Climate Change Adaptation of Urban Drainage Systems Using the Resilience Framework Approach – Case study in Dordrecht, Netherlands

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Abstract

While flooding is the most common natural hazard and third most damaging after storms and earthquakes, climate change is likely to exacerbate the issue. In the Netherlands, regional climate projections predict increases in rainfall intensity, which are likely to cause more frequent and severe floods, thereby putting people and assets increasingly at risk. The projected impacts and uncertainties associated with climate change therefore reveal the need for urban planners and water managers to plan ahead and anticipate extreme weather events. Traditional approaches to storm water management present shortcomings such as statistical uncertainties and limited flexibility for modifying a selected adaption strategy to future climatic variability. In this study, an emerging approach termed the *resilience framework approach* (RFA) was tested on Dordrecht's drainage systems, and presented as an alternative approach to storm water management. The RFA builds on already existing approaches, while enhancing the flexibility of climate adaptation strategies to future climatic variability, and takes opportunity of urban renewal to perform the drainage system's retrofit.

The RFA was applied to Dordrecht's drainage systems in order to evaluate the systems' resilience and adaptation potential to climate change. More specifically, the aim of the study was to determine thresholds for the desired level of system performance, and to determine how much climate change the current drainage systems could cope with before exceeding those thresholds. A set of adaptation measures was researched and tested to determine if the resilience of the drainage system to climate change would be enhanced. The adaptation measures were tested in this study were: the *incremental change strategy*, which consisted of disconnecting 40% of open paved roads and flat roofs from the sewer system by 2045, and the *transformational change strategy*, which consisted of using the overland drainage system. The windows of opportunities identified to perform the system retrofit were scheduled road and building maintenance.

The quantification of the current and proposed modified drainage systems' response to climate change was performed using a geographical information system (ArcGIS) and two hydrodynamic-hydraulic models (DORD-BAS, 1D and DORD_ODS, 1D2D).

The results showed that the incremental change strategy was effective in most districts, but not all. Under synthetic rainfall designs, only 60% to 65% of the districts showed considerable improvement, that is, the proposed modified sewer system could cope with more rainfall than the current sewer system. Results for the transformational change strategy were positive for two out of three districts, that is, with an adapted terrain, less buildings flooded. These results provide great insight into the capacity of the proposed modified drainage system to deal with the impacts of climate change. However, more research is needed to find adaptation measures that will increase the entire sewer system's resilience to climate change. Moreover, additional research should be performed on the use of the overland drainage system, since only three districts were evaluated in this study.

In conclusion, the contributions of the RFA to storm water management are 1) its capacity to cope with uncertainty, 2) the flexibility of adaptation strategies to future changing climate, and 3) the use of windows of opportunity, such as urban renewal, in the development of adaptation strategies. Moreover, the RFA facilitates the development of responses and adaptation measures that are appropriate at the right time and place. The results of this study show that the RFA can contribute to the adaptation of urban drainage systems to climate change. The RFA can be considered as an alternative or complementary approach to already existing approaches in storm water management.

Keywords

Climate change, urban storm water management; drainage; tipping point; resilience; adaptation; land use planning; transformational change; incremental change.

Executive Summary

While flooding is the most common natural hazard and third most damaging after storms and earthquakes, climate change is likely to exacerbate the issue. In the Netherlands, the KNMI has developed four regional scenarios based on the IPCC's global circulation models. These scenarios predict increases in rainfall intensity, which are likely to cause more frequent and severe floods, thereby putting people and assets increasingly at risk. The effects of changes in hydrology are also expected to put greater pressure on drainage infrastructure. Despite climate projections from the IPCC and the KNMI, great scientific uncertainty remains as to how exactly the climate will change and what its impact will be on communities. The projected impacts and uncertainties associated with climate change therefore reveal the need for urban planners and water managers to plan ahead and anticipate extreme weather events. Current approaches to storm water management include the top-down, bottom-up, cause-based and effect-based approaches. These approaches are commonly used in the development of climate change adaptation strategies for drainage systems, yet these approaches present shortcomings such as statistical uncertainties and limited flexibility for modifying a selected adaption strategy to future climatic variability. This study aims to test an emerging approach as an alternative or complementary approach to these traditional approaches to storm water management. The approach is termed the *resilience framework approach* (RFA), and uses aspects of the bottom-up and effect-based approaches. The RFA also draws on the minimax and the Bayesian decision support strategies in order to determine desired levels of system performance, and to continually adapt the system as new information becomes available. In addition, the RFA uses windows of opportunity such as urban renewal to introduce selected adaptation measures to the system.

In this study, the RFA was tested on Dordrecht's drainage systems in order to evaluate the systems' resilience and adaptation potential to a changing climate. The questions addressed in this study focus on the four steps of the RFA: (1) What are the climate-incurred tipping points of the current sewer system and of the current overland drainage system of Dordrecht? (2) What incremental changes and long-term transformations could improve Dordrecht's resilience to flooding, and what opportunities exist for their implementation? (3) What are the climate-incurred tipping points of the proposed modified sewer and overland drainage systems? (4) Which adaptation strategy is most effective in improving Dordrecht's resilience to flooding?

The research was performed using a geographical information system (ArcGIS) and two hydrodynamic-hydraulic models (DORD-BAS, 1D and DORD_ODS, 1D2D) to simulate the response of both the sewer system and the overland drainage system's response to climate change. Climate change was expressed by increasing the intensity of various synthetically designed extreme rainfall events. The desired drainage system performance was first defined; then the systems' tipping points were determined. The tipping points of the drainage systems were said to occur when the system fails to meet its intended performance. For the sewer system, the tipping point was expressed in terms of percentage of overtopped manholes, with an acceptable performance threshold set to 1% of overtopped manholes. For the overland drainage system, the tipping point was expressed in terms of percentage of flooded buildings and was set to an acceptable performance threshold of 1% of buildings flooded.

Two adaptation strategies were tested and contrasted in terms of effectiveness in increasing the resilience of the drainage systems. These are the *incremental change strategy*, which takes place over relatively short time periods and involves maintaining the essence and integrity of the current system, and the *transformational change strategy*, which takes place over longer time periods and involves crossing thresholds at multiple scales to allow development into a fundamentally new system and way of thinking. The incremental change strategy consisted of disconnecting 40% of open paved roads and flat roofs from the sewer system by 2045. The transformational change strategy consisted of using the overland drainage system. The transformational change was tested on three districts only, and involved using and adapting the terrain of the overland drainage system to have the street profile used as temporary storage or as flow path to direct excess runoff to lower lying areas for temporary retention. The windows of opportunities identified to perform the system retrofit were urban renewal and scheduled road and building maintenance.

The tipping point analysis was performed for the current and modified drainage systems. The analysis revealed that most districts of Dordrecht have already reached the tipping point with the sewer system currently in place. Under the Bui 6 synthetic design, 25% of the districts reach the tipping point without even simulating the effects of climate change; for Bui 8, it is 40% of the districts. However, the remaining districts reach a tipping point at various rainfall intensities, and thus at different points in time. The incremental change strategy proved to be effective in most districts, but not all. The response of the adapted sewer system showed a shift in tipping point, meaning that the adapted system could cope with greater rainfall quantities than the current system. Under the Bui 6 synthetic rainfall design, only 65% of the districts showed considerable improvement, that is, there was a shift in tipping point from the current system to the adapted system. Under the Bui 8 synthetic rainfall design, only 60% of the districts showed improvement. Results for the transformational change strategy were positive for two out of three districts. With an adapted terrain, less buildings flooded, and the tipping point of the system shifted to sometime well after 2050 when comparing the rainfall series used and the scenarios developed by the KNMI. As new information becomes available, if for example studies suggest that rainfall will keep on intensifying past 2050, the drainage system may have to be adapted again.

Results indicated that in some districts, the disconnection of roads and roofs from the sewer system can be highly effective in decreasing the amount of runoff reaching the sewer system. The preliminary results suggest that the use of the overland drainage system may offer a good alternative to the disconnection strategy for some of the districts where the disconnections proved to be ineffective. However, more research is needed to conclude definitively on the effectiveness of the overland drainage system. Further research on the resilience of the overland drainage system should extend to the other urban districts of Dordrecht in order to assess and compare the effectiveness of both the incremental and transformational change strategies in increasing the resilience of the drainage systems to climate change. Additionally, a cost-benefit analysis should be performed at the district level to determine whether the incremental or the transformational change strategy is more cost-effective. With more research offering a clearer picture on the cost-effectiveness of each strategy in all districts, decision makers in Dordrecht and worldwide could incorporate the findings into future spatial planning and water management plans.

These results provide great insight into the capacity of the current drainage system to deal with the impacts of climate change. The RFA offers some degree of flexibility to change the adaptation strategy in the future since it is based on the desired level of performance, and because the tipping point analysis can be expressed in terms of when and how much rainfall the system can cope with before it exceeds a specified threshold. Moreover, the incremental changes and transformational changes can be incorporated into the system gradually as they are needed. Since the retrofit is not a fixed single-time retrofit, but rather a gradual one, the adaptation measures can be reviewed as new information comes in should the initial adaptation strategy no longer be appropriate for the climate.

The contributions of the RFA to storm water management are 1) its capacity to cope with uncertainty, 2) the flexibility of adaptation strategies to future changing climate, and 3) the use of windows of opportunity, such as urban renewal, in the development of adaptation strategies. Moreover, the RFA facilitates the development of responses and adaptation measures that are appropriate at the right time and place. The results of this study show that the RFA can contribute to the adaptation of urban drainage systems to climate change. The RFA can be considered as an alternative or complementary approach to already existing approaches in storm water management. Municipalities facing the pressures of climate change could use the RFA to assess the resilience of their drainage system and to develop flexible adaptation strategies to climate change.

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Acronyms

ATP: Adaptation Tipping Point

CC: Climate Change

CPT: Climate Proofing Toolbox

DEM: Digital Elevation Model

DTM: Digital Terrain Model

IPCC: Intergovernmental Panel on Climate Change

KNMI: Koninklijk Nederlands Meteorologisch Instituut

LAA: Learning Action Alliances

MARE: Managing Adaptive REsponses

RFA: Resilience Framework Approach

1. Introduction

1.1 Storm water management and climate change adaptation

While flooding is the most common natural hazard and third most damaging after storms and earthquakes (World Bank/United Nations, 2010), climate change is likely to exacerbate the issue. Scientific studies such as the scenarios developed by the Intergovernmental Panel on Climate Change, project intensified rainfall events worldwide (IPCC, 2007). In the Netherlands, the Royal Dutch Meteorological Institute (*Koninklijk Nederlands Meteorologisch Instituut,* KNMI) has translated the results of the IPCC into four scenarios applicable to the Dutch situation; scenarios G, G+, W, and W+. All four scenarios predict increases in average rainfall in the winter; in the summer as well, but only for scenarios G and W. Increases in rainfall intensity are thus likely to cause more frequent and severe floods, thereby putting people and assets increasingly at risk (Flood Resilience Group, n.d.). The effects of changes in hydrology are also expected to alter the magnitude and frequency of peak flows over the service life of drainage infrastructure (Arisz and Burrell 2006). The projected impacts of climate change therefore reveal the need for urban planners and water managers to plan ahead and anticipate extreme weather events.

In the Netherlands, the increasing complexity of the urban hydrology, along with uncertainties regarding future climate has forced a shift from an engineering flood defense paradigm towards an integrated approach involving an array of multi-disciplinary stakeholders such as policy makers, engineers, urban planners, hydrologists, and researchers (MARE, 2012). The MARE project (Managing Adaptive Responses to changing flood risk), initiated by the cities of Dordrecht, Bergen, Hanover, and Sheffield, seeks to develop and implement local adaptive measures to reduce and adapt to flood risk in the North Sea region. The project employs a trans-national approach to flood risk management through the setup of Learning and Action Alliances (LAA). The LAA work on developing a Climate Proofing Toolbox (CPT) that is to be tested, validated and enhanced through flood risk management projects conducted in the four cities partaking in the project (MARE, 2012). In the Netherlands, the MARE project focuses on the city-island of Dordrecht. Dordrecht is located in the deltaic region of the Netherlands and has been susceptible to flooding for centuries (MARE, 2012). The type of flooding considered in this research project is pluvial flooding that occurs when the minor drainage system (sewers and highway drains) is overwhelmed by intense rainstorms. In the Netherlands, urban water management is an important task undertaken by the Water Board and the municipality, who together ensure that appropriate water levels are maintained at all times (Dutch Ministry of Infrastructure and Environment, 2010). Since intensified rainfall events are predicted to occur more frequently and severely in the Netherlands, it is important to determine whether Dordrecht's drainage system will be able to cope with the impacts of climate change, and to research ways of improving the city's resilience to increasing storm events. For simplicity, the minor drainage system will be referred to as 'the sewers', whereas the major drainage system which typically consists of roadways and streams will be referred to as the 'overland drainage system'.

