en wethouders kunnen gedeputeerde staten in het belang van de bescherming van het milieu ontheffing verlenen van de verplichting, bedoeld in het eerste lid, voor:

a) Een gedeelte van het grondgebied van een gemeente, dat gelegen is buiten de bebouwde kom, en
b) Een bebouwde kom van waaruit stedelijk afvalwater met een vervuilingswaarde van minder dan 2000 inwonerequivalenten wordt geloosd.

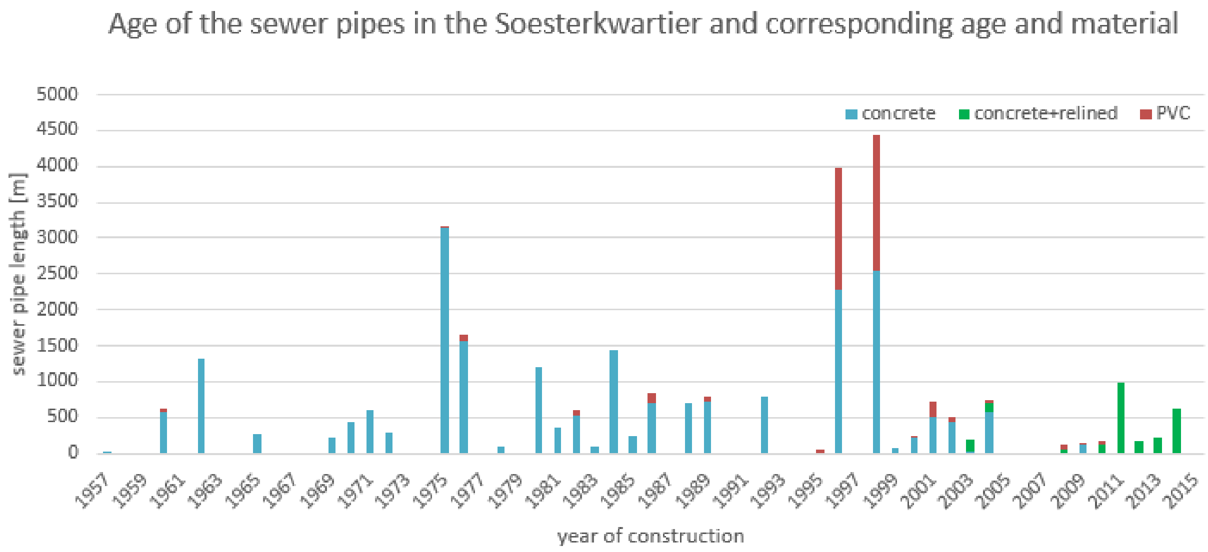
4. De ontheffing bedoeld in het derde lid kan, indien de ontwikkelingen in het gebied waarvoor de ontheffing is verleend daartoe aanleiding geven, door gedeputeerde staten worden ingetrokken. Bij de intrekking wordt aangegeven binnen welke termijn in inzameling en transport van stedelijk afvalwater wordt voorzien.

Appendix B The ten sustainable principles of the municipality of Amersfoort

De tien duurzaamheidsprincipes van Amersfoort

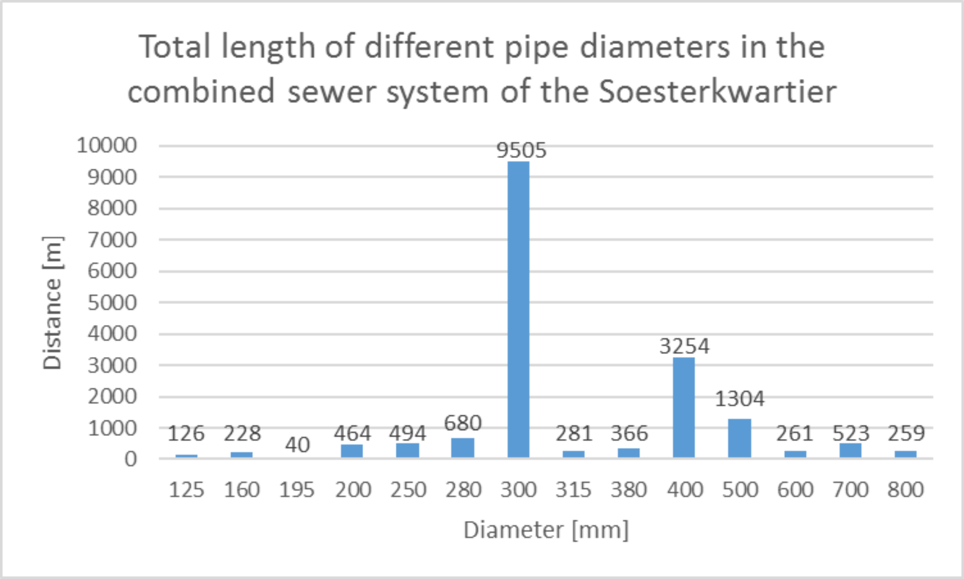
1. *Laat het watersysteem optimaal functioneren, binnen maatschappelijk acceptabele grenzen*
2. *Houdt water zo lang mogelijk schoon*
3. *Sluit de waterbalans zo veel mogelijk*
4. *Sluit aan bij (natuurlijke) processen en kansen*
5. *Behoud en versterk de gebruikswaarde*
6. *Het functioneren van het watersysteem moet beheer(s)baar zijn*
7. *Maak flexibele en robuuste ontwerpen*
8. *Wentel problemen niet af*
9. *Werk samen, vanuit een heldere verdeling van rollen en taken.*
10. *Laat het water en zijn beheerders tegen aanvaardbare kosten de maatschappelijke behoefte vervullen*

Appendix C Information about the type, age, materials and length of the sewer pipes in the Soesterkwartier



The table below gives the different types of sewer systems in the Soesterkwartier and their corresponding length

sewer system		length [m]
Combined		18808
Separated	DWS	1922
	RWS	3216
Improved separated	DWS	3125
	RWS	3224



Appendix D Common drainage terms

This appendix provides a list of words and terms common in drainage issues, many used in this research. The most terms and words are derived from the IOWA drainage Law manual unless another source is mentioned.

Sewerage system: A system used for carrying away water and sewage (Merriam webster, 2016). This includes inter alia the sewer system, retention basins, drains, etc.

Domestic sewer pipes: Sewer pipes that transports the domestic wastewater from households towards the municipal sewer system. They are the responsibility of the house owner.

Sewage: Household and commercial wastewater (such as faeces).

Sewer: A pipe or conduit that carries waste- and/or stormwater

Sewer system: A system of pipes and conduits that collects and transports waste- and/or stormwater

Drain: A ditch and any watercourse or conduit, whether open, covered, or enclosed, natural or artificial, or partly natural and partly artificial, by which waters coming or falling upon a property are carried away.

Sewer water: Waste and/or stormwater in the sewer system. Sewer water in a combined system could contain sewage and rainwater.

Sewage treatment plant: Facility that treats sewer water in such a way that the effluent has no unacceptable consequences for the local environment.

Sewer pumping station [NL:rioolgemaal]: Station were water is being pumped/circulated (NL: verpompt)

Pumpovercapacity [NL:pompovercapaciteit]: The part of the capacity of a sewer pumping station that is available for pumping stormwater. Pumpovercapacity = pumping capacity – sewage.

Appendix E Urban Heat Island Effect

The Urban Heat Island (UHI) effect is the consequence of differences in thermal and radiative properties of the urban infrastructure relative to the rural infrastructure as well as the impact buildings can have on the local micro-climate (ibid.). There could be three UHI types distinguished:

- The surface UHI, which is the difference in surface temperature between the urban area and surrounding rural area (Rovers et al., 2014).
- The atmospheric UHI, which is the difference in air temperature between the urban area and surrounding rural area. This could be subdivided in (ibid.):
    - Urban Boundary Layer (UBL) heat island. The intensity of the urban boundary layer is dependant of the geographical position, structure and morphology of the city (ibid.). The layer starts from the treetops and rooftops till the height urban areas no longer influence the atmosphere (van Hove et al., 2011).
    - Urban Canopy Layer (UCL) heat island. The urban canopy layer is defined as the layer between the ground surface and the tops of trees and buildings (figure E.2) (ibid.). The presence of buildings, street surface, trees and water have a direct noticeable effect on the micro climate (living conditions) (Rovers et al., 2014). Discussions about the UHI effect are predominantly about this layer because this is the layer where people in live and which affects health conditions (van Hove et al., 2011; Rovers et al., 2014).

The surface UHI reaches a maximum during the day when the urban surfaces absorb the radiation of the sun (Rovers et al., 2014). After sunset, the differences in surface UHI become smaller but could still be significant (figure E.1)(ibid.). On the other hand, the atmospheric UHI is small or absent during the day and largest after sunset because urban areas cool down slower than rural areas (figure E.1) (ibid.).

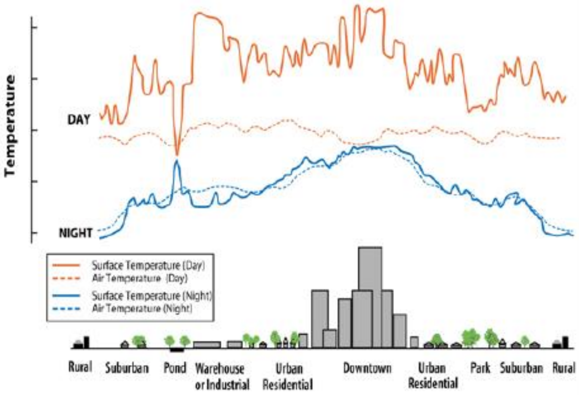


Figure E.1: The Urban Heat Island effect: the difference in surface and air temperature between the city and countryside at day- and nighttime (EPA, 2015)

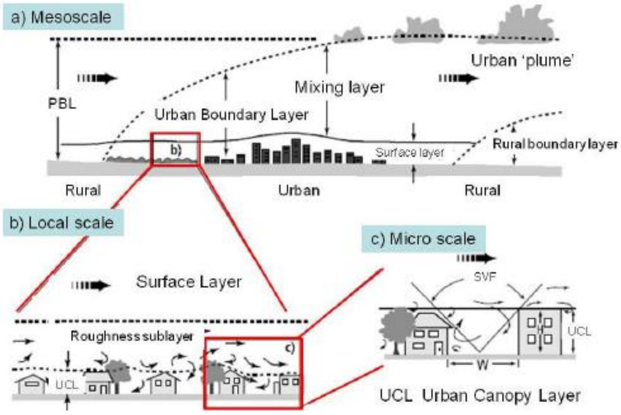


Figure E.2: The atmospheric urban heat island layers. The thick arrows indicate the dominant wind direction and the thin arrows illustrate the turbulent air flow (Oke, 1976; Rovers et al., 2014)

Despite the small cities in the Netherlands UHIs could diverge from three up to ten degrees celsius (Steeneveld et al., 2011a; Steeneveld et al., 2011b; Wolters en Brandsma, 2012; Rovers et al., 2014). These values are comparable with UHI values for other European cities. Following Klok et al. (2012) Amersfoort has one of the larger Surface Heat Islands (SHIs) of the Netherlands. During the day it has an average SHI of 5.2°C (3rd place of all Dutch cities) which could reach up to 7.5 °C maximum (Klok et al., 2012). In the night, the average SHI of Amersfoort is 4.3°C (7th place) which could be rise to 5.5°C maximum (ibid.).

Steeneveld et al. (2011a) investigated the UCL heat island effect in the Netherlands based on high quality observations records of at least one year by hobby meteorologists. They examined twenty cities in the Netherlands and concluded that the average maximum UHI during a diurnal cycle is 2.3°C, while the average 95 percentile over all cities is 5.3°C (Steeneveld et al., 2011a). They calculated these UCL heat island values by means of subtracting the rural air temperature at screen level (2m above the land surface) from the urban canyon air temperature (ibid.). Unfortunately, this study did not include the city of Amersfoort whereby there are not known any exact numbers for the UCL of Amersfoort. However, Steeneveld et al., (2011a) discovered a positive correlation between the 95 percentile of the UCL heat Island and the population density. Besides that, a significant decrease of the UCL heat island was discovered in greener urban areas. This decrease was strongest during the hottest days which confirms the hypothesis that greening the city is an adequate method to mitigate strong UHIs (ibid.).

A small survey of the NMU (Natuur and Milieu federatie Utrecht) whereby residents measured for a week, three times a day the temperature, showed that the districts Stadskern and Soesterkwartier were the hottest places of Amersfoort.

In Amersfoort, there is a lack of data about the UHI and more research about this topic has be done for Amersfoort. However, literature studies about the UHI of other cities show that measures against pluvial flooding may also help against the UHI effect and reduce the heat stress. In particular, greening the city and reducing the amount of paved area are seen as effective measures against the UHI effect and pluvial flooding.

Appendix F The PCRaster Python code

Making research area map

```
from pcraster import *
from pcraster.framework import *

class MyFirstModel(DynamicModel):

  def __init__(self):
    DynamicModel.__init__(self)
    setclone("Soesterkwartier")

def initial(self):
    #loading maps
    rivierenbuurtWest=readmap('Rivierenbuurt-west')
    rivierenbuurtOost=readmap('Rivierenbuurt-oost')
    bloemenbuurtWest=readmap('Bloemenbuurt-west')
    bloemenbuurtOost=readmap('Bloemenbuurt-oost')
    gerritvanstellingwerfstraat=readmap('Gerrit van Stellingwerfstraat')
    buurten=readmap('alle_buurten_Soesterkwartier')

    onderzoeksgebied = rivierenbuurtWest | rivierenbuurtOost | bloemenbuurtWest
                    |bloemenbuurtOost | gerritvanstellingwerfstraat
    self.report(onderzoeksgebied, 'RA')
    buurten=ifthenelse(onderzoeksgebied,buurten,False)
    self.report(buurten,'RAbuurt')

def dynamic(self):
    pass

nrOfTimeSteps=1
myModel = MyFirstModel()
dynamicModel = DynamicFramework(myModel,nrOfTimeSteps)
dynamicModel.run()
```

The script

```
from pcraster import *
from pcraster.framework import *

class MyFirstModel(DynamicModel):

 def __init__(self):
  DynamicModel.__init__(self)
  setclone("RA")

  #loading maps
  onderzoeksgebied = readmap('RA')
  panden=readmap('panden')
  self.gemeentePerceel=readmap('gemeentePercelen')
  wegen=readmap('wegen')
  water=readmap('water')
  self.hoogte=readmap('hoogte')
  self.partTuin= readmap('partTuin')
  self.gemGroen = readmap('gemGroen')
  buurten=readmap('RAbuurt')
  self.asfalt=readmap('Asfalt')
  self.openroad=readmap('openroad')
  self.restroad=readmap('restRoad')
  hoogte= readmap('hoogtekaart')

  self.panden= onderzoeksgebied & panden
  self.wegen= onderzoeksgebied & wegen
  self.water=onderzoeksgebied & water

  #delete missing values from dem.map
  #1st loop to delete missing values in map
  missingvalue=defined(hoogte)
  hoogteAVG=windowaverage(hoogte,5)   #Sum of values within a specified square neighbourhood
  hoogteMV=ifthenelse(missingvalue,hoogte,hoogteAVG)
  mv=defined(hoogteMV)

  #2nd loop to delete missing values in map
  hoogteAVG2=windowaverage(hoogteMV,5)  #Sum of values within a specified square
neighbourhood
  hoogteMV2=ifthenelse(mv,hoogteMV,hoogteAVG2)
  mv2=defined(hoogteMV2)

  #3rd loop to delete missing values in map
  hoogteAVG3=windowaverage(hoogteMV2,5)   #Sum of values within a specified square
neighbourhood
  hoogteMV3=ifthenelse(mv,hoogteMV2,hoogteAVG3)
  mv3=defined(hoogteMV3)
```

```
  #4th loop to delete missing values in map
  hoogteAVG4=windowaverage(hoogteMV3,5)   #Sum of values within a specified square
neighbourhood
  hoogteMV4=ifthenelse(mv,hoogteMV3,hoogteAVG4)
  mv4=defined(hoogteMV4)

  #5th loop to delete missing values in map
  hoogteAVG5=windowaverage(hoogteMV4,5)   #Sum of values within a specified square
neighbourhood
  hoogteMV5=ifthenelse(mv,hoogteMV4,hoogteAVG5)

  #Vijver
  waterClump= clump(water)
  vijver=waterClump==83        #vijver is true value

  hoogtefilled=ifthenelse(panden, scalar(20),hoogteMV5)
  hoogtefilled=ifthenelse(onderzoeksgebied,hoogtefilled,False)
  hoogtefilled=ifthenelse(vijver,hoogte,hoogtefilled)
  mv=defined(hoogtefilled)

  self.report(hoogtefilled,'hoogtefill')
  self.report(mv, 'mv')

  #create ldd
  lddfill1=lddcreate(hoogtefilled,1e31,1e31,1e31,1e31)
  lddfill1=lddrepair(lddfill1)
  lddfill=lddmask(lddfill1, onderzoeksgebied)
  lddfill_nom=nominal(lddfill)
  self.report(lddfill1, 'ldd1')
  self.report(lddfill_nom,'ldd')

  #gradient
  gradfill=(hoogtefilled-downstream(lddfill,hoogtefilled))/downstreamdist(lddfill)
  gradfill=cover(gradfill, slope(hoogtefilled))
  gradfill=sin(atan(max(0.001, gradfill)))
  self.report(gradfill, 'gradfill')

  #correction gradient for pitcells (outer cells) and curbs
  pitcells=pitcells==0      #pitcells=false
  corGrad1=ifthenelse(pitcells, gradfill,max(0.001,0.05))
  corGrad=ifthenelse(self.wegen, gradfill,0)
  corGrad=ifthenelse(corGrad>0.1,0.1,corGrad)
  corGrad=ifthenelse(self.wegen,corGrad,corGrad1)
  self.report(corGrad,'corGrad')

  #ID.map
  ID=ifthenelse(onderzoeksgebied, nominal(1), nominal(1))
  self.report(ID,'ID')
```

```
#Land-unit.map
water=ifthenelse(self.water,scalar(1),0)
self.partTuinS=ifthenelse(self.partTuin,scalar(2),0)
self.pandenS=ifthenelse(self.panden, scalar(3),0)
self.asfaltS=ifthenelse(self.asfalt, scalar(4),0)
self.openroadS=ifthenelse(self.openroad, scalar(5),0)
self.restroadS=ifthenelse(self.restroad, scalar(6), 0)
self.gemGroenS=ifthenelse(self.gemGroen, scalar(7),0)

result=water+self.pandenS+self.asfaltS+self.openroadS+self.restroadS+self.gemGroenS+/
        self.partTuinS
result=ifthenelse(result>7,False,result)
result=ifthenelse(result<1, False, result)
result=nominal(result)
self.report(result, 'landunit')

#Surface area for RA, panden, wegen
RA1=ifthenelse(onderzoeksgebied, scalar(1), 0)
self.wegenS= ifthenelse(self.wegen, scalar(1), 0)
self.pandenS=ifthenelse(self.panden, scalar(1),0)
self.asfaltS=ifthenelse(self.asfalt, scalar(1),0)
self.openroadS=ifthenelse(self.openroad, scalar(1),0)
self.restroadS=ifthenelse(self.restroad, scalar(1), 0)

self.OppWeg=areatotal(self.wegenS, onderzoeksgebied)
self.OppRA=areatotal(RA1,onderzoeksgebied)
OppPand_buurt= areatotal(self.pandenS,buurten)
OppAsfalt_buurt= areatotal(self.asfaltS,buurten)
OppOpenroad_buurt= areatotal(self.openroadS,buurten)
OppRestroad_buurt= areatotal(self.restroadS,buurten)
OppWeg_buurt=OppOpenroad_buurt+OppAsfalt_buurt+OppRestroad_buurt

#ratios
pandWeg_buurt=(OppPand_buurt/OppWeg_buurt)

#create map that gives the ratio of precipitation
Pweg=ifthenelse(self.wegen,pandWeg_buurt+1,0)       #Extra precipitation on streets
P=ifthenelse(self.panden,0,RA1)                     #no precipitation on buildings
self.Pratio=ifthenelse(self.wegen,Pweg,P)           #new map of precipitation values
self.report(self.Pratio, 'Pratio')

#Vegetation height CH [m]
ch=scalar(0.00)     #no interception/infiltration
ch=ifthenelse(onderzoeksgebied,ch,False)
self.report(ch, 'ch')
```

```
  #Leaf Area Index LAI
  lai=scalar(0)      #no interception/infiltration
  lai=ifthenelse(onderzoeksgebied, lai, False)
  self.report(lai, 'lai')

  #Fraction of soil covered by vegetation
  per=scalar(0)      #no interception/infiltration
  per=ifthenelse(onderzoeksgebied, per, False)
  self.report(per, 'per')

  #Outlet
  outlet = scalar(0)
  self.report(outlet, 'outlet')

  #pit cells
  pitcellsfill=pit(lddfill)

  #Outpoint
  outpointfill=pitcellsfill
  outpoint=outpointfill==3169     #1pit cell as outpoint
  self.report(outpoint, 'outpoint')

  #Random roughness rr
  self.pandenS=ifthenelse(self.panden, scalar(0),0)
  self.asfaltS=ifthenelse(self.asfalt, scalar(0.1),0)
  self.openroadS=ifthenelse(self.openroad, scalar(0.5),0)
  self.restroadS=ifthenelse(self.restroad, scalar(0.5), 0)
  self.gemGroenS=ifthenelse(self.gemGroen, scalar(2),0)
  self.partTuinS=ifthenelse(self.partTuin, scalar(1),0)
  self.waterS=ifthenelse(self.water, scalar(0),0)
  rr=self.pandenS+self.asfaltS+self.openroadS+self.restroadS+self.gemGroenS+/
     self.partTuinS+self.waterS
  rr=ifthenelse(onderzoeksgebied, rr, False)
  self.report(rr, 'rr')

  #infiltration rate [mm/5minuten]
  self.Ipand=0
  self.IAsfalt = 0
  self.Iopenroad = 0.0833
  self.Irestroad= 0.167
  self.IgemGroen = 0.33
  self.IpartTuin = 0.7*self.Iopenroad+0.3*self.IgemGroen
  self.Iwater = 0

def dynamic(self):
  self.timestep=self.timestep+1
  precipitation1 = timeinputscalar('28july_Netto P.txt',1)
  precipitation= (precipitation1/12)*self.Pratio
```

```
    self.report(precipitation,'prec')

    #Netto precipitation for each class(NP) mm/5minutes
    NPpanden=ifthenelse(self.panden,(precipitation-self.Ipand),0)
    NPasfalt=ifthenelse(self.asfalt,(precipitation-self.IAsfalt),0)
    NPopenroad=ifthenelse(self.openroad,(precipitation-self.Iopenroad),0)
    NPrestroad=ifthenelse(self.restroad,(precipitation-self.Irestroad),0)
    NPgemGroen=ifthenelse(self.gemGroen,(precipitation-self.IgemGroen),0)
    NPpartTuin=ifthenelse(self.partTuin,(precipitation-self.IpartTuin),0)
    NPwater= scalar(0)

    #Prevent that NP is negative
    NPpanden=ifthenelse(NPpanden<0,0,NPpanden)
    NPasfalt=ifthenelse(NPasfalt<0,0,NPasfalt)
    NPopenroad=ifthenelse(NPopenroad<0,0,NPopenroad)
    NPrestroad=ifthenelse(NPrestroad<0,0,NPrestroad)
    NPgemGroen=ifthenelse(NPgemGroen<0,0,NPgemGroen)
    NPpartTuin=ifthenelse(NPpartTuin<0,0,NPpartTuin)

    #creating new Precipitation map [mm/5minutes]
    Pnew=NPpanden+NPasfalt+NPopenroad+NPrestroad+NPgemGroen+NPpartTuin+NPwater
    Pnew=Pnew*12 #mm/hour
    self.report(Pnew, 'Pnew28')

nrOfTimeSteps=22
myModel = MyFirstModel()
dynamicModel = DynamicFramework(myModel,nrOfTimeSteps)
dynamicModel.run()
```