Traditionally, storm water management consisted of using historical data to determine peak flows and design underground sewer systems accordingly (Nlingenieurs Sewer Systems Workgroup, 2009). Statistical properties of historical data were used for future predictions, where it was assumed that the probability density functions of future events would be similar to those of the recent past. This stationary hydrology-based approach is becoming obsolete given the fact that external drivers (climate change and urban growth) are nowadays changing faster than the expected lifetime of the system's infrastructure (Gersonius, 2012). Today, several approaches exist in replacement of this stationary hydrology-based approach. Gersonius (2012) for example, describes four general categories of approaches currently used in storm water management. These are the top-down, bottom-up, caused-based and effect-based approaches. The top-down and bottom-up approaches relate to the spatial scale (e.g. global to local) at which the climate change impact assessment and adaptation is performed, whereas the cause and effect–based approaches relate to the temporal scale, and the direction of the cause and effect chain reasoning (Gersonius, 2012). The top-down approach, as described by Mastrandrea et al. (2010), typically consists of examining changes in climate variables such as rainfall, and their impacts on ecological, man-made and social systems. Top-down approaches begin at the global scale as they are usually based on regional climate model projections that have been scaled-down from global climate models. The shortcomings of the top-down approach are the uncertainties associated with the response of the climate system to increasing greenhouse gas emissions, and well as uncertainties associated with the techniques used to downscale global climate models into regional climate models (Mastrandrea et al., 2010). Moreover, the top-down approach lacks flexibility in that it constrains the adaptation strategy to develop only around the scenarios selected (Kwadijk, 2009). On the other hand, the bottom-up approach begins at the local scale by assessing current or emerging risks for social and environmental systems. Key thresholds are typically determined by multiple stakeholders, and the likelihood of exceeding these thresholds is assessed. Then, scenarios are developed to assess future adaptation needs. The bottom-up approach recognizes adaptation as a social process, involving multiple stakeholders (Jones and Preston, 2010). However, the bottom-up approach often requires rigorous investigations about social, economic, institutional and political processes associated with climate change risks, and can thus be labor intensive and time consuming. Moreover, the bottom-up approach is usually context or system specific and the results obtained cannot be generalized (Jones and Preston, 2010). Now in the cause-based approach, the impacts of climate change on the drainage system are first assessed, and responses are then formulated to ensure the system meets its expected level of performance. The down-side of this approach is that the strategies developed rely on estimates of climate change scenarios, which could reveal to be erroneous in the future. The cause-based approach therefore does not allow for flexibility in adapting to changing climate, especially when dealing with strategies such as fixed engineering structures that require substantial economic investments (Gersonius, 2012). Conversely, in the effect-based approach, the desired drainage system's performance is first specified, and then the likelihood of attaining this performance level with the impacts of climate change is assessed. The effect-based approach is therefore removed from climate change scenarios, and the strategy developed rather depends on input from decision makers and stakeholders to determine the desired level of system performance. Besides the four approaches described above, Gregersen and Arnbjerg-Nielsen (2011) and Crawford-Brown (2011), identify three decision support strategies to climate change adaptation and storm water management: the precautionary principle, the minimax strategy and the Bayesian decision theory. According to these authors, the precautionary principle entails that the uncertainty of the future climate and its impacts is in itself a motivation to use precautionary action. Under the precautionary principle, storm water managers must anticipate a flood event before it occurs and provide some sort of measure against it, even if the probability of occurrence cannot be fully established scientifically (Crawford-Brown, 2011). The minimax strategy on the other hand, is based on the inter-dependency of stakeholders (urban planners, water managers, sewer managers, policy makers, and the local population among others) to achieve benefits or to incur costs, and on their desire to minimize their potential loss. Lastly, the Bayesian decision theory provides a mean of updating current knowledge when new information (observations) becomes available (Gregersen and Arnbjerg-Nielsen, 2011). The approaches and decision support systems described in this paragraph provide good grounds for storm water managers to develop adaptation strategies. Nevertheless, uncertainty about the future climate remains an issue, and the lack of adaptive flexibility resulting from some of these approaches may translate into selecting adaptation strategies that will not be appropriate in the future. It is therefore necessary to research ways of dealing with the uncertainty of the future climate and to assess its impact on urban drainage systems.

In replacement of the traditional approaches described above, and within the context of the MARE project, this study tests a novel bottom-up/effect-based approach focusing on risk management, tipping points and adaptation opportunities that seeks to increase the drainage system's capacity and flexibility to cope with climate change (Gersonius, 2012 and Kwadijk, 2009). This emerging approach is referred to as the resilience framework approach (RFA) (Gersonius, 2012). The approach is an effect-based approach in that it involves determining the desired level of performance, identifying what will fail first (what will flood first), when it will fail in terms of changing rainfall patterns, and finding flexible adaptive solutions (Gersonius, 2012 and Kwadijk, 2009). The RFA is also a bottom-up approach as it assesses local flood risks, to then develop scenarios to assess the adaptation potential. Moreover, the RFA uses adaptation opportunities such as urban renewal, in order to determine mainstreaming moments, that is ideal windows of opportunity to retrofit the system with the adaptation measures identified. In addition, the RFA draws upon an array of stakeholders to define the desired system performance, and the acceptable adaptation measures, and thus builds upon the minimax strategy as explained by Gregersen and Arnbjerg-Nielsen (2011). Finally, the RFA builds on the Bayesian decision theory as the adaptation strategies selected are not fixed ones, but are rather flexible to accommodate for new information that could become available over time. In summary, the RFA is a novel approach that draws upon the already existing bottom-up and effect-based approaches, as well as on the minimax strategy and the Bayesian decision theory, in addition to using windows of opportunity. Four main steps of the RFA can be identified as follows: 1) identify when the current drainage system fails, 2) identify adaptation strategies, 3) identify windows of opportunity to introduce the adaptation strategies, and 4) identify when the modified drainage system fails. Resilience in this context is defined as "the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedbacks" (Walker et al., 2004). The RFA uses acceptable societal and economic limits as threshold values, and builds on three key processes: incremental change, adaptation and transformational change. Incremental change takes place over relatively short time periods and involves maintaining the essence and integrity of the current system (Park et al., 2012). For example, keeping the sewer infrastructure the same, but decreasing the amount of storm water runoff that reaches the system by disconnecting impervious surfaces from the system. Adaptation is a state between incremental change and transformational change; it is a process by which the system adjusts its structure and processes to cope with the impacts of climate change, and reduce its sensitivity to changes. Adaptation measures are the technical and non-technical solutions that are intended to help the system cope with the impacts of climate change; examples of adaptation measures include communication, education and awareness of local populations, larger sewer pipes, land use planning, retention ponds, and swales among others. While taking place over longer time periods, transformational change involves crossing thresholds at multiple scales to allow development into a fundamentally new system and way of thinking (Folke et al., 2010). For example, a long term transformation would be to give water more space on the surface without creating health, safety, and environmental hazards. This type of transformation would involve a shift from people's current desire to burry excess water underground to giving water more space on the surface. The fundamental difference between incremental change and transformational change is that transformational change implies a change in people's perception and attitude (Folke et al., 2010). Typical windows of opportunity to introduce incremental and transformational changes to the drainage system include urban renewal, development plans, and renewal of public infrastructure (roads, sewers, canals).

1.2 Aim of the MARE project in Dordrecht

The aim of the MARE project in Dordrecht is to develop and demonstrate an integrated approach to urban water management. The specific objectives of the MARE project are two-fold; the first objective relates to the development of the Climate Proofing Toolbox to help assess the drainage capacity and surface water management system's ability to cope with the impacts of climate change. The methodology used involves identifying tipping points at which the system's performance fails, and will be addressed in this paper. The second objective (not dealt with in this thesis project) covers urban flood risk from the sea and rivers, and uses the "MultiSafetyLevel" methodology (refer to Van Herk et al. (2011) for details (MARE, 2012)). As the municipality of Dordrecht is currently promoting sustainable development, it is seeking opportunities to integrate water safety and policy to the process of urban development (MARE, 2012). Since areas of Dordrecht may undergo (re)development in the coming years, adaptation measures should ideally include both the sewer system and the overland drainage system to convey excess runoff. The challenge here is to make allowances for hydro-climatic changes in the design and retrofit of the drainage system, and to ensure current and future public interests are met in terms of financial, social and environmental interests (Arisz and Burrell, 2006).

The LAA in Dordrecht is composed of different levels of government, knowledge institutions and private contractors (MARE, 2012). Since the management of sewer systems overlaps the field of road management, water management, and environmental management, several agencies were consulted during this project. The main knowledge resources used were the Flood Resilience Group at UNESCO-IHE, the Departments of Sustainable Development and Physical Geography at Utrecht University, Tauw (a consulting firm), and the Water Systems'

Analysis Team, which is composed of a water policy maker and a sewer manager from the municipality of Dordrecht, and a water planner from the Water Board Hollandse Delta.

1.3 Aim of research thesis

The general aim of this research was to provide insight into the applicability of the emerging RFA to urban storm water management by performing a case study on Dordrecht's drainage system. More specifically, the research aims to first determine the climate-incurred tipping points of the current sewer system and of the major overland drainage system for a desired level of performance. Further, to determine what incremental changes and long-term transformations could improve Dordrecht's drainage system's resilience to climate change, and to determine what opportunities exist to retrofit the systems. The research then seeks to determine the climate-incurred tipping points of the modified sewer system and of the modified overland drainage system, and finally, to evaluate the effectiveness of the adaptation strategy in improving Dordrecht's resilience to flooding. The results of this research then aim to provide insight into the extent of flooding the city of Dordrecht and its inhabitants are likely to face in the coming decades, with and without the adoption of adaptation measures. The findings of this research contribute to the knowledge base of storm water management and climate change adaptation, and can help inform the decision making process and design of future spatial planning and storm water management in Dordrecht.

1.4 Research questions and hypothesis

Based on the aim of the study, the main research question is put forward as follows:

How can the resilience framework approach be used to develop a climate change adaptation strategy to improve Dordrecht's drainage system and its resilience to flooding?

While the four main steps involved in the RFA are to 1) identify when the current drainage system fails, 2) identify adaptation strategies, 3) identify windows of opportunities to introduce the adaptation strategies, and 4) identify when the modified drainage system fails, the main research question can be addressed by answering the following sub-research questions:

- RQ1: *What are the climate-incurred tipping points of the current sewer system and of the current overland drainage system of Dordrecht?*
- RQ2: *What incremental changes and long-term transformations could improve Dordrecht's resilience to flooding, and what opportunities are there to implement these?*
- RQ3: *What are the climate-incurred tipping points of the proposed modified sewer and overland drainage systems?*
- RQ4: *Which adaptation strategy is effective in improving Dordrecht's resilience to flooding?*

Since the main research question cannot be directly answered, hypotheses for the sub-research questions are developed as follows:

- Sub-hypothesis 1: *previous studies performed by Gersonius (2012) and Nasruddin (2010) on sections of Dordrecht's drainage system suggest that the tipping point of Dordrecht's current drainage system should occur before the year 2050.*
- Sub-hypothesis 2*: decreasing the extent of impervious surfaces connected to the sewers should improve the resilience of Dordrecht's drainage system. Long-term transformations such as the use of the overland drainage system should also increase the resilience of Dordrecht's drainage system. Preliminary discussions with the local authorities suggest that (re)development plans should provide an opportunity to retrofit the current drainage system.*
- Sub-hypothesis 3: *the tipping point of the proposed modified sewer system and overland drainage system are expected to occur decades after the tipping point of the current systems, while continually pushed back in time with new information becoming available.*
- Sub-hypothesis 4: *the disconnection of impervious surfaces from the sewer system, as well as the use of the overland drainage system are expected to be effective strategies in improving Dordrecht's drainage system's resilience to flooding.*

2. Methodology

2.1 Overview of data processing and analysis

The objective of the research project was to apply the RFA to Dordrecht's drainage system. Two hydrodynamic-hydraulic models and a geographical information system were used to simulate the response of the drainage systems to a range of rainfall conditions. Drainage systems can be split into two categories: the major overland drainage system, which basically consists of the earth's surface, open surface waters, roads, parks and culverts, and the minor drainage system, which is artificially constructed and includes sewers and highway drains (Ashley et al., 2008). A 1D model was used for the sewer system, and a 1D2D model for the overland drainage system. Figure 1 provides an overview of the data processing and tipping point analysis performed, and shows what type of data is processed in ArcGIS, the 1D model and the 1D2D model, as well as how the system's response and adaptation strategies are evaluated.

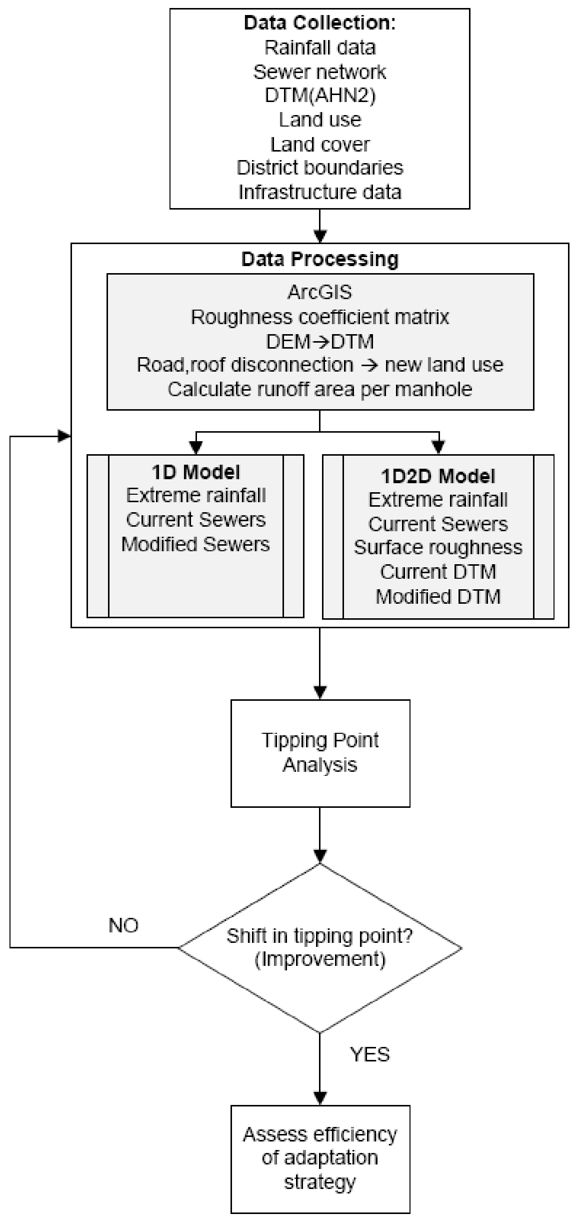

Figure 1 *Data processing and tipping point analysis flow chart*

2.2 Research process and phases

The research process was split into four distinct phases. Phase 1, the analysis of the current drainage system's response to climate change. Phase 2, the selection of adaptation measures and the identification of windows of opportunity to introduce adaptation measures. Phase 3, the analysis of the modified drainage system's response to climate change. Phase 4, the comparative tipping point analysis of the current and modified drainage systems, and the evaluation of the effectiveness of each adaptation strategy in coping with climate change. The flow chart in Figure 2 shows the four phases of the research process.