Appendix G Calculation of the net precipitation

Parameters used for calculating the net precipitation

Surface area of research area (RA) [m^2]	1060000.00
paved surface area [m^2]	490049.00
ratio paved/unpaved surface area	0.46
Storage capacity sewer system[m^3]	2646.22
Sewer buffer [mm] in relation to paved area	5.40
Sewer buffer [mm] in relation to unpaved area	2.50
Sewage flow [m^3/h]	94.17
pumping capacity [m^3/h]	550.80
pumpovercapacity[m^3/h]	456.63
pumpovercapacity[mm/5minuten]	0.04
internal overflow [m^3/s]	1.70
internal overflow [m^3/5minuten]	510.00
internal overflow [mm/5minuten]	0.48

Land use class	infiltration [mm/5min]
Green areas of the municipality	0.333
Open pavement	0.083
Asphalt pavement	0.000
Building	0.000
Private areas	0.183

Total infiltration in research area

Calculation of the total infiltration in the research area before the sewer system is completely filled. Two examples of different amounts of precipitation [0.4 and 0.1] are given: The land use classes ‘water’ and ‘remaining pavement’ are ignored because their surface area in relation to the total surface area of the research area is less than 0.5 percent.

Land use class	infiltration rate I [mm/5min]	P [mm]	runoff= P-I [mm/5min]	Corrected runoff [mm]	ratio class/ surface area	Net runoff [mm]= Corrected runoff * ratio	total infiltration [mm]
Green areas of the municipality	0.333	0.100	-0.233	0.000	0.170	0.000	0.017
Open pavement	0.083	0.100	0.017	0.017	0.170	0.003	0.014
Asphalt pavement	0.000	0.100	0.100	0.100	0.040	0.004	0.000
Building	0.000	0.100	0.100	0.100	0.260	0.026	0.000
Private areas	0.183	0.100	-0.083	0.000	0.360	0.000	0.036
Total					1.000	0.033	0.067

Land use class	infiltration rate I [mm/5min]	P [mm]	runoff= P-I [mm/5min]	Corrected runoff [mm]	ratio class/ surface area	Net runoff [mm]= Corrected runoff * ratio	total infiltration [mm]
Green areas of the municipality	0.333	0.400	0.067	0.067	0.170	0.011	0.057
Open pavement	0.083	0.400	0.317	0.317	0.170	0.054	0.014
Asphalt pavement	0.000	0.400	0.400	0.400	0.040	0.016	0.000
Building	0.000	0.400	0.400	0.400	0.260	0.104	0.000
Private areas	0.183	0.400	0.217	0.217	0.360	0.078	0.066
Total					1.000	0.263	0.137

Net precipitation on the 28th of July 2014

Time-step	Time [min]	P [mm]	pumpovercapacity [mm/5min]	Total infiltration [mm/5min]	Internal overflow [mm/5min]	Runoff [mm]= P-pumpovercapacity-Internal overflow-average infiltration	Corrected Runoff [mm]	cumulative Runoff [mm]	Storage capacity sewer [mm]	Net P [mm/5min]	Net P [mm/hour]
0	0	0.0	0.00	0.00		0.00	0.00	0.00	2.50		0.00
1	5	0.2	0.04	0.11		0.05	0.05	0.00	2.45		0.00
2	10	0.1	0.04	0.07		0.00	0.00	0.00	2.45		0.00
3	15	0.3	0.04	0.13		0.13	0.13	0.13	2.31		0.00
4	20	0.3	0.04	0.13		0.13	0.13	0.26	2.18		0.00
5	25	0.4	0.04	0.14		0.23	0.23	0.49	1.95		0.00
6	30	0.8	0.04	0.14		0.63	0.63	1.12	1.33		0.00
7	35	2.2	0.04		0.48	1.68	1.68	2.80	0.00	0.36	4.30
8	40	0.2	0.04		0.48	-0.32	0.00	2.48		0.00	0.00
9	45	2.5	0.04		0.48	1.98	1.67	4.47		1.67	19.99
10	50	1.6	0.04		0.48	1.08	1.08	5.55		1.08	13.00
11	55	2.9	0.04		0.48	2.38	2.38	7.93		2.38	28.60
12	60	1.4	0.04		0.48	0.88	0.88	8.82		0.88	10.60
13	65	0.3	0.04		0.48	-0.22	0.00	8.60		0.00	0.00
14	70	0.5	0.04		0.48	-0.02	0.00	8.58		0.00	0.00
15	75	1.9	0.04		0.48	1.38	1.15	9.97		1.15	13.79
16	80	1.6	0.04		0.48	1.08	1.08	11.05		1.08	13.00
17	85	2.2	0.04		0.48	1.68	1.68	12.73		1.68	20.20
18	90	1.2	0.04		0.48	0.68	0.68	13.41		0.68	8.20
19	95	5.9	0.04		0.48	5.38	5.38	18.80		5.38	64.60
20	100	5.9	0.04		0.48	5.38	5.38	24.18		5.38	64.60
21	105	3.3	0.04		0.48	2.78	2.78	26.96		2.78	33.40
22	110	2.2	0.04		0.48	1.68	1.68	28.65		1.68	20.20
23	115	0.5	0.04		0.48	-0.02	0.00	28.63		0.00	0.00

24	120	0.2	0.04		0.48	-0.32	0.00	28.31		0.00	0.00
25	125	0.1	0.04		0.48	-0.42	0.00	27.90		0.00	0.00
26	130	0.8	0.04		0.48	0.28	0.00	28.18		0.00	0.00
27	135	3.3	0.04		0.48	2.78	2.31	30.96		2.31	27.78
28	140	1.2	0.04		0.48	0.68	0.68	31.64		0.68	8.20
29	145	0.3	0.04		0.48	-0.22	0.00	31.43		0.00	0.00
30	150	0.2	0.04		0.48	-0.32	0.00	31.11		0.00	0.00
31	155	0.2	0.04		0.48	-0.32	0.00	30.79		0.00	0.00