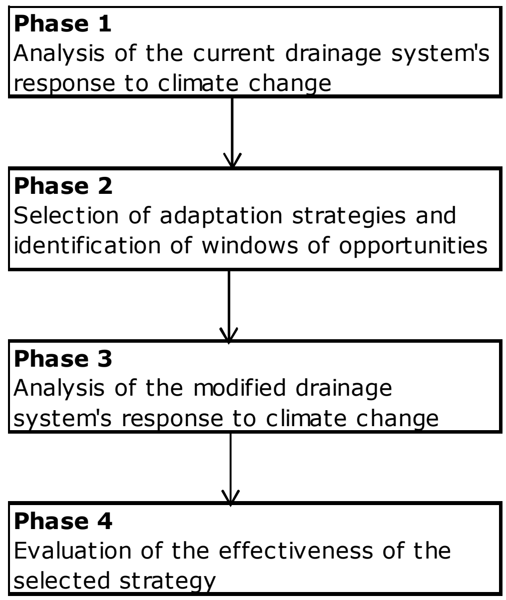

Figure 2 *Four main phases of the research process*

2.3 The models

Two hydrodynamic-hydraulic models developed with the software package SOBEK were used for this research project. The 1D model called DORD_BAS, was developed by Meijer et al. (2006) and served to analyze the sewer system. The 1D2D model called DORD_ODS, was created by Koukoui (2012) for this research, and served to simulate interactions between the minor and the major overland drainage systems. The flowchart shown in Figure 3 illustrates the input and outputs for each of the models.

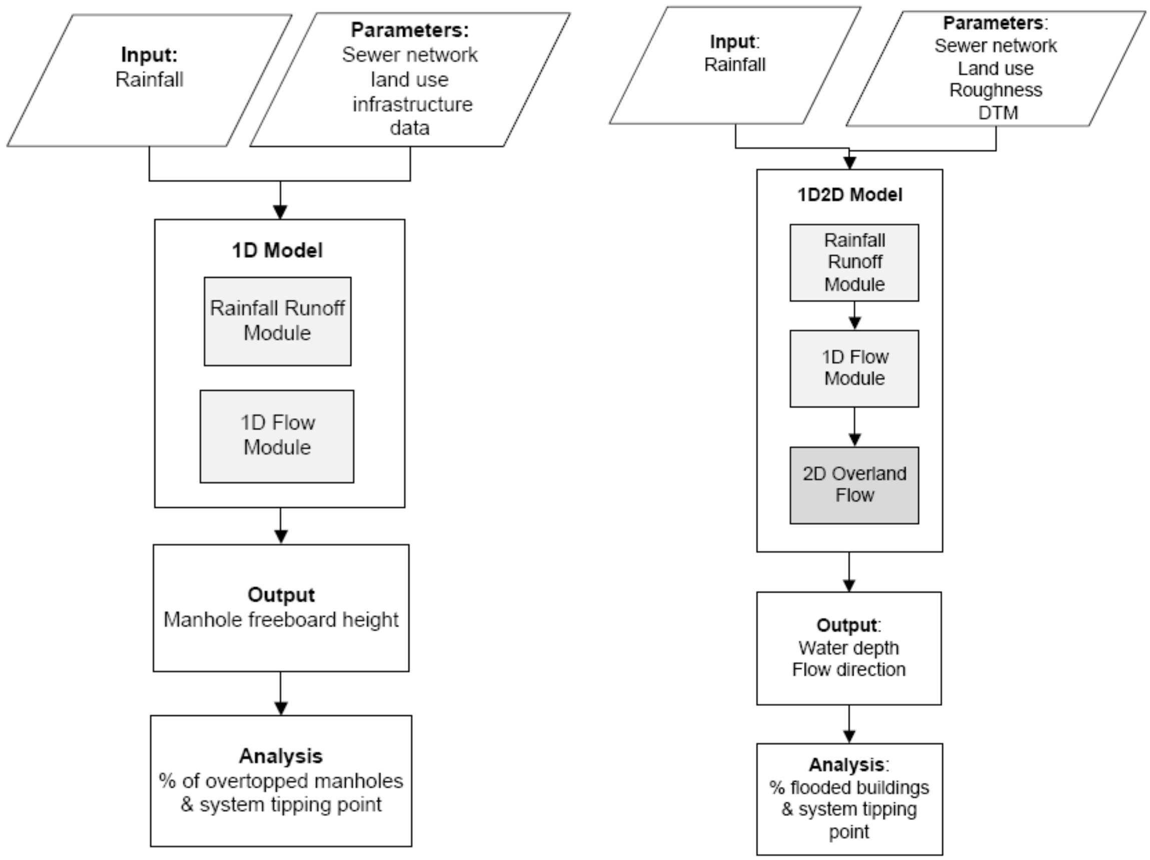

Figure 3 *Left: 1D model flow chart, Right: 1D2D model flow chart*

1D model

Two modules of the program SOBEK are used to run the 1D model: the RR (rainfall-runoff) open water and the Flow 1D pipe (Deltares, 2010). The RR hydrological module is mainly based on the rainfall patterns and the characteristics of the catchment area, such as land cover. The runoff area associated with each manhole is calculated by defining Thiessen Polygons in ArcGIS. This method, in which polygons define individual areas of influence around each sets of points, is typically used for the analysis of spatially distributed data such as rainfall, and is thus appropriate for this study (Tchoukanski, 2011). The four types of runoff surfaces used in this model are: flat roof, sloped roof, flat open paved, flat closed paved. These surface types belong to the twelve categories defined in the Dutch Guidelines for sewer systems computations (Deltares 2009 in Nasruddin 2011). The 1D pipe flow hydraulic module is based on the Saint Venant equations and simulates one-dimensional flow in the sewer piping system (Deltares, 2010). The inflow volume into the sewer network is influenced by factors such as rainfall and runoff, wastewater, groundwater seepage, land cover type, and intake capacity of the sewer system.

1D2D model

The 1D2D model simulates one-dimensional channel flow and two-dimensional overland flow. Three modules of SOBEK are used to run the 1D2D model: the RR open water, the Flow 1D pipe, and the 2D Overland Flow. The 2D overland flow module simulates water conveyance above ground. This module uses a 2 x 2 meters resolution digital terrain model imported from ArcGIS. A matrix of Manning's roughness coefficient values varying per land covers type is overlaid onto the digital terrain model. The 1D2D model accounts for interactions between the sewer system and the above ground surface, and provides an estimate of the extent of surface flooding and the water and depth.

2.3.1. Input variables

The input variables for both models are synthetic storm events based on intensity-duration-frequency (IDF) curves. IDF curves represent statistical distributions of extreme precipitation data for a given location (Arisz and Burrell, 2006). The RIONED Foundation in the Netherlands has derived 10 synthetic storm events from the standard precipitation sequence recorded by the KNMI for the period 1955-1979. These are available in the Urban Drainage Guideline module C2100 published by RIONED in 2004 (refer to www.riool.net).

<u>1D model</u>
For the 1D model, two synthetic storms events were used to simulate increasing rainfall intensity: Bui 6 and Bui 8. Bui 6 simulates a 1.5 hour distributed rainfall event of 17 mm rainfall depth that occurs once a year, while Bui 8 simulates a 1 hour distributed rainfall event of 20 mm rainfall depth that occurs once in 2 years. According to RIONED, the recommended storm event for urban sewer design is Bui 8 (RIONED, 2006). Due to the uncertainties associated with climate change, Bui 6 was also used here in order to assess the sewer system's response to storms of slightly lower intensities but with greater reoccurrence frequency. Figure 4 shows the rainfall quantity per simulation time step for Bui 6 and Bui 8. The simulation time step is plotted on the x-axis, and the rainfall quantity, expressed in mm, is plotted on the y-axis.

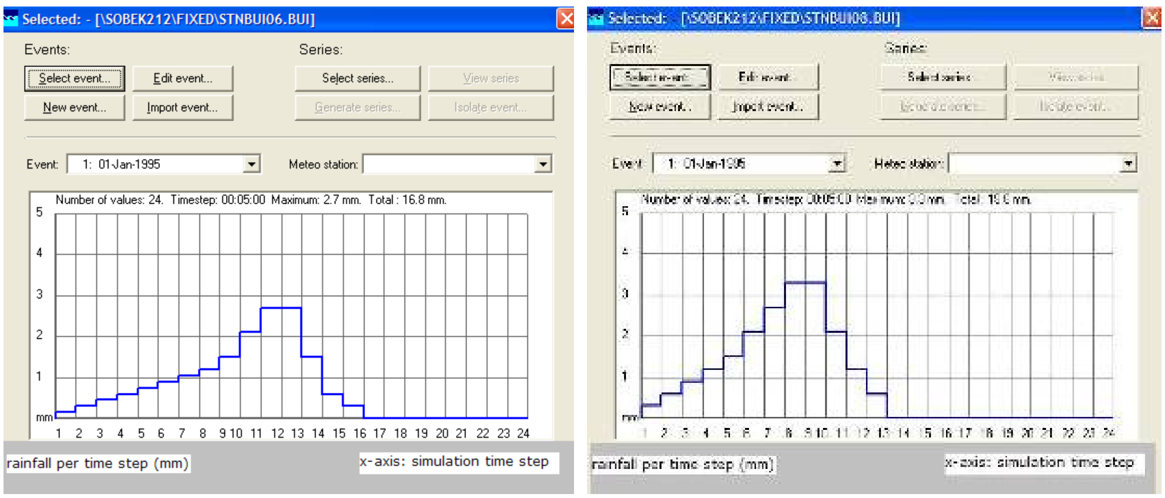

Figure 4 Left: Bui 6 rainfall event, Right: Bui 8 rainfall event (RIONED, 2004)

Climate change is simulated here by increasing the intensity of the rainfall event; this means that Bui 6 and Bui 8 are intensified by increments of 5% up to 60% from the standards shown in Figure 4.

<u>1D2D model</u>
The 1D2D model was run with 1 in 50 year synthetic event developed by Gersonius (2012) from the IDF curves of Buishand and Wijngaard (2007). The event simulates a 2 hour distributed rainfall event of 43 mm rainfall depth, and will be referred to as "Storm 50".

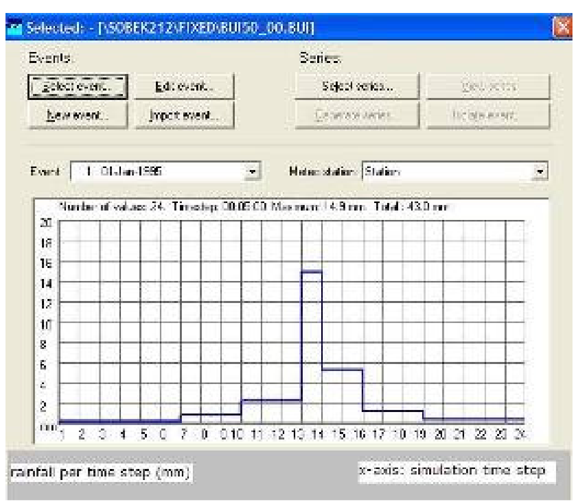

***Figure 5** Storm 50 synthetic design rainfall event (Gersonius, 2012)*

2.3.2. Parameters

The parameters required to run the 1D model are the sewer system and land use data. The parameters used to run the 1D2D model include the sewer system, the land use, the land cover and the digital terrain model derived from the AHN2.

<u>*The parameters of the sewer system*</u>

In Dordrecht, three types of sewers exist: the combined sewer type (most widely used), which contains storm water and wastewater, the separate sewer type, where storm water is transported and treated separately from wastewater, and the improved separate sewer type. Figure 6 shows the sewer network that was used for both the 1D and the 1D2D models. The sewer network used contains the principal elements of Dordrecht's sewer system: the manholes, pipes, overflows, and pumps. Integral to the system, are some 11,306 manholes and 34 combine sewer overflow outlets which discharge to the open water system.

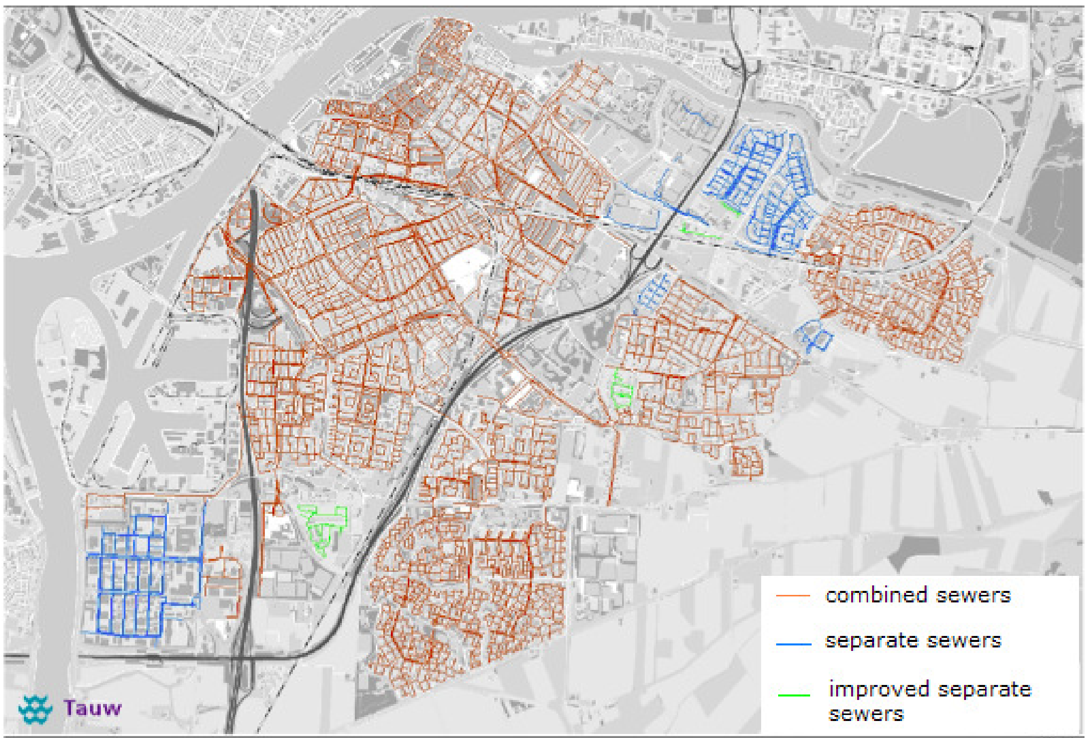

Figure 6 *Sewer system type in Dordrecht, the Netherlands (Tauw in Meijer et al., 2006)*

<u>*Land use*</u>

The land use is associated with the runoff area, which is the total of impervious surfaces in a built-up area on which rain collects and drains into the sewers. The amount of runoff and the runoff flow rate depend on evapo-transpiration, infiltration, interception and retention (NIingenieurs Sewer Systems Workgroup, 2009). These were accounted for by the model builders by using runoff, storage and infiltration coefficients for each type of runoff surface. The land use data was processed in ArcGIS and built from 3 large databases provided by the municipality and the water board. The databases contained information pertaining (among other) to the type of road (open paved or closed paved, asphalt or brick), the type of building (flat roof or sloped roof), and to the construction year of the roads and buildings. Knowing the year of construction and the average lifetime of the structures, it was possible to establish a maintenance schedule which then served to identify windows of opportunity for adaptation. The land use map is shown in Figure 7.

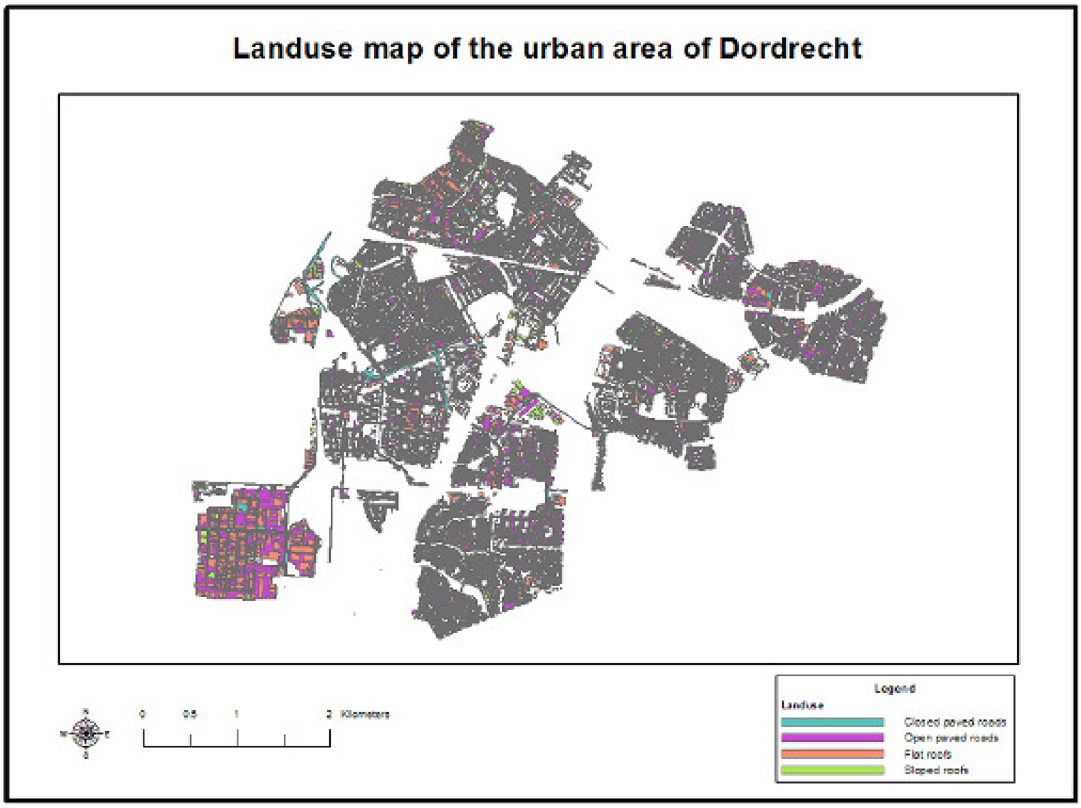

Figure 7 *Land use map of Dordrecht (Gemeente Dordrecht)*

<u>*Digital terrain model*</u>
For the 1D2D model, the digital elevation map ahn2 was obtained from the municipality. Originally, the ahn2 has a resolution of 0.5 m x 0.5 m. However, because of software limitations (Sobek), the ahn2 map was "reshuffled" in ArcGIS so as to obtain the 2m x 2m resolution map shown in Figure 8. Moreover, since the buildings and trees were removed from the original ahn2, the terrain at those locations was approximated by inverse distance weighted interpolation, using 12 neighboring cells. It is important to use the digital terrain model in which all cells have a value, instead of the digital elevation map in which buildings and trees have no assigned value, so that the water can reach those areas (buildings) during the model simulation.

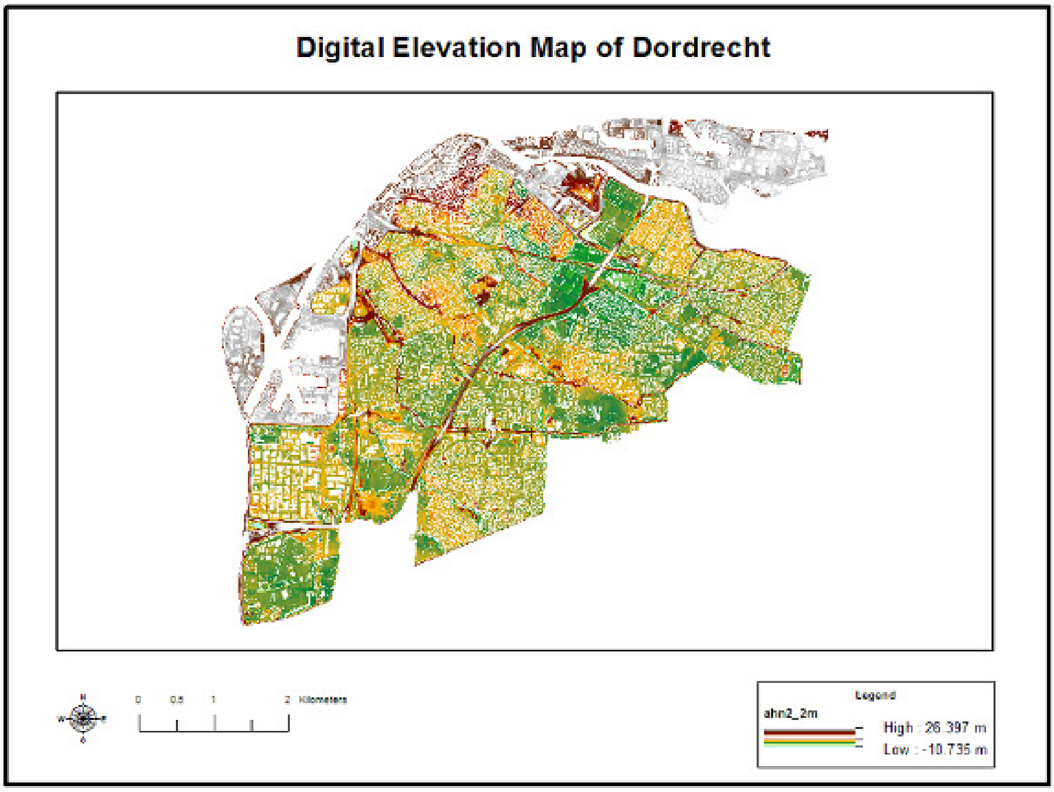

Figure 8 *AHN2, Digital Elevation Map of Dordrecht (EUROSENSE, 2011)*

<u>*Land cover*</u>
The land cover map used for the 1D2D model is shown in Figure 9.This data was used to determine the roughness coefficient of the land surface.

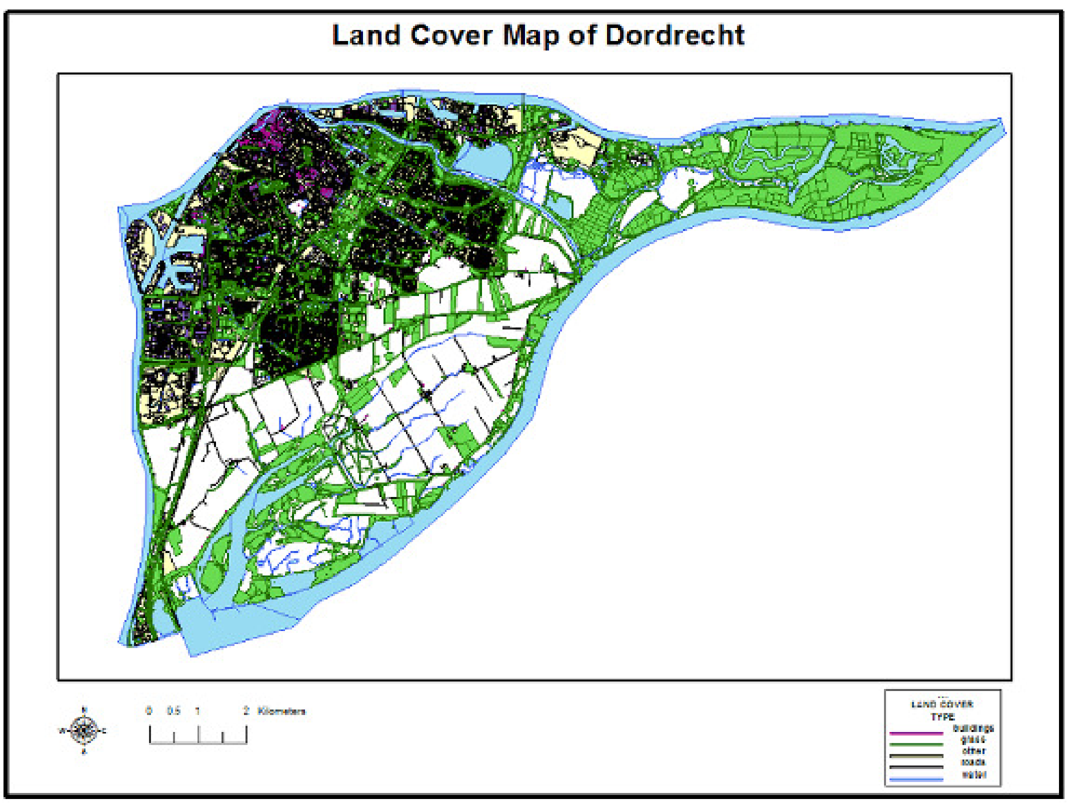

Figure 9 *Land cover map of Dordrecht (Gemeente Dordrecht)*

The land cover data was obtained from the water board and was assigned an average roughness coefficient as shown in Table 1.

Land cover type	Roughness coefficient
Buildings	0.024
Grass	0.015
Roads	0.011
Water	0.000
Other	0.013

***Table 1** Land cover roughness*

The ASCII files obtained from ArcGIS processing (DTM and surface roughness) were imported to Sobek and used to determine the runoff flow rate, direction and infiltration rate.

2.3.3. Output variables

<u>*1D model*</u>
The output variable from the 1D model is the manhole freeboard height in meters. The output is processed in Excel to determine the percentage of manholes that are overtopped under increasing rainfall quantities. The analysis is performed at the district level in order to determine which districts are most susceptible to flooding.

<u>*1D2D model*</u>
The output from the 1D2D model is the maximum water depth in cm and the water flow direction which are processed in ArcGIS. Water depths greater or equal to 5 centimeters are kept and are intersected with buildings; this reveals which buildings would flood given a Storm 50 rainfall event. The assumption here is that the doorstep height of buildings is 5 centimeters, and that buildings start flooding when the water depth exceeds the doorstep height. The water flow direction serves to determine from which direction the water comes from, and is useful in designing the adaptation strategy.

2.4 PHASE 1: Analysis of the current drainage system's response to climate change

The following section presents the methodology used to determine the current sewer system's response to climate change, and the methodology used for the major overland drainage system. Phase 1 relates to RQ1.

2.4.1. The sewer system

In order to simulate an increase in rainfall intensity, the model is run using the rainfall standards Bui 6 and Bui 8 events with 5% increments up to 60%. The output of the 1D model reveals the amount of freeboard between the water level and the street level. Figure 10 illustrates the definition of the freeboard height variable.

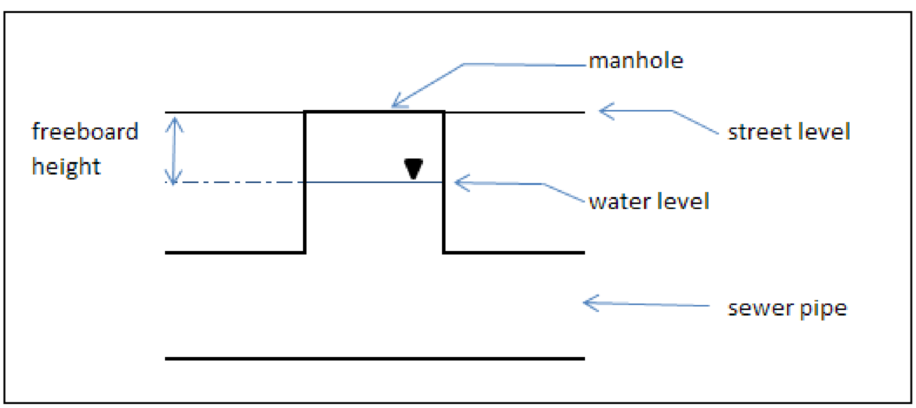

***Figure 10** Manhole freeboard height*

The output of the 1D model is analyzed in Excel to obtain the percentage of manholes that overtop. This analysis is performed for each district of Dordrecht in order to determine which districts have the greatest flood potential. In order to determine which manhole belongs to which district, the sewer system must be "intersected" with the districts in ArcGIS. Figure 11 show the sewer system overlaid on top of the urban districts of Dordrecht.