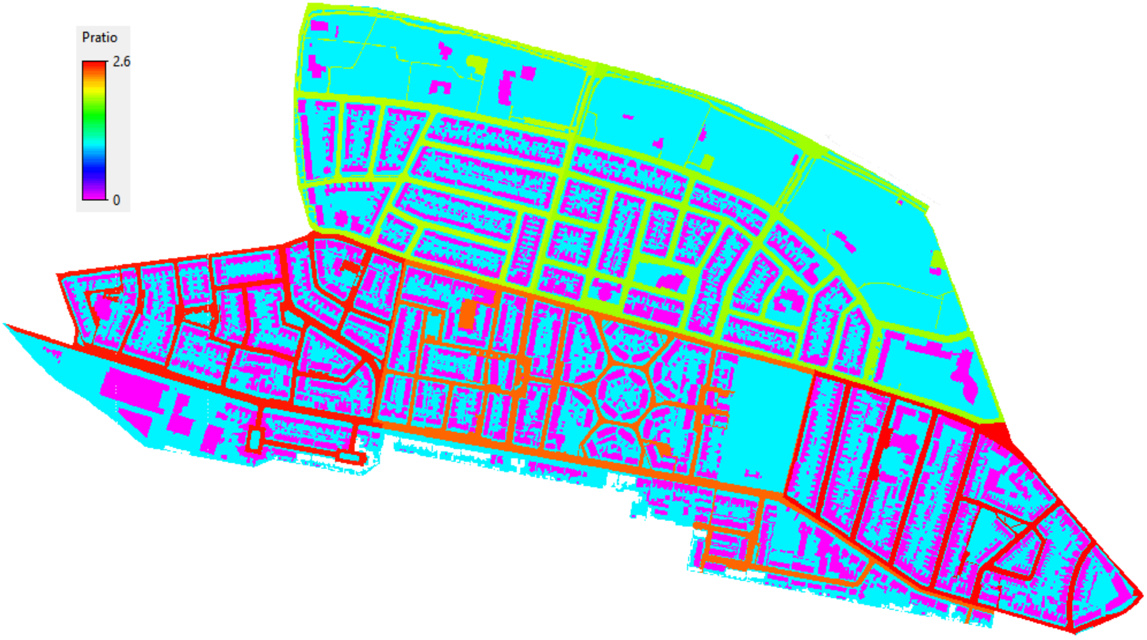
Net precipitation on the 11th of July 2014

Time-step	Time [min]	P [mm]	pumpovercapacity [mm/5min]	Total infiltration [mm/5min]	Internal overflow [mm/5min]	WaterOnStreet [mm]= P-pumpovercapacity-Internal overflow-average infiltration	Corrected WaterOn-Street[mm]	cumulative WaterOn-Street [mm]	Storage capacity sewer [mm]	Net P [mm/5min]	Net P [mm/hour]
0	0	0	0.00	0.00		0.00	0.00	0.00	2.50		0.00
1	5	0.1	0.04	0.07		0.00	0.00	0.00	2.50		0.00
2	10	0.9	0.04	0.14		0.73	0.73	0.73	1.77		0.00
3	15	4.3	0.04		0.48	3.78	3.78	4.51	0.00	2.01	24.16
4	20	6.6	0.04		0.48	6.08	6.08	10.59		6.08	73.00
5	25	4.3	0.04		0.48	3.78	3.78	14.38		3.78	45.40
6	30	1.6	0.04		0.48	1.08	1.08	15.46		1.08	13.00
7	35	1.4	0.04		0.48	0.88	0.88	16.34		0.88	10.60
8	40	1.2	0.04		0.48	0.68	0.68	17.02		0.68	8.20
9	45	0.8	0.04		0.48	0.28	0.28	17.31		0.28	3.40
10	50	0.1	0.04		0.48	-0.42	0.00	16.89		0.00	0.00

Appendix H PCRaster maps

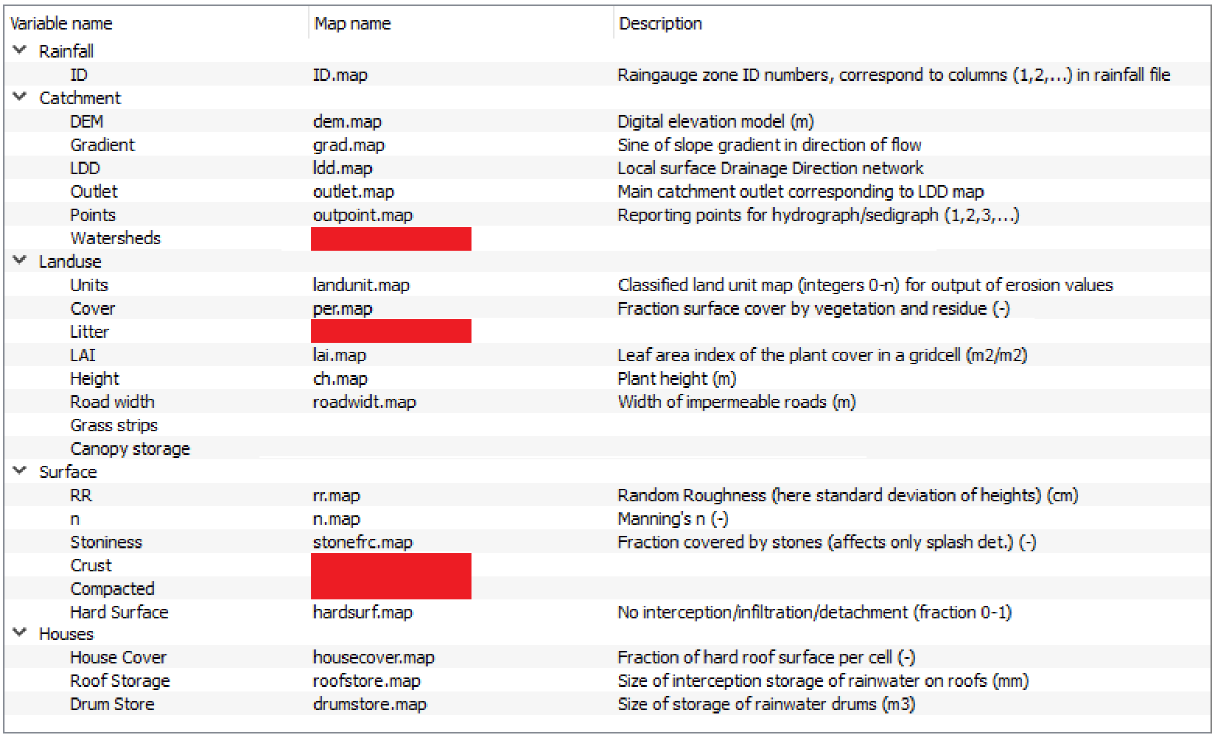
RAbuurt: The five districts of the research area. 30) Rivierenbuurt-Oost; 31)Rivierenbuurt-West; 32) Gerrit van Stellingwerfstraat; 33) Bloemenbuurt-Oost; 34) Bloemenbuurt-West

Pratio: Gives the building/pavement ratio +1 for each district of the research area. A ratio of 2.6 means that the surface area occupied by buildings in the district is 1.6 times larger than the surface area occupied by pavement. It is assumed that all the water that falls on the roof is equally distributed for each district over the paved area. Originally the whole map had a value of 1 but because of this assumption the Pratio value for buildings changed into 0 and for the paved area it increased by the ratio of buildings/pavement. The map is used to calculate the net precipitation maps for every individual timestep.



Appendix I Input maps OpenLISEM

The table below shows all the input maps except the rainfall maps that are used for the openLISEM model. The rainfall maps are loaded via a textfile for each timestep of five minutes and are made with the help of PCRaster Python (Called Pnew in appendix F). The Pratio map (Appendix H), the net precipitation values (appendix G) and the infiltration values (chapter 3.3.2) for each land use class.



Variable name	Map name	Description
Rainfall		
ID	ID.map	Raingauge zone ID numbers, correspond to columns (1,2,...) in rainfall file
Catchment		
DEM	dem.map	Digital elevation model (m)
Gradient	grad.map	Sine of slope gradient in direction of flow
LDD	ldd.map	Local surface Drainage Direction network
Outlet	outlet.map	Main catchment outlet corresponding to LDD map
Points	outpoint.map	Reporting points for hydrograph/sedigraph (1,2,3,...)
Watersheds	🟥	
Landuse		
Units	landunit.map	Classified land unit map (integers 0-n) for output of erosion values
Cover	per.map	Fraction surface cover by vegetation and residue (-)
Litter	🟥	
LAI	lai.map	Leaf area index of the plant cover in a gridcell (m2/m2)
Height	ch.map	Plant height (m)
Road width	roadwidt.map	Width of impermeable roads (m)
Grass strips		
Canopy storage		
Surface		
RR	rr.map	Random Roughness (here standard deviation of heights) (cm)
n	n.map	Manning's n (-)
Stoniness	stonefrc.map	Fraction covered by stones (affects only splash det.) (-)
Crust	🟥	
Compacted		
Hard Surface	hardsurf.map	No interception/infiltration/detachment (fraction 0-1)
Houses		
House Cover	housecover.map	Fraction of hard roof surface per cell (-)
Roof Storage	roofstore.map	Size of interception storage of rainwater on roofs (mm)
Drum Store	drumstore.map	Size of storage of rainwater drums (m3)

Appendix J Letter to the residents

Beste Wijkbewoner,

Momenteel studeer ik aan de Universiteit Utrecht en ben ik bezig met mijn afstudeeronderzoek bij de Gemeente Amersfoort en ingenieursbedrijf Aveco de Bondt. Het onderwerp van mijn afstudeeronderzoek is: ‘wateroverlast ten gevolge van hevige neerslag in het Soesterkwartier’. Hiervoor ben ik op zoek naar informatie over de mate van overlast tijdens en na afloop van twee extreme buien in het Soesterkwartier. Hiervoor vraag ik u om uw hulp. Heeft u op 11 juli 2014 of 28 juli 2014 overlast ondervonden van de hevige buien die op deze dagen gevallen zijn? Stond er water op straat en/of in uw tuin? Heeft u schade ondervonden ten gevolge van de neerslag? Indien u informatie over deze vragen heeft hoor ik dat graag van u. Ook foto’s en video’s van de mate van overlast zijn meer dan welkom. Indien u deze zou ik willen weten:

1) op welke dag deze gemaakt zijn;
2) Waar deze gemaakt zijn (adres).

Alle informatie met betrekking tot de overlast en schade ten gevolge van de hevige regenval is welkom (denk hierbij bijvoorbeeld aan stankoverlast, losgekomen putdeksels, water op straat/ in huis etc) en kan verzonden worden naar onderstaand mailadres. Deze informatie is van groot belang voor mijn onderzoek want hiermee wil ik de exacte probleemgebieden in het Soesterkwartier in kaart brengen. Daarnaast zal ik aan het eind van mijn onderzoek locatie gerichte oplossingen aandragen voor deze probleemgebieden.

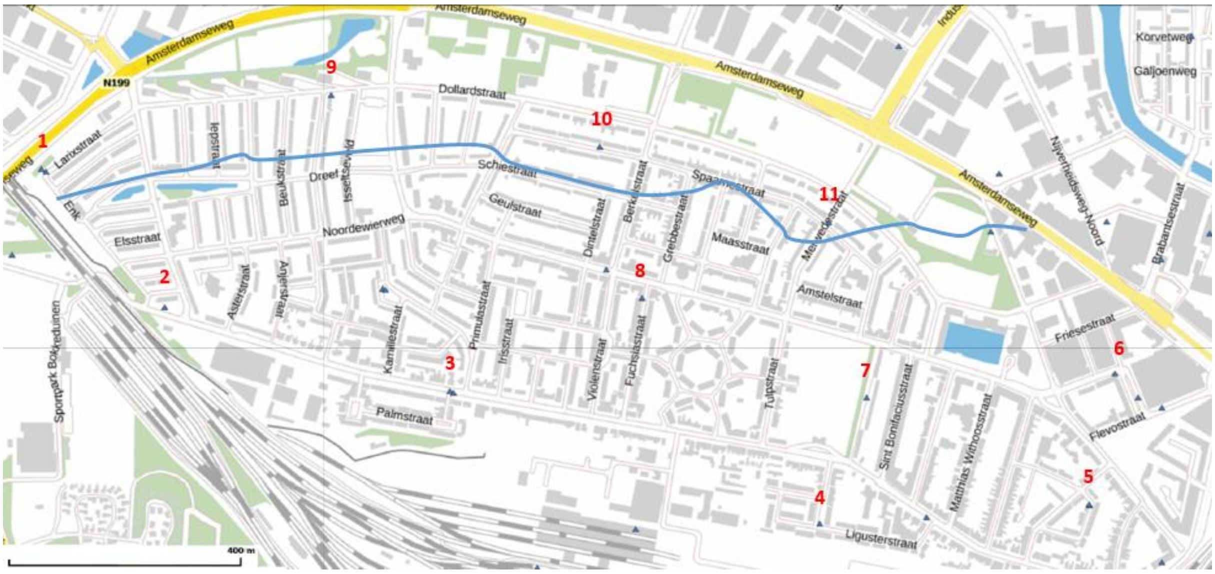
Bij voorbaat dank voor uw hulp.

Met vriendelijke groet,
Lennart Elijzen

Informatie kan verzonden worden naar: lennartelijzen@hotmail.com

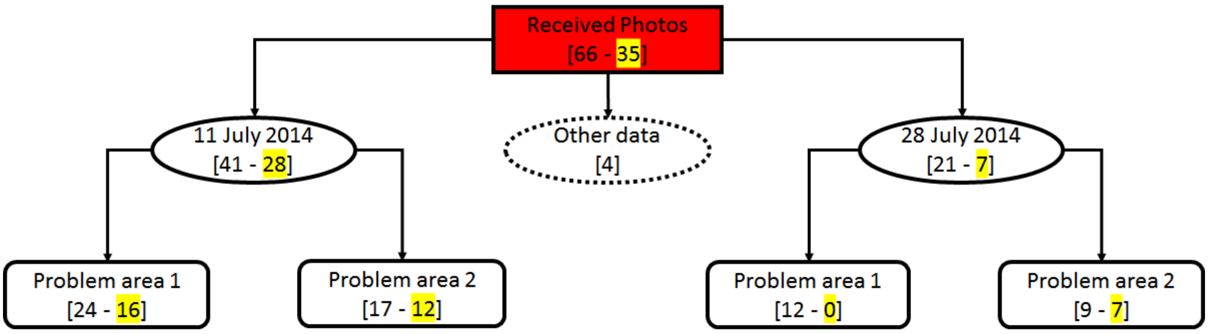
Appendix K Groundwater levels in the Soesterkwartier district

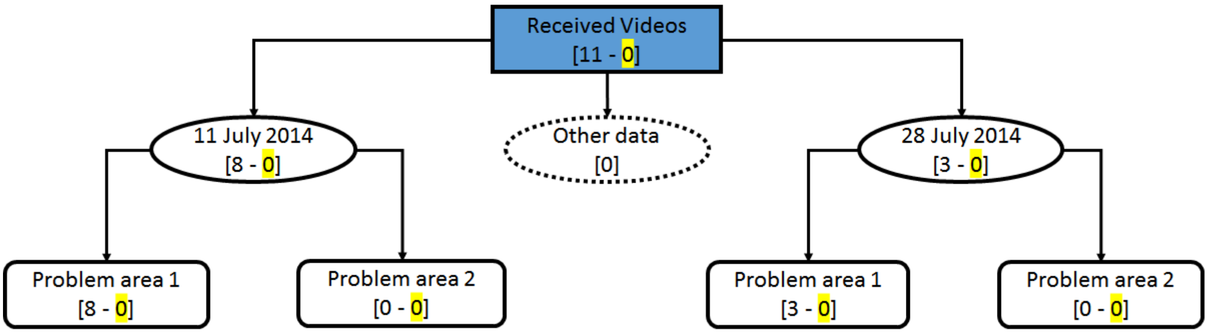
In the map below are the stations shown that measure the groundwater levels in the Soesterkwartier. In the table below are the corresponding groundwater levels relative to the Dutch Ordnance Level (DOL) and surface level given. The thick blue line gives an indication of the average highest groundwater level of 1.5 meter relative to the surface. This level is important for the construction of wadis (chapter 5.1). North of the blue line the average highest groundwater level is lower than 1.5 and to the south its higher. All the values are derived from Dinoloket [https://www.dinoloket.nl/ondergrondgegevens].



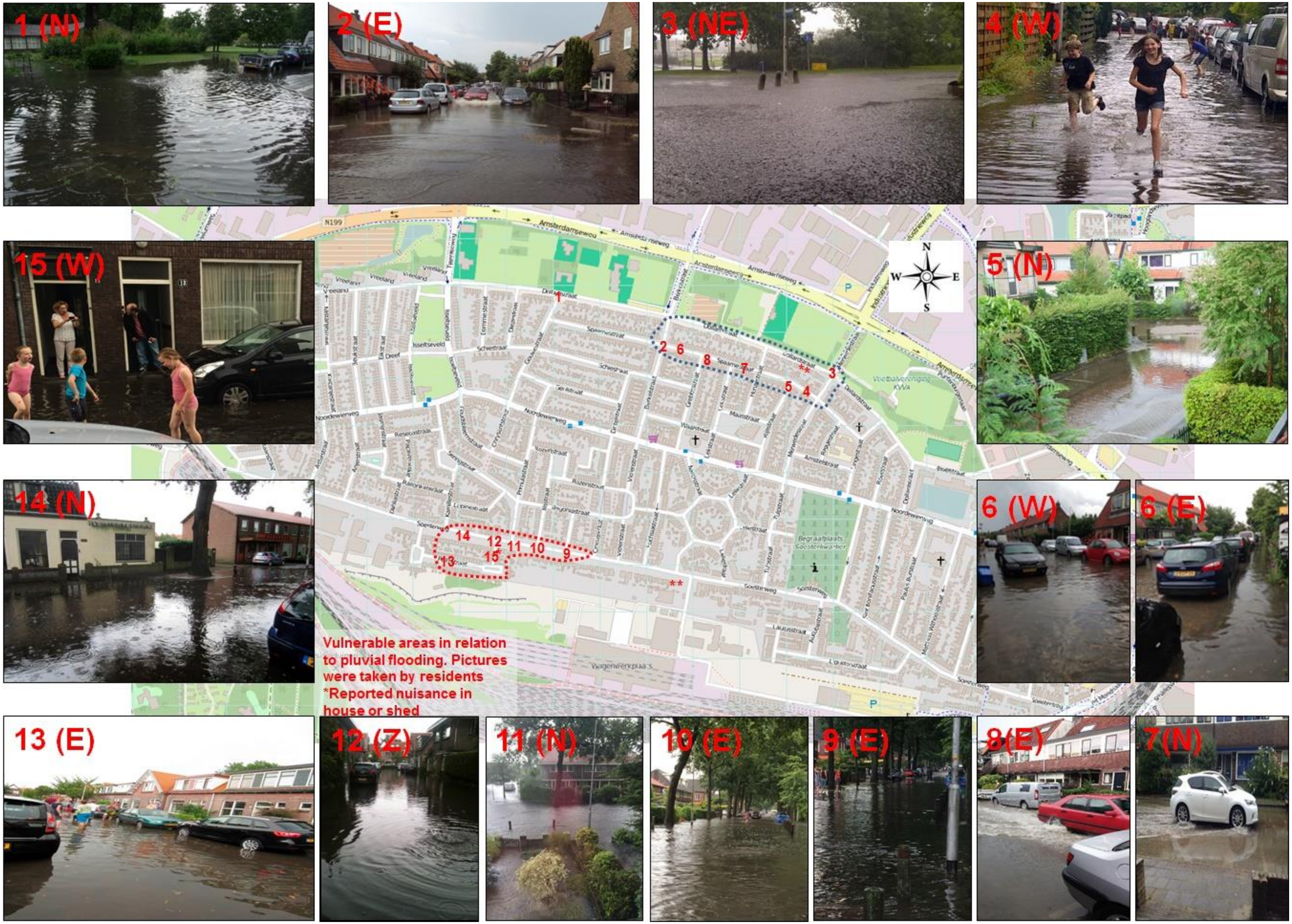
Groundwater station	Surface level [m]	Average groundwater level relative to DOL [m]		Average groundwater level relative to surface level [m]	
		High	Low	High	Low
1	4.32	3.00	2.20	1.32	2.12
2	6.41	4.20	3.20	2.21	3.21
3	6.00	4.30	3.80	1.70	2.20
4	6.80	4.40	3.60	2.20	3.20
5	5.68	3.60	2.90	2.08	2.78
6	4.67	2.80	2.00	1.87	2.67
7	6.72	4.40	3.70	2.32	3.02
8	6.60	4.23	3.23	2.37	3.37
9	3.59	2.60	2.10	0.99	1.49
10	4.16	3.05	2.60	1.11	1.56
11	4.69	4.20	3.60	0.49	1.09

Appendix L Overview of the feedback from the residents





Overview of the problem areas and a part of the pictures received from the residents (next page).