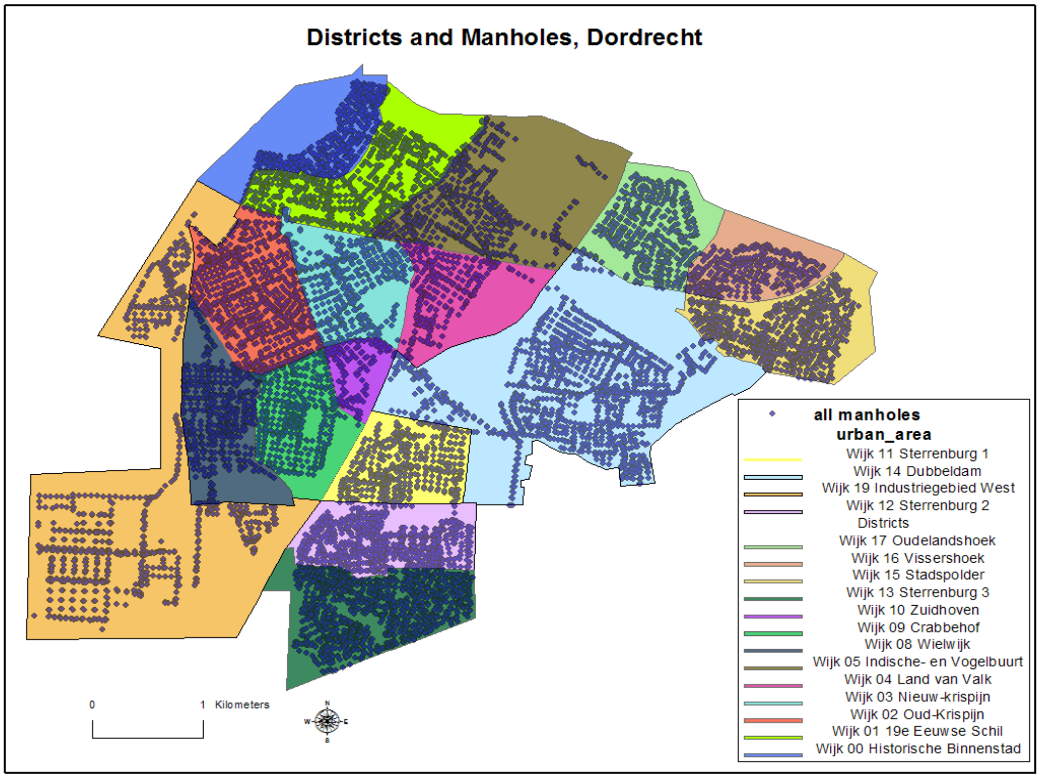

Figure 11 *Districts and location of manholes (Gemeente Dordrecht, 2012)*

The 1D model was first run for the current drainage system using the Bui 6 synthetic design event. The resilience of the drainage system was tested by increasing the intensity of the Bui 6 event. A similar analysis was performed for Bui 8.

2.4.2. The overland drainage system

The overland drainage system is not currently used in Dordrecht. Its use therefore constitutes an adaptation strategy in itself. The 1D2D model was run using the Storm 50 extreme rainfall event. Climate change was simulated by 20% increments up to 40%. The digital terrain data and the land cover data were obtained from the Water Board Hollandse Delta in raster format. However, in order to design a 2D terrain grid cell and friction grid cell in Sobek, the raster data must be converted to ASCII format in ArcGIS. Careful attention was paid here to obtain the exact same dimensions for the DTM and the roughness coefficient matrices; otherwise, the model would not run in Sobek. Due to the large amount of data to be processed, the 1D2D model was run over several weeks on a super computer for Sterrenburg1 only. The municipality had indicated that they were interested in testing the overland system in this particular district because of redevelopment plans occurring in a near future. The model output is the maximum water depth and the water flow direction. The output is exported to ArcGIS for further processing so as to intersect the areas where the water reaches a depth of 5 cm or more, with the buildings. This process allows identifying exactly which buildings would flood given the occurrence of a Storm 50 event.

2.4.3. The systems' tipping points

A tipping point is reached when the system fails to meet its intended performance. For the sewer system, the tipping point is reached when the sewers have exceeded their maximum operating capacity; at which point manholes overtop, and streets start filling with rainfall runoff or sewer overflow. For the major overland drainage system, the tipping point is expressed here in terms of number of flooded buildings. The major overland drainage system, or the land surface, should be regarded as a means of temporarily accommodating for water on the streets, in parks and parking lots, with little inconvenience and no hazard for the public. However, when buildings flood, permanent damage to people's assets typically occurs, and this should be avoided as much as possible.

The "tipping points", or thresholds, occur at a given rainfall intensity. The tipping points can be expressed here in terms of climate change factor (cc factor). This method is described by Larsen et al. (2009) in Gersonius (2012) as the ratio between future and present rainfall intensity. The public, together with local authorities and experts should decide on what is acceptable to people; are 10 overtopped manholes acceptable or too much? Are 5 flooded buildings acceptable or intolerable? A cut-off value must be chosen in order to determine if the tipping point has been reached. This study, uses three threshold values to reflect varying levels of social acceptance towards flooding, and changing attitudes. The three performance criteria are: overtopping of 0% of the manholes, 1% and 5%. The results for the 1% criteria are presented in section "3. Results", as this threshold value is likely to be most socially and economically acceptable in comparison to 0% and 5%. The results for the 0% and 5% criteria are included in Annex 1. In order to illustrate the principle of the threshold criteria, say the threshold is set to 1%, and the model is run using Bui 6 at an intensity increase of 20%, then if less than 1% of the manholes overflow the threshold has not been exceeded. However if at 25% intensity increase more than 1% of the manholes overflow the threshold has been exceeded and the tipping point of the system lies somewhere between 20% and 25% increase in rainfall intensity. To remain conservative with the tipping point definition previously stated, the tipping point is then said to occur at cc factor = 1.20, or at 20% rainfall intensity increase.

The G and W scenarios developed by the KNMI in 2006 were used in order to determine at which moment in time those tipping points would occur. For short duration rainfall, the KNMI only provides the G and W scenarios. Those scenarios are based on the IPCC's global climate change models for Western Europe. The scenario G reflects an increase in temperature of 1 °C by 2050 without circulation change, whereas the W scenario reflects an increase in temperature of 2 °C by 2050 without circulation change (Hurk van den 2007). These scenarios give information on rainfall intensities for different durations and frequencies. As such, the values shown in Table 2 were interpolated to obtain changes in rainfall intensity for the synthetic events used in this research project.

Projected changes in rainfall intensity in % from 1990 till 2050						
Frequency	Events					
	1 hour event		10 hour event		10 day event	
	G	W	G	W	G	W
1	7	21	9	18	6	11
10	11	22	11	22	7	14
100	12	23	11	24	8	15

Table 2 *KNMI 2006 scenarios (Hurk van den 2007)*

It was found that the G scenario would occur at about 7.11% increase in Bui 6, 7.44% for Bui 8 and 11.44% for Storm 50, whereas the W scenario would occur at about 20.83% for Bui 6, 21.11% for Bui 8, and 22.40% for Storm 50.

2.5 PHASE 2: Selection of adaptation strategies and windows of opportunity

With respect to the RFA, phase 2 relates to the identification of adaptation strategies, as well as the identification of opportunities for adaptation. Phase 2 helps answer RQ2.

Adaptation strategy

The general objective of the adaptation strategy was to reduce the extent and occurrence of localized flooding. Standard ways of reducing the volume of runoff entering a sewer system are to capture rainfall at the source and return it to the natural hydrological cycle through infiltration and evaporation, or to retain rainfall locally and to discharge of it at a later time, instead of conveying it immediately into the sewer system. Increasing local rainfall infiltration into the soil by reducing the amount of impervious surfaces can also reduce the amount of runoff generated from these surfaces. In terms of sewer system response to climate change, this would mean that the number of overtopped manholes should decrease in comparison to the current sewer system. One requirement expressed by the municipality and the water board, was to steer away from traditional permanent engineering structures such as larger sewer pipes, and towards a more sustainable, closer to nature, and "no regret" measures. "No-regret" measures are described by Laaser et al. (2009) as "*measures that contribute to more sustainable water management (…), to solving existing water management problems, and enhance adaptive capacity in the future.*" The WWF-Madagascar describes no-regret measures as "activities that will increase people's capacity to deal with a range of likely climate change scenarios, and whose benefits exceed their costs." In 2007, the Dutch Ministries for Spatial Planning and the Environment Public, and Transport, Public Works and Water Management put together a "Routeplanner for a climate-proof Netherlands". In this document 12 options were proposed for water related issues, and 8 for dealing with housing and infrastructure. The options were evaluated against five criteria: no-regret, importance, urgency, side effects, and mitigation effects. In addition to no-regret measures, new developments were expected to include the modification of the traditional sewer system, as well as the use of the overland drainage system to convey the excess runoff when the capacity of the sewer system is exceeded.

Finally, the three strategies selected for testing are as follows: 1) roof disconnection from the sewer system for public buildings and social housing units, 2) road disconnection from the sewer system, and 3) the use of the major overland drainage system.

The adaptation strategies modeled in this study can be divided into two categories: incremental changes brought to the sewer system, and a transformational change using the overland drainage system. Changes involving the sewer system are referred to as incremental changes, whereas the use of the major overland drainage system is considered here as a transformational change. Transformational changes take place over longer periods of time in comparison to the incremental changes, as they involve changing social concepts, tolerance levels, and bringing about education and awareness.

The selection of the incremental change strategy was performed by the municipality of Dordrecht as well as the water board. This strategy was presented in Meijer et al.'s report (2006) and involves disconnecting roof and roads from the sewer system. The transformational change involving the use of the overland drainage system was previously recommended by RIONED and constitutes an international best practice to enhanced urban drainage. The transformational change strategy was presented by a researcher from the Flood Resilience Group of Unesco-IHE to three members of the Water System Analysis Team, including a policy maker and a sewer manager from the municipality, and a water planner from the Water board.

<u>Incremental changes to the sewer system</u>

Roof disconnection of public buildings from the sewer system means that rainwater collected on the roof surface is either retained locally or directed away from the sewer system. Green infrastructure is a way of achieving this. Components of green infrastructure suitable for roof disconnection include green roofs, gutters directed towards a garden or grass area, and rainwater harvesting systems. Figure 12 and Figure 13 show examples of green infrastructure used to disconnect the roof of buildings from the sewer system.

Figure 12 *Philadelphia with green roofs and trees; left: current; right: future (Ashley et al., 2011)*

Figure 13 *Transfer of roof drainage to impervious area (Ashley et al., 2011)*

Road disconnection from the sewer system means that rainwater collecting on pavement is directed away from the sewer system. There exist several ways of achieving this, such as introducing filter drains, swales, wetlands, soak ways and geocellular systems on the side of the roads, or permeable pavement to allow the water to infiltrate into the soil. Figure 14 shows examples of green infrastructure used to disconnect roads from the sewer system.

Figure 14 *Left: grass growing through a lattice permeable pavement; Right: swale (Ashley et al., 2011)*

In order to disconnect the roads and roofs from the sewer system, these were removed from the area contributing to runoff generation in ArcGIS. Thiessen polygons formed around each manhole determine the runoff area contributing to each manhole. These polygons are intersected with the type of surface to determine what surface area and area type contributes to the runoff entering each manhole. The final product is a database containing each manhole, and for each manhole the associated surface area that contributes to runoff. This file, referred to here as the pluvius file, is input into the 1D model and represents the road and roof disconnections from the sewer system, or the change is surface area that contributes to runoff.

Transformational change: use of the overland drainage system
The use of the overland drainage system is and adaptation measure in itself. The idea is to create a safe flow path for excess runoff. First, the buildings that would be inundated under Storm 50 in the current system must be identified. Next, the runoff flow path and direction must be determined. The plan is to use the street profile as temporary storage for excess runoff and/or to direct the flow path of storm water runoff using roads, channels and swales as conveyance ways to lower lying retention areas, such as parks. The conveyance paths and retention areas should be chosen so as to avoid inundating private property and critical public infrastructure (Harisz and Burrell, 2006). As such, excess storm runoff should follow the path of least nuisance to the inhabitants. Embankments, speed bumps of 8 to 12cm as per Dutch road standards (CROW, 2002) and trench troughs could be used to direct runoff to surface water, parks and parking lots with grounds lower than the surrounding area. The curb height of street section could also be increased. These terrain elevation changes were made in ArcGIS, where the DTM was modified at strategic locations. **Table 3** presents an overview of the selected adaptation strategies, the tipping point thresholds and their corresponding modeling parameters.

Strategy	Type	Acceptance criteria (or tipping point threshold)	Model	Input variables	Parameters
Disconnection of impervious surfaces from the sewer system	Incremental change	1% of manholes flooded	1D	Bui 6 rainfall series	Current drainage system
					40% disconnection of roads and roofs
				Bui 8 rainfall series	Current drainage system
					40% disconnection of roads and roofs
Use of land surface to direct runoff towards safe storage areas	Transformational change	1% of buildings flooded	1D2D	Storm 50 rainfall series	current land surface cover
					Modified land surface cover

Table 3 *Summary of selected adaptation strategies*

Windows of opportunity for system adaptation
In the RFA, the timing of the drainage system's tipping point in response to climate change determines when an adaptive measure will be required. Climate change therefore acts as a driver for adaptation. Urban renewal however also provides an opportunity to reconsider the existing drainage system. Timing the drainage system's adaptation with the scheduled urban infrastructure maintenance could allow municipalities to save on costs. Urban renewal can thus be seen as a driver for adaptation as well. (Van de Ven et al., 2011 in Gersonius, 2012) Urban renewal was thus considered as an opportunity to retrofit Dordrecht's current drainage system. Databases containing information on road and building types, as well as their construction years were obtained from the municipality. Average lifetime for the roads and buildings were obtained from the municipality as well, and a maintenance schedule was established.