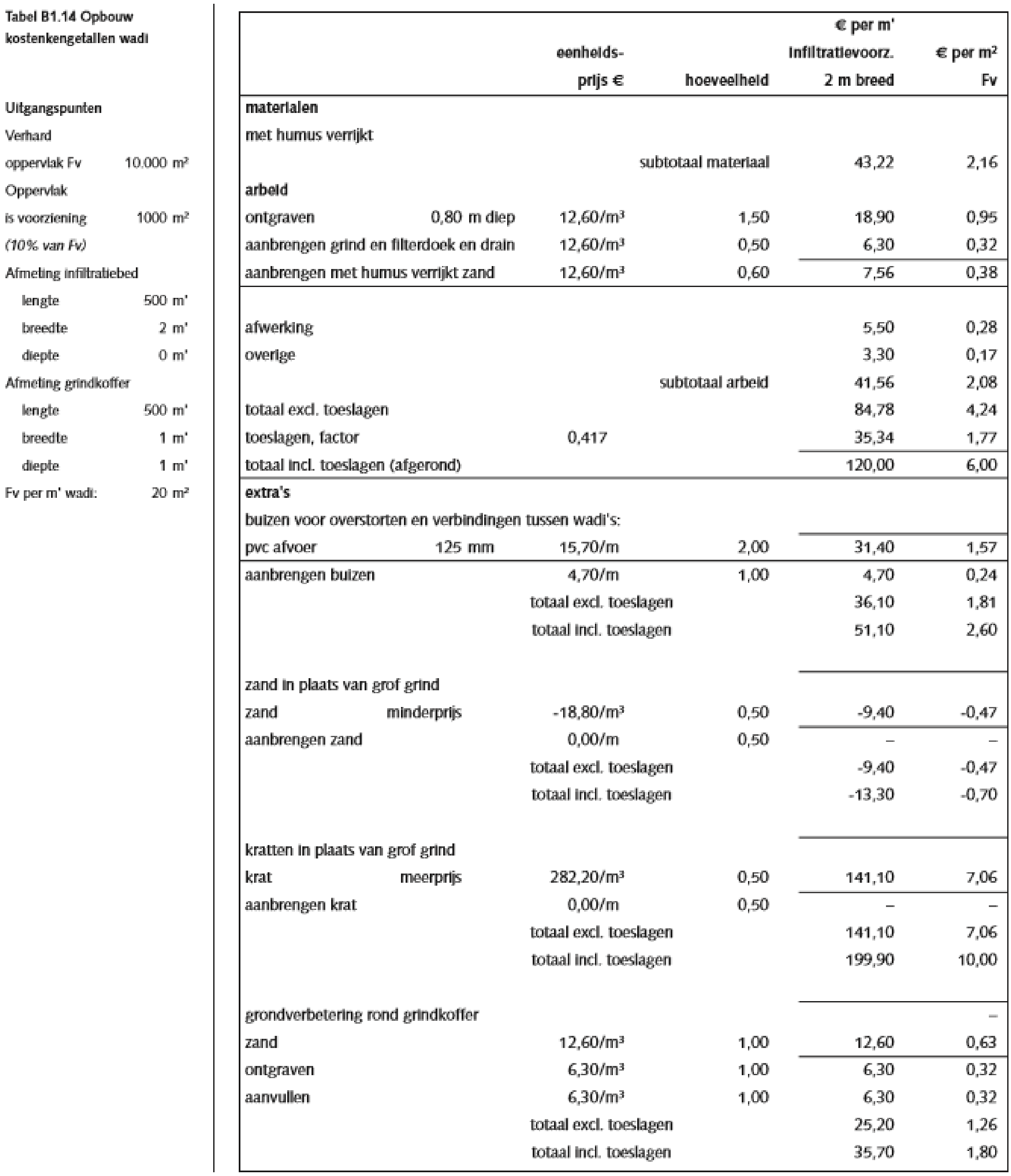


Vulnerable areas in relation to pluvial flooding. Pictures were taken by residents
*Reported nuisance in house or shed

Appendix M Unit costs of potential measures

All unit prices are copied from RIONED, 2015 except of the Drainvoeg which is derived from Drainvast, 2016.

1. Wadi

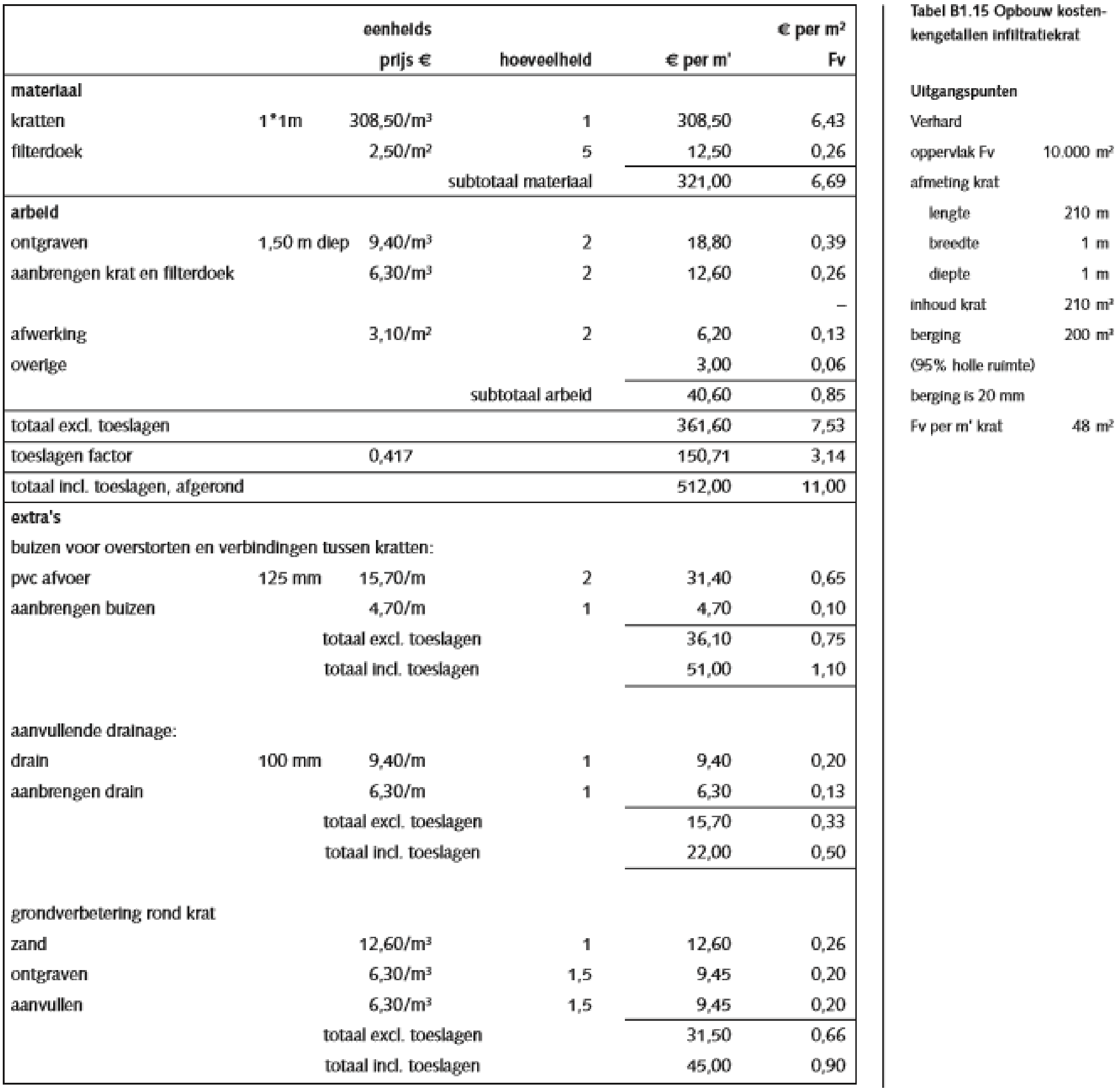


Tabel B1.14 Opbouw kostenkengetallen wadi

Uitgangspunten	
Verhard	
oppervlak Fv	10.000 m²
Oppervlak	
is voorziening	1000 m²
(10% van Fv)	
Afmeting infiltratiebed	
lengte	500 m'
breedte	2 m'
diepte	0 m'
Afmeting grindkoffer	
lengte	500 m'
breedte	1 m'
diepte	1 m'
Fv per m' wadi:	20 m²

		eenheids-prijs €	hoeveelheid	€ per m' infiltratievoorz. 2 m breed	€ per m² Fv
materialen					
met humus verrijkt					
			subtotaal materiaal	43,22	2,16
arbeid					
ontgraven	0,80 m diep	12,60/m³	1,50	18,90	0,95
aanbrengen grind en filterdoek en drain		12,60/m³	0,50	6,30	0,32
aanbrengen met humus verrijkt zand		12,60/m³	0,60	7,56	0,38
afwerking				5,50	0,28
overige				3,30	0,17
			subtotaal arbeid	41,56	2,08
totaal excl. toeslagen				84,78	4,24
toeslagen, factor		0,417		35,34	1,77
totaal incl. toeslagen (afgerond)				120,00	6,00
extra's					
buizen voor overstorten en verbindingen tussen wadi's:					
pvc afvoer	125 mm	15,70/m	2,00	31,40	1,57
aanbrengen buizen		4,70/m	1,00	4,70	0,24
		totaal excl. toeslagen		36,10	1,81
		totaal incl. toeslagen		51,10	2,60
zand in plaats van grof grind					
zand	minderprijs	-18,80/m³	0,50	-9,40	-0,47
aanbrengen zand		0,00/m	0,50	–	–
		totaal excl. toeslagen		-9,40	-0,47
		totaal incl. toeslagen		-13,30	-0,70
kratten in plaats van grof grind					
krat	meerprijs	282,20/m³	0,50	141,10	7,06
aanbrengen krat		0,00/m	0,50	–	–
		totaal excl. toeslagen		141,10	7,06
		totaal incl. toeslagen		199,90	10,00
grondverbetering rond grindkoffer					–
zand		12,60/m³	1,00	12,60	0,63
ontgraven		6,30/m³	1,00	6,30	0,32
aanvullen		6,30/m³	1,00	6,30	0,32
		totaal excl. toeslagen		25,20	1,26
		totaal incl. toeslagen		35,70	1,80

2. Infiltration box



		eenheids prijs €	hoeveelheid	€ per m'	€ per m² Fv
materiaal					
kratten	1*1m	308,50/m³	1	308,50	6,43
filterdoek		2,50/m²	5	12,50	0,26
			subtotaal materiaal	321,00	6,69
arbeid					
ontgraven	1,50 m diep	9,40/m³	2	18,80	0,39
aanbrengen krat en filterdoek		6,30/m³	2	12,60	0,26
					–
afwerking		3,10/m²	2	6,20	0,13
overige				3,00	0,06
			subtotaal arbeid	40,60	0,85
totaal excl. toeslagen				361,60	7,53
toeslagen factor		0,417		150,71	3,14
totaal incl. toeslagen, afgerond				512,00	11,00
extra's					
buizen voor overstorten en verbindingen tussen kratten:					
pvc afvoer	125 mm	15,70/m	2	31,40	0,65
aanbrengen buizen		4,70/m	1	4,70	0,10
		totaal excl. toeslagen		36,10	0,75
		totaal incl. toeslagen		51,00	1,10
aanvullende drainage:					
drain	100 mm	9,40/m	1	9,40	0,20
aanbrengen drain		6,30/m	1	6,30	0,13
		totaal excl. toeslagen		15,70	0,33
		totaal incl. toeslagen		22,00	0,50
grondverbetering rond krat					
zand		12,60/m³	1	12,60	0,26
ontgraven		6,30/m³	1,5	9,45	0,20
aanvullen		6,30/m³	1,5	9,45	0,20
		totaal excl. toeslagen		31,50	0,66
		totaal incl. toeslagen		45,00	0,90

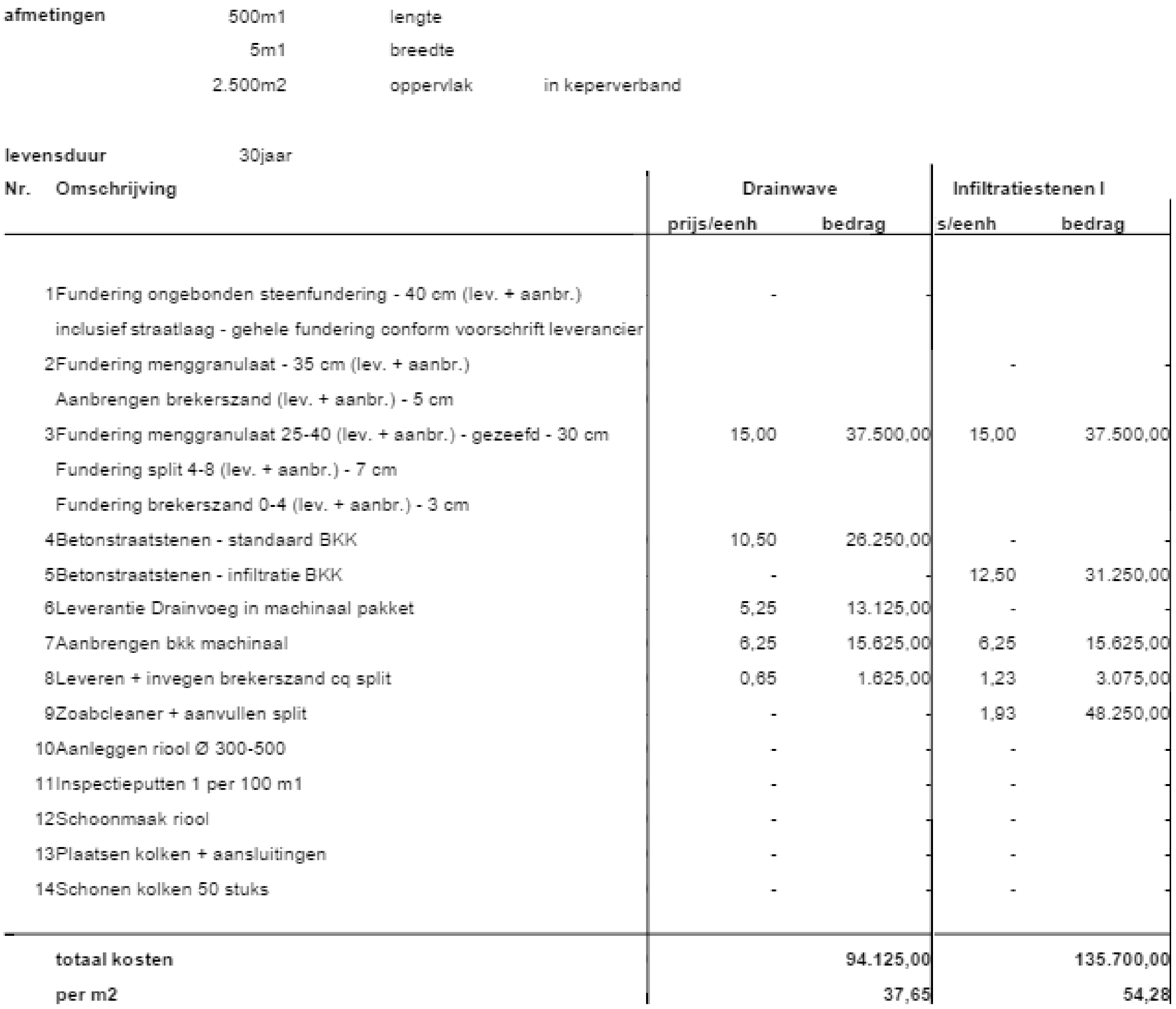
Tabel B1.15 Opbouw kostenkengetallen infiltratiekrat

Uitgangspunten

Verhard	
oppervlak Fv	10.000 m²
afmeting krat	
lengte	210 m
breedte	1 m
diepte	1 m
inhoud krat	210 m³
berging	200 m³
(95% holle ruimte)	
berging is 20 mm	
Fv per m' krat	48 m²

3. Permeable pavement (Drainvoeg)

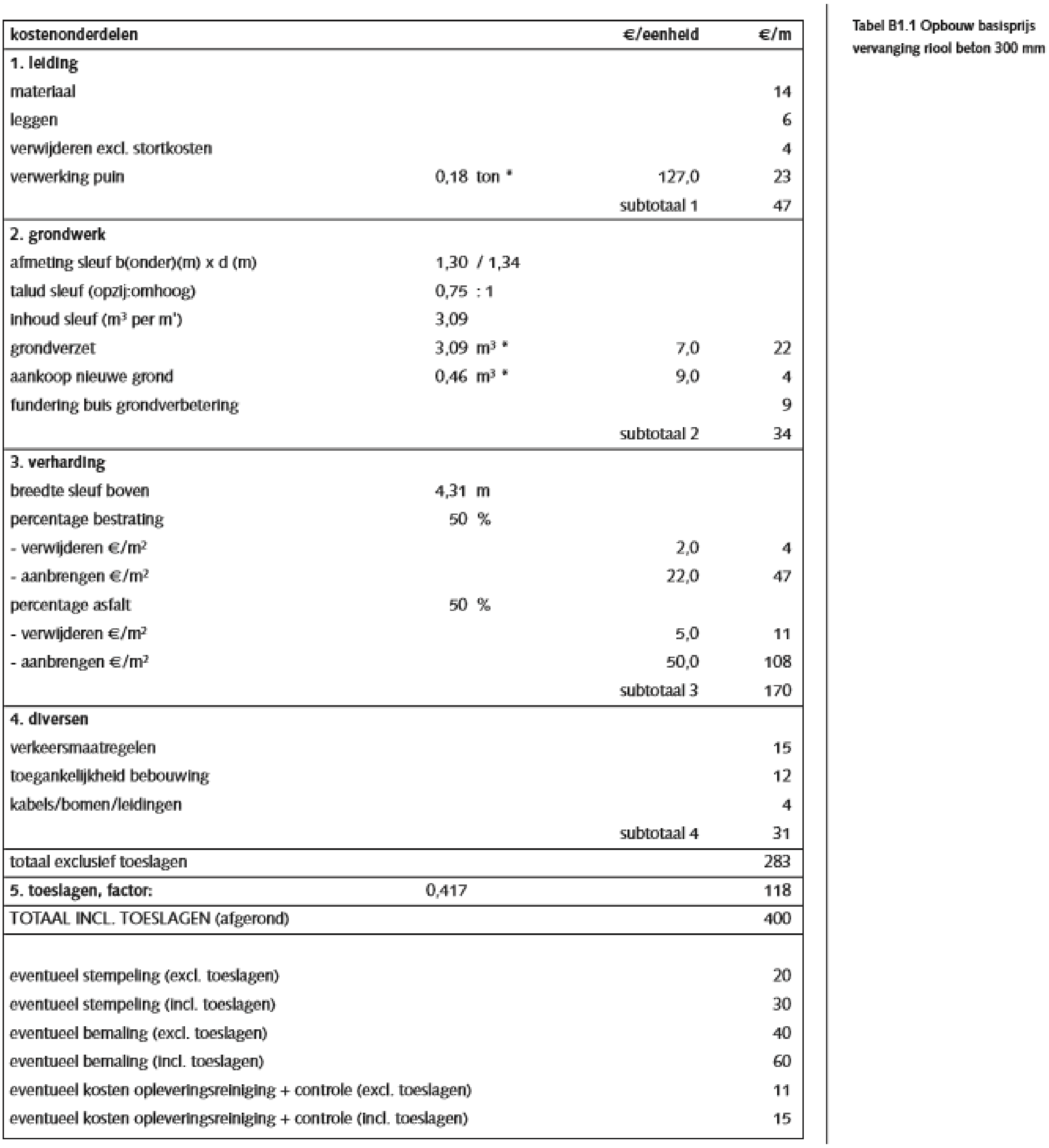
Note: regular maintenance is not taken into account.