For the roads, one of the databases obtained contained the type of runoff surface: open paved roads and closed paved roads, while the other database contained the materials used to build the roads and their year of construction. This information allowed classifying the roads according to two general categories of material: asphalt and brick. It was assumed that open paved roads were made from bricks whereas closed paved roads were made from asphalt (Gersonius, 2012). For water quality purposes, the roads considered in this research exclude highways and boulevards because these are usually highly polluted impervious surfaces, and water that accumulates on these surfaces should be treated before being conveyed to nearby surface waters. Knowing that brick roads have a 30 year average lifetime, 100% of the brick roads or open paved roads would theoretically undergo maintenance by 2045 (Municipality of Dordrecht, 2012). Realistically however, only about 40% of the roads in Dordrecht would undergo renovations by 2045. It was therefore assumed that 40% of open paved roads would undergo maintenance by 2045.

For roof disconnections, privately owned buildings were excluded from this study, since no maintenance schedule could be established. Furthermore, it was assumed that the municipality and social housing companies would be more likely to retrofit their buildings in order to disconnect them from the sewer system than individuals would. Two databases pertaining to buildings were provided by the municipality. The first database contained information on the type of building and the scheduled year of maintenance. About 80% of the buildings with flat roofs had a scheduled maintenance prior to 2045. Again, it was assumed that only about 40% of the buildings with flat roofs would actually undergo maintenance by 2045. The second database contained information on the type of roof (flat and sloped). It is important to note here that because no information was available as to which buildings are publicly owned in Dordrecht, it was assumed that buildings with a flat roof (as opposed to sloped roofs) were publicly owned, or belonged to social housing companies. The two databases were overlaid in ArcGIS, and the information was classified per roof type and per year of maintenance so as to determine the new areas contributing to runoff.

Figure 15 shows the surface area of flat roofs and open paved roads scheduled for maintenance in the urban area of Dordrecht. It appears that most flat roofs and open paved roads will need maintenance during the period 2015 to 2024, which creates an opportunity to retrofit the land use to allow for better drainage. Other opportunities to adapt will occur after 2025, but the majority of the maintenance should be performed between 2015 and 2024.

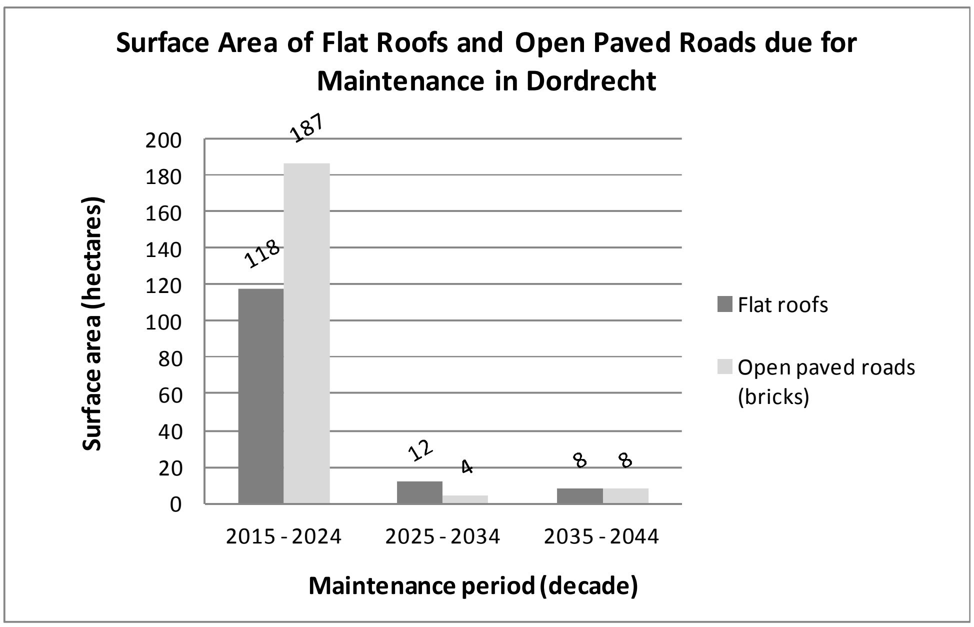

Figure 15 *Adaptation opportunity based on roof and road maintenance schedule*

It is important to note that the database provided for the roads was rather incomplete in comparison to that of the buildings. Table 4 shows the proportion of flat roofs and brick roads for which sufficient data existed. The second and third columns contain the proportion of flat roofs and brick roads respectively, having sufficient data to determine the projected year of maintenance. The low percentages in column three reveal the lack of data for the roads. This lack of data was another reason to assume that 40% of the open paved roads would undergo maintenance by 2045.

Proportion of data containing sufficient information to perform disconnection		
	% flat roofs with sufficient data for disconnection opportunity	% brick roads with sufficient data for disconnection opportunity
Wijk 00 Historische Binnenstad	95.36%	16.14%
Wijk 01 19e Eeuwse Schil	95.93%	15.94%
Wijk 02 Oud-Krispijn	96.80%	23.88%
Wijk 03 Nieuw-krispijn	95.80%	8.78%
Wijk 04 Land van Valk	98.02%	25.75%
Wijk 05 Indische- en Vogelbuurt	96.00%	17.35%
Wijk 06 Staart-West	95.08%	15.19%
Wijk 07 Staart-Oost	97.30%	49.56%
Wijk 08 Wielwijk	96.46%	28.74%
Wijk 09 Crabbehof	97.64%	13.68%
Wijk 10 Zuidhoven	96.00%	6.68%
Wijk 11 Sterrenburg 1	98.90%	35.88%
Wijk 12 Sterrenburg 2	95.45%	53.05%
Wijk 13 Sterrenburg 3	96.12%	41.00%
Wijk 14 Dubbeldam	97.57%	10.12%
Wijk 15 Stadspolder	96.46%	15.31%
Wijk 16 Vissershoek	92.21%	18.21%
Wijk 17 Oudelandshoek	98.72%	8.83%
Wijk 18 Industriegebied Staart	90.48%	3.16%
Wijk 19 Industriegebied West	98.35%	9.85%

Table 4 *Percentage of brick roads and flat roofs with sufficient data for disconnection*

<u>Major overland drainage system</u>
The overland drainage system was analyzed for Sterrenburg1 only because of redevelopment plans in Sterrenburg1 in the near future, and also because of time restrictions. Generally speaking, it is wise to allocate space for the overland drainage system during planning and layout of new development, because it is more difficult and costly to retrofit existing development (Arisz and Burrell, 2006).

2.6 PHASE 3: Analysis of the modified drainage system's response to climate change

The methodology used to determine the modified sewer system's response to climate change is the same as that used to determine the current drainage system's response to climate change. The models and their input variables are kept the same as for the current systems; only two parameters are changed, the land use and the digital terrain. The same tipping point analysis is performed again here to determine the modified system's response to climate change. Phase 3 relates to RQ3.

2.7 PHASE 4: Evaluation of the effectiveness of the selected adaptation strategies

With respect to the RFA, phase 4 relates to the quantification of the increase in system's resilience to flooding with the introduction of adaptation measures. Part C will help answer RQ4.

Phase 4 consists of 1) comparing the resilience of the current to the modified systems, and 2) of determining which adaptation strategy is more effective in coping with climate change. The strategy is deemed successful if the number of overtopped manholes and the number of flooded buildings decrease in the modified drainage system. Most importantly, there should be a shift in tipping point when introducing adaptation measures; that is, the system should fail under higher rainfall conditions. Additionally, the adaptation strategies (incremental change and transformational change) are compared in order to determine which is most effective for each district. This component of phase 4 is limited to Sterrenburg1, Sterrenburg2, and Sterrenburg3, since the transformational change was only tested for these districts.

3. Results

The following sections will first present the response of the current drainage system to climate change, followed by the chosen adaptation strategy and windows of opportunities. Finally, the response of the modified drainage system to climate change will be presented.

3.1 PHASE 1: Analysis of the current drainage system's response to climate change

The sewer system was first tested for Bui 6, then Bui 8. The major overland drainage system was tested for Storm 50. The analysis of the sewer system consisted of determining at which point streets start to flood as a result of exceeded sewer capacity.

3.1.1. Current Sewer System

The 1D model was run to simulate the Bui 6 and Bui 8 synthetic design storm event over the urban area of Dordrecht. Twenty six runs were performed to simulate climate change in terms of intensified rainfall (13 runs for Bui 6 with intensity increments from 0 to 60% and 13 runs for Bui 8 with the same intensity increments). The output of each run revealed the freeboard height of the 11,306 manholes. The results expressed in percent overtopped manholes (zero freeboard height) were divided so as to represent each district individually, in order to determine which neighborhoods were most susceptible to flooding.

For Bui 6, the districts of Sterrenburg1, Sterrenburg2, and Dubbeldam were found to be the areas with the highest percentage of overtopped manholes. Whereas for Bui 8, four districts were found to have a high percentage of overtopped manholes: Sterrenburg1, Sterrenburg2, Dubbeldam, and Industriegebied West. The four districts are identified in hatched patterns in Figure 16.

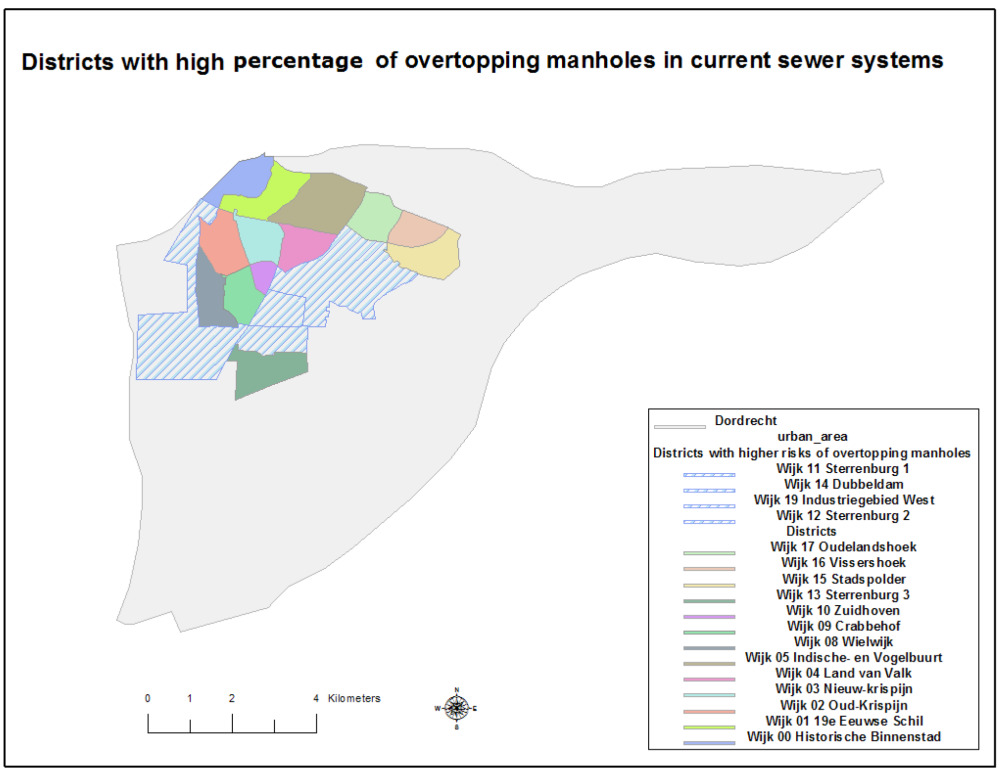

Figure 16 *Location of districts having a highest percentage of overtopping manholes*

The histograms shown in Figure 17, Figure 18, Figure 19, and Figure 20 represent the percentage of overtopped manholes under Bui 6 and Bui 8 rainfall conditions for Sterrenburg1, Sterrenburg2, Dubbeldam, and Industriegebied West, respectively. The percentage of overtopped manhole is plotted against each rainfall intensity. The vertical axis represents the percentage of overtopped manholes, while the horizontal axis shows the rainfall intensity increase per 5% increments, along with the corresponding rainfall quantities shown below the increments. The increase in rainfall intensity shown on the horizontal axis represents climate change. The freeboard heights of the manholes decrease with increasing rainfall intensity, and as such, the number of overtopping manholes increases.

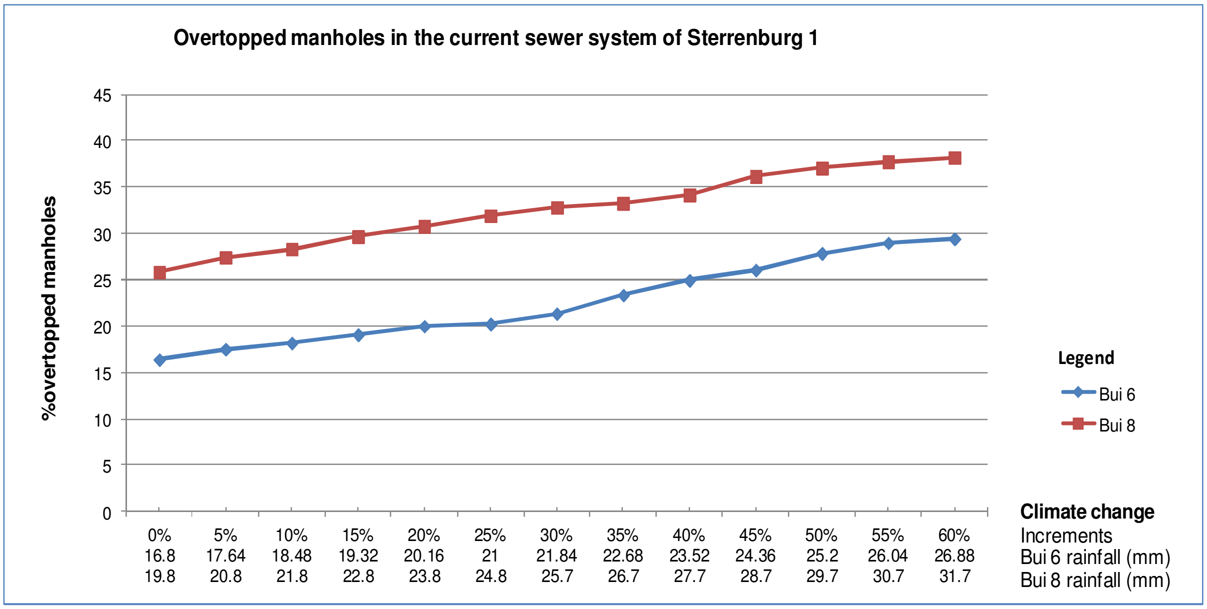

Figure 17 *Response of Sterrenburg1's current sewer system to climate change*

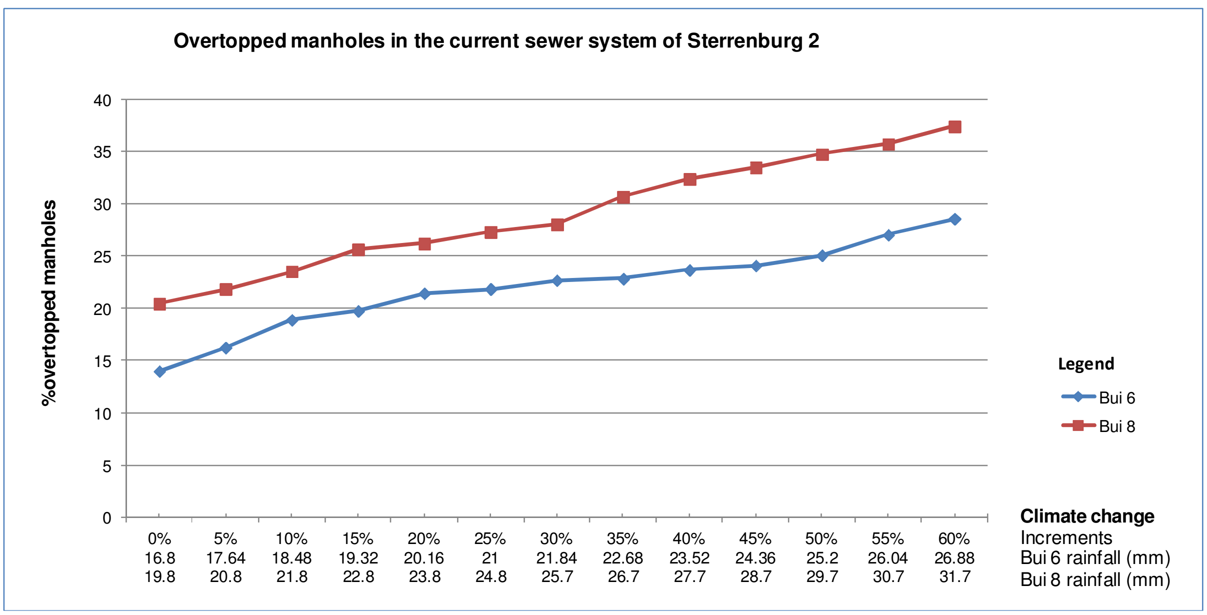

Figure 18 *Response of Sterrenburg2's current sewer system to climate change*

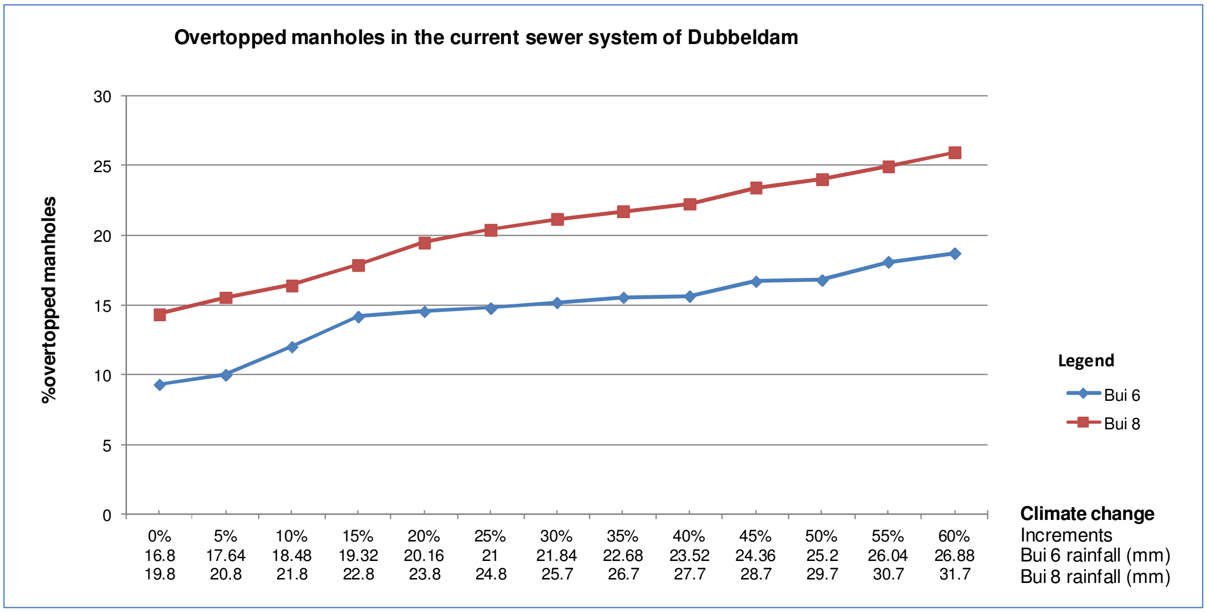

Figure 19 *Response of Dubbeldam's current sewer system to climate change*

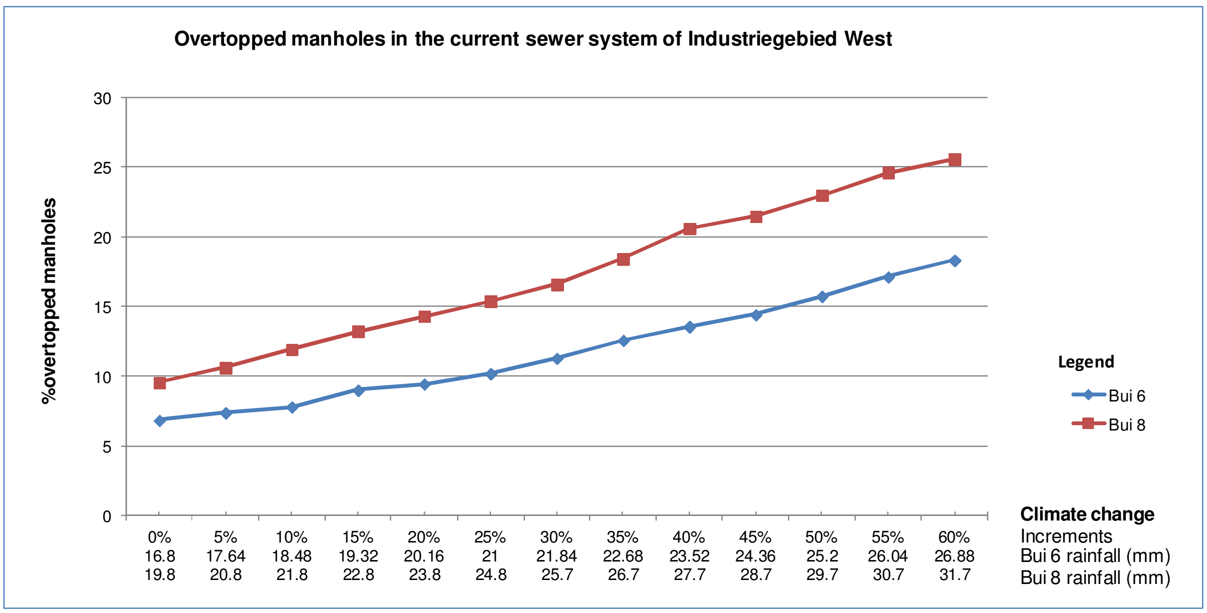

Figure 20 *Response of Industriegebied West's current sewer system to climate change*

The four graphs above reveal that the percentage of overtopped manholes (0% increment; that is no effects of climate change) is already quite high (9% to 16% for Bui 6 and 9.5% to 26% for Bui 8) for Sterrenburg1, Sterrenburg2, Dubbeldam, and Industriegebied West.

As expected, the flood extent is greater under the Bui 8 storm event than the Bui 6 storm event. This can be seen by the greater percentage of overtopped manholes under Bui 8 conditions, and can be explained by the greater total rainfall quantity under Bui 8.

3.1.2. The current sewer systems' tipping points

The final output of phase1 is the computation of the system's tipping point with respect to climate change. The threshold was set to an acceptable limit of 1% of total manholes "allowed" to overtop. This threshold was selected based on engineering judgment (Koukoui & Gersonius). Figure 21 and Figure 22 show the tipping point chart for Bui 6 and Bui 8 rainfall events respectively. The vertical axes represent the districts of the urban area, while the horizontal axes represents climate change as a function of the rainfall events Bui 6 and Bui 8.

While Sterrenburg1, Sterrenburg2, and Dubbeldam were found to be the districts with highest percentage of overtopped manholes, Figure 21 shows that the historic district, 19e Eeuwse Schil, Indische en Volgebuurt, Crabbehof, Sterrenburg1, Sterrenburg2, Sterrenburg3, Dubbeldam, Oudelandshoek, and Industriegebied West all reach the tipping point at 0% climate change for Bui 6. Meanwhile, the districts of Vissershoek and Land van Valk reach a tipping point at 10% rainfall intensity increase, which would occur well after the occurrence of the G scenario developed by the IPCC, which is forecasted to occur in 2050. The districts of Oud-Krispijn and Nieuw-Krispijn reach a tipping point at 20% increase in rainfall intensity, which would occur just before the W 2050 scenario. Moreover, the districts of Stadspolder, Zuidhoven and Wielwijk would reach the tipping point well after the occurrence of the W scenario developed by the IPCC. This result shows that the current sewer system fails to meet its intended function in several areas of Dordrecht, in the occurrence of a Bui 6 rainfall event. It is therefore important to identify adaptation measures that will improve the sewer system's resilience to climate change.

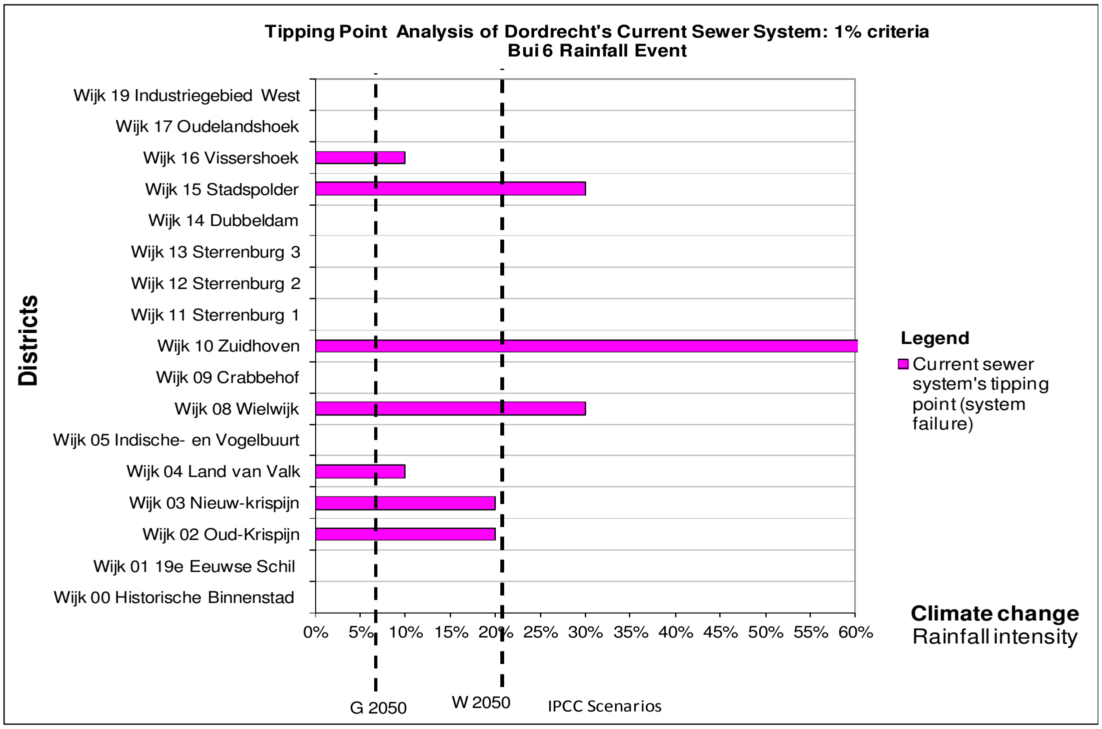

Figure 21 *Tipping point of the current sewer system under Bui 6*

Figure 22 shows the tipping point chart for the current sewer system under Bui 8 rainfall conditions. Most of the districts reach a tipping point at 0% climate change. Four districts reach the tipping point at 5% rainfall intensity increase, and only one district reaches the tipping point at 35% rainfall intensity increase. This result suggests that the current system has already reached a tipping point in most areas of Dordrecht under Bui 8 rainfall conditions. The tipping point is reached earlier under Bui 8 rainfall conditions than Bui 6.