afmetingen	500m1	lengte	
	5m1	breedte	
	2.500m2	oppervlak	in keperverband
levensduur	30jaar		

Nr.	**Omschrijving**	**Drainwave**		**Infiltratiestenen I**	
		prijs/eenh	**bedrag**	**s/eenh**	**bedrag**
1	Fundering ongebonden steenfundering - 40 cm (lev. + aanbr.)	-	-		
	inclusief straatlaag - gehele fundering conform voorschrift leverancier				
2	Fundering menggranulaat - 35 cm (lev. + aanbr.)			-	-
	Aanbrengen brekerszand (lev. + aanbr.) - 5 cm				
3	Fundering menggranulaat 25-40 (lev. + aanbr.) - gezeefd - 30 cm	15,00	37.500,00	15,00	37.500,00
	Fundering split 4-8 (lev. + aanbr.) - 7 cm				
	Fundering brekerszand 0-4 (lev. + aanbr.) - 3 cm				
4	Betonstraatstenen - standaard BKK	10,50	26.250,00	-	-
5	Betonstraatstenen - infiltratie BKK	-	-	12,50	31.250,00
6	Leverantie Drainvoeg in machinaal pakket	5,25	13.125,00	-	-
7	Aanbrengen bkk machinaal	6,25	15.625,00	6,25	15.625,00
8	Leveren + invegen brekerszand cq split	0,65	1.625,00	1,23	3.075,00
9	Zoabcleaner + aanvullen split	-	-	1,93	48.250,00
10	Aanleggen riool Ø 300-500	-	-	-	-
11	Inspectieputten 1 per 100 m1	-	-	-	-
12	Schoonmaak riool	-	-	-	-
13	Plaatsen kolken + aansluitingen	-	-	-	-
14	Schonen kolken 50 stuks	-	-	-	-
	totaal kosten		**94.125,00**		**135.700,00**
	per m2		**37,65**		**54,28**

4. Rainwater sewer



Tabel B1.1 Opbouw basisprijs vervanging riool beton 300 mm

kostenonderdelen		€/eenheid	€/m
1. leiding			
materiaal			14
leggen			6
verwijderen excl. stortkosten			4
verwerking puin	0,18 ton *	127,0	23
		subtotaal 1	47
2. grondwerk			
afmeting sleuf b(onder)(m) x d (m)	1,30 / 1,34		
talud sleuf (opzij:omhoog)	0,75 : 1		
inhoud sleuf (m³ per m')	3,09		
grondverzet	3,09 m³ *	7,0	22
aankoop nieuwe grond	0,46 m³ *	9,0	4
fundering buis grondverbetering			9
		subtotaal 2	34
3. verharding			
breedte sleuf boven	4,31 m		
percentage bestrating	50 %		
- verwijderen €/m²		2,0	4
- aanbrengen €/m²		22,0	47
percentage asfalt	50 %		
- verwijderen €/m²		5,0	11
- aanbrengen €/m²		50,0	108
		subtotaal 3	170
4. diversen			
verkeersmaatregelen			15
toegankelijkheid bebouwing			12
kabels/bomen/leidingen			4
		subtotaal 4	31
totaal exclusief toeslagen			283
5. toeslagen, factor:	0,417		118
TOTAAL INCL. TOESLAGEN (afgerond)			400
eventueel stempeling (excl. toeslagen)			20
eventueel stempeling (incl. toeslagen)			30
eventueel bemaling (excl. toeslagen)			40
eventueel bemaling (incl. toeslagen)			60
eventueel kosten opleveringsreiniging + controle (excl. toeslagen)			11
eventueel kosten opleveringsreiniging + controle (incl. toeslagen)			15

Tabel B1.2 Opbouw basisprijs vervanging riool gewapend beton 700 mm

kostenonderdelen			**€/eenheid**	**€/m**
1. leiding				
materiaal				103
leggen				10
verwijderen exclusief verwerking puin				8
verwerking puin	0,625	ton *	127,0	79
			subtotaal 1	201
2. grondwerk				
afmeting sleuf b(onder)(m) x d (m)	1,7	/ 2,29		
talud sleuf (opzij:omhoog)	0,75	: 1		
inhoud sleuf (per m')	7,81	m³		
grondverzet	7,81	m³ *	7,0	55
aankoop nieuwe grond	1,17	m³ *	9,0	11
fundering buis grondverbetering				9
			subtotaal 2	74
3. verharding				
breedte sleuf maaiveld	6,13	m		
percentage bestrating	50	%		
- verwijderen €/m²			2,0	6
- aanbrengen €/m²			22,0	67
percentage asfalt	50	%		
- verwijderen €/m²			5,0	15
- aanbrengen €/m²			50,0	153
		subtotaal 3		242
4. diversen				
verkeersmaatregelen				32
toegankelijkheid bebouwing				12
kabels/bomen/leidingen				4
			subtotaal 4	48
totaal exclusief toeslagen				565
5. toeslagen, factor:	0,417			235
TOTAAL INCL. TOESLAGEN (afgerond)				800
eventueel stempeling (excl. toeslagen)				40
eventueel stempeling (incl. toeslagen)				60
eventueel bemaling (excl. toeslagen)				50
eventueel bemaling (incl. toeslagen)				70
eventueel kosten opleveringsreiniging + controle (excl. toeslagen)				20
eventueel kosten opleveringsreiniging + controle (incl. toeslagen)				30

Appendix N Spreadsheet about the effectivity and costs of the different measures

Input

rainfall events	total amount of precipitation [mm]	duration [minutes]	return period [years]
Bui 08	19,8	60	T=2
Bui 09	29,4	60	T=5
Bui 10	35,7	45	T=10

Land use class	ratio class/ surface area	infiltration rate [mm/hour]	netto infiltration [mm/hour]
Green areas of the municipality	0,170	4	0,68
Openroad	0,170	1	0,17
Asphalt roads	0,040	0	0
Building	0,260	0	0
Private areas	0,360	2,200	0,792
Average			1,642

Original situation

green area Palmstraat/Hulststraat		
length	33	m
width	10	m
surface area	330	m2
height	0,15	m
buffer capacity	0	m3
infiltration rate	4	mm/hour

Pavement Hulststraat		
surface area	395	m2
buffer capacity	0	m3
infiltration rate	1	mm/hour

Roof surface research area		
total surface area	269400	m2
households	4190	-
buffer capacity	0	m3
infiltration rate	0	mm/hour

Measures

wadi Palmstraat/Hulststraat		
length	33	m
width	10	m
surface area	330	m2
depth	0,3	m
slope	1/3	-
buffer capacity	88,36	m3
infiltration rate	12,5	mm/hour

Drainwave Hulststraat		
surface area	395	m2
buffer capacity	0	m3
infiltration rate	360	mm/m2/hour

Rain barrel		
surface area	-	m2
households	4190	-
Volume [1 rain barrel]	0,2	m3
infiltration capacity	0	mm/hour
fraction households with rain barrel	0,5	-
buffer capacity	419	m3

Effectivity

	potential decoupled surface area [m2]	ratio decoupled area/ m2 wadi
Bui 08	5075	15,38
Bui 09	3324	10,07
Bui 10	2679	8,12

	potential decoupled surface area [m2]	ratio decoupled area/ m2 drainwave
Bui 08	7401	18,74
Bui 09	4704	11,91
Bui 10	2685	6,80

	potential decoupled roof surface area [m2]	ratio decoupled roof area/rain barrel
Bui 08	21162	10,10
Bui 09	14252	6,80
Bui 10	11737	5,60

Unit costs

wadi	€ 60,00	m2

drainwave	€ 37,65	m2

rain barrel	€ 50,00	barrel

Invested euros per m2 decoupled surface area		
Bui 08	€	3,90
Bui 09	€	5,96
Bui 10	€	7,39

Invested euros per m2 decoupled surface area		
Bui 08	€	2,01
Bui 09	€	3,16
Bui 10	€	5,54

Invested euros per m2 decoupled roof surface area		
Bui 08	€	4,95
Bui 09	€	7,35
Bui 10	€	8,93

Input

See last page

Original situation

schoolyard 'obs De Magneet'		
length	35	m
width	35	m
surface area	1225	m2
infiltration rate	1	mm/hour
buffer capacity	0	m3
groundwater depth	1,9	m

Measures

Infiltration box under schoolyard		
length	30	m
width	30	m
top of the box to surface	0,6	m
bottom of the box to surface	1,4	m
surface area	900	m2
infiltration rate	5	mm/hour
buffer capacity	684	m3

Effectivity

	potential decoupled surface area [m2]	ratio decoupled area/ m3 infiltration box
Bui 08	37897	52,63
Bui 09	24795	34,44
Bui 10	19970	27,74

Unit costs

infiltration box	€ 512,00	m3

Invested euros per m2 decoupled surface area	
Bui 08	€ 9,73
Bui 09	€ 14,87
Bui 10	€ 18,46