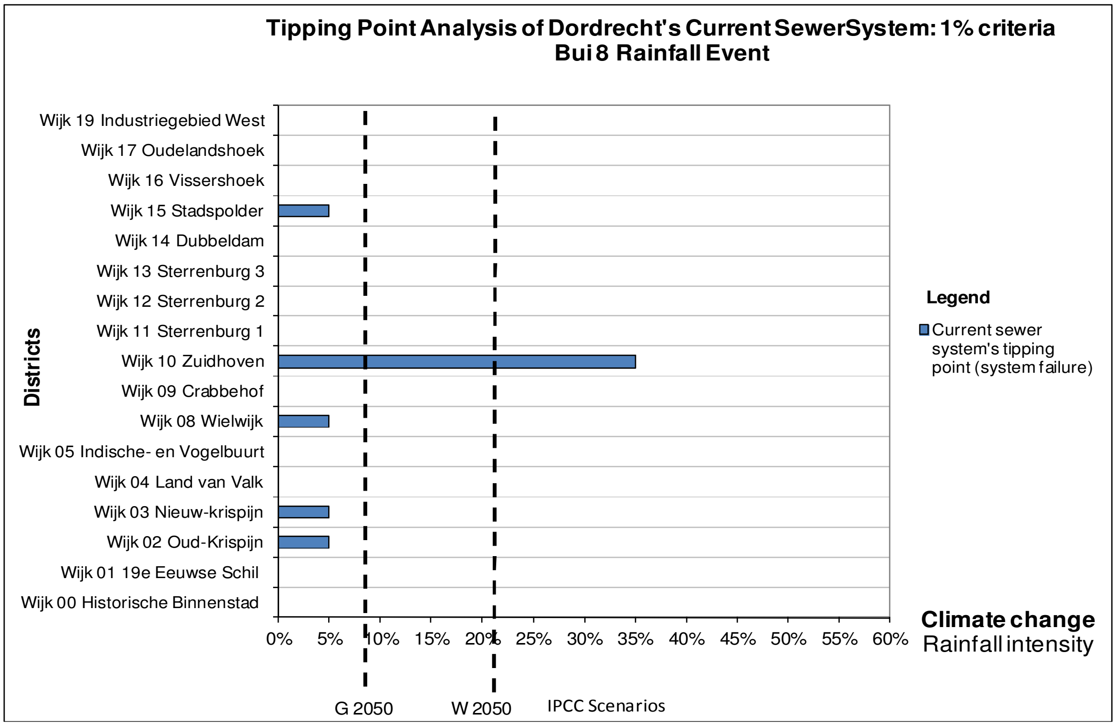

Figure 22 *Tipping point of the current sewer system under Bui 8*

3.1.3. Analysis of the current overland drainage system

The current overland major drainage system is currently not intended for use in Dordrecht, hence its use can be considered an adaptation measure in itself for runoff storage and conveyance. The response of the overland major drainage system was simulated using the rainfall event Storm 50 for Sterrenburg1, Sterrenburg2, and Sterrenburg3 only. The municipality of Dordrecht expressed a desire to test the overland drainage system in these particular districts due to upcoming public infrastructure renewal. The output of the 1D2D model was the accumulated water depth on the land surface. The water depth was exported to ArcGIS as an ASCII file and converted to a polygon shape file which was then intersected with a shape file containing the location of buildings. It was assumed, based on engineering judgment (Koukoui and Gersonius), that an accumulated water depth of 5 cm or more would result in a building being flooded. It was possible to see which buildings would be flooded under Storm 50 rainfall conditions. The map shown in Figure 23 illustrates the flood extent (in blue) for Sterrenburg1 under Storm 50 with a 20% increase in rainfall intensity.

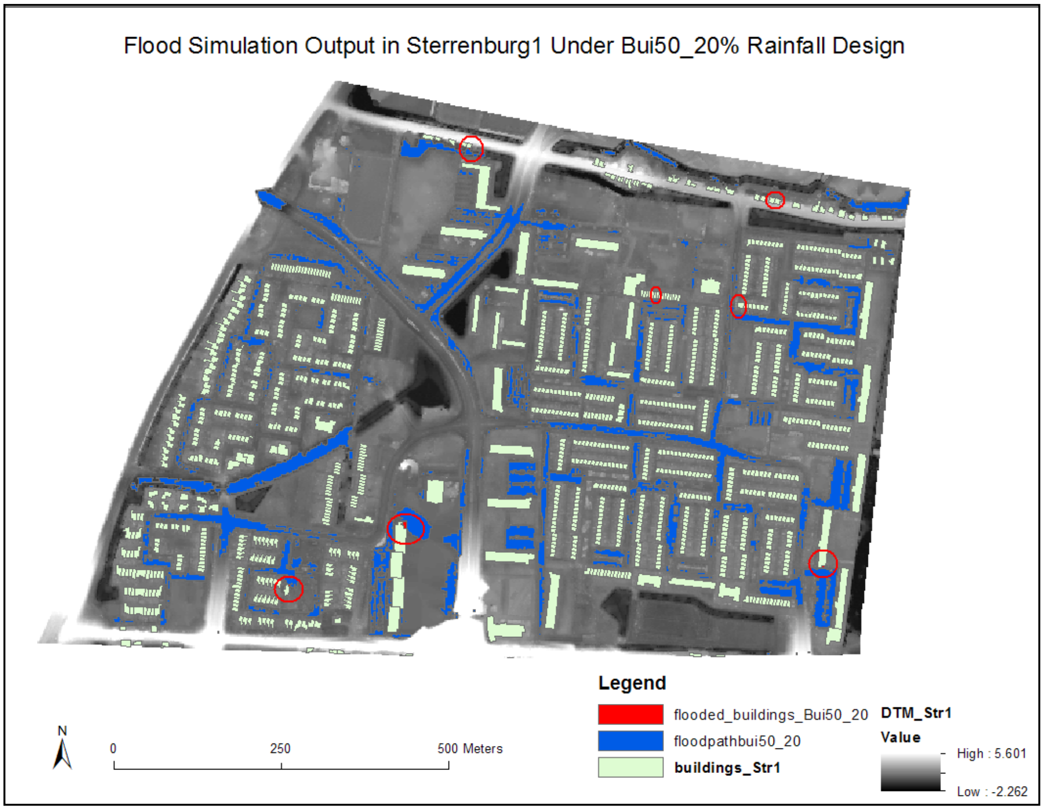

Figure 23 *Flood extent in Sterrenburg1 for 20% increase in Storm50 rainfall design*

Figure 24 shows the flood extent for Sterrenburg2 under Storm50 rainfall condition with a 20% increase in rainfall intensity.

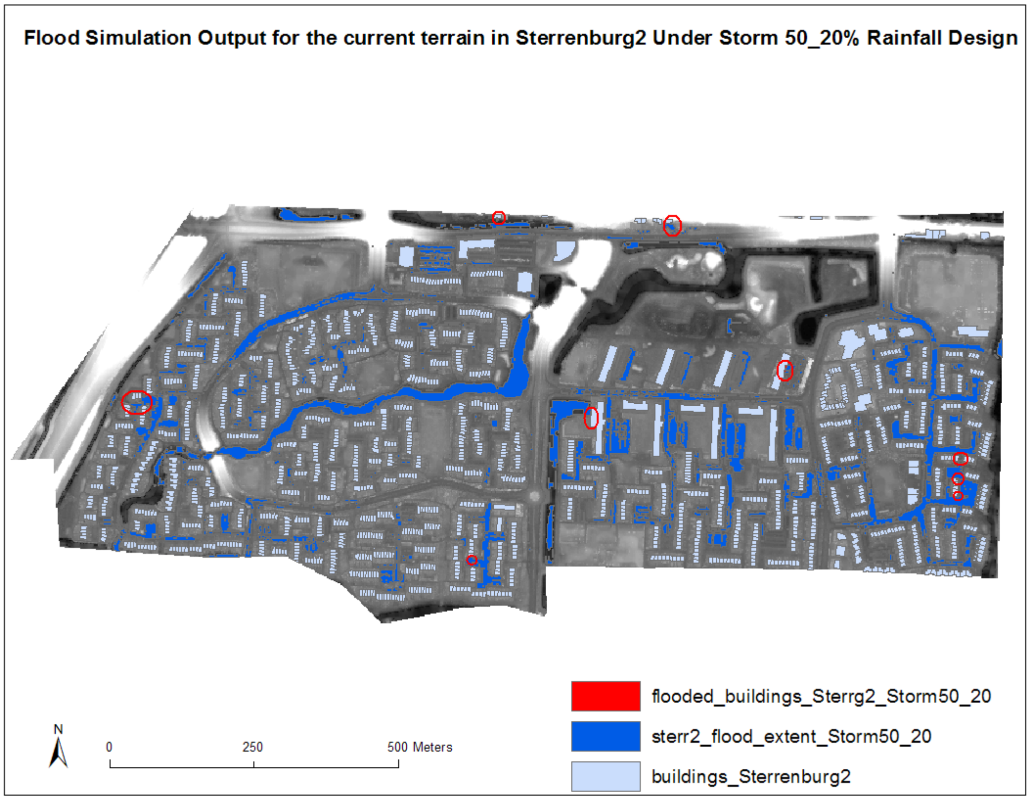

Figure 24 *Flood extent in Sterrenburg2 for 20% increase in Storm50 rainfall design*

Figure 25 shows the flood extent for Sterrenburg3 under Storm 50 with a no increase in rainfall intensity.

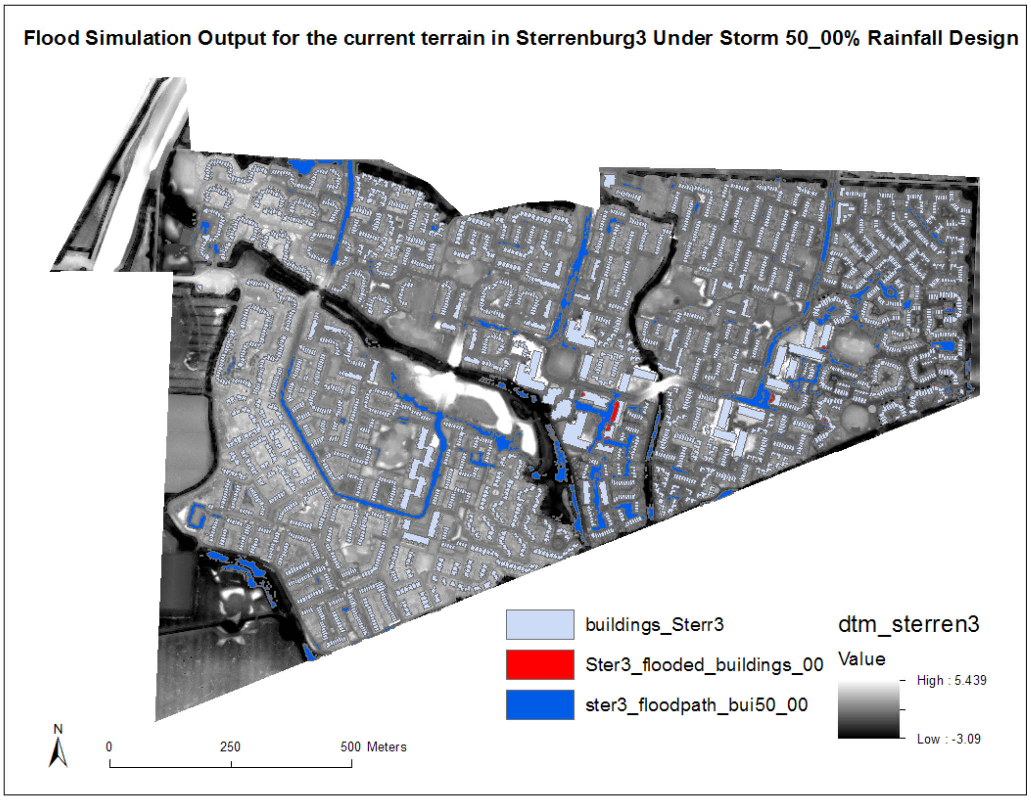

Figure 25 *Flood extent in Sterrenburg3 without increase in Storm50 rainfall design*

The tipping point at which the system fails to meet its intended purpose (convey water on the streets) was set to 1% of the total buildings to be "allowed" to flood. For Sterrenburg1, the analysis revealed that this tipping point would be reached with a 20% increase in rainfall intensity from the standard Storm 50 rainfall design. For Sterrenburg2, the tipping point occurred at 10% increase in rainfall intensity, and for Sterreburg3 the tipping point is already reached with no influence from climate change. These results are shown in the tipping point graph of Figure 26.

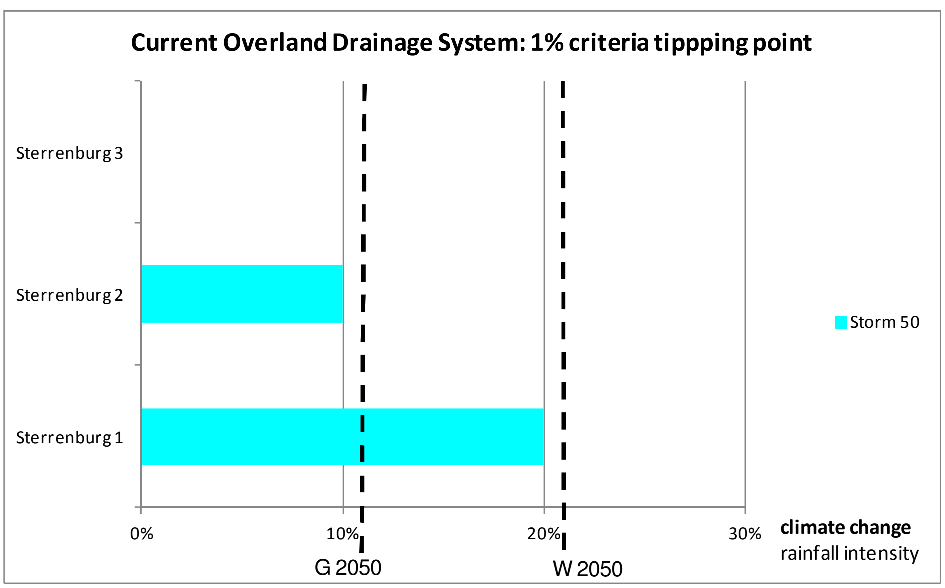

Figure 26 *Tipping point analysis of the current overland drainage system*

3.2 PHASE 2: Adaptation strategies and opportunities

The adaptation strategy proposed for the sewer system is to disconnect open paved roads (brick roads) and flat roofs (public buildings) from the sewers so as to direct the runoff from these impervious surfaces away from the sewers. Forty percent of the open paved roads and flat roof were disconnected in the urban area of Dordrecht.

For the overland drainage system the adaptation strategy consists of using the roads and natural flow paths to direct excess runoff to low lying area. In Sterrenburg1, the digital terrain model was modified for the four areas shown in Figure 27. The numbered items correspond to the adaptation measures selected and are described in Table 5.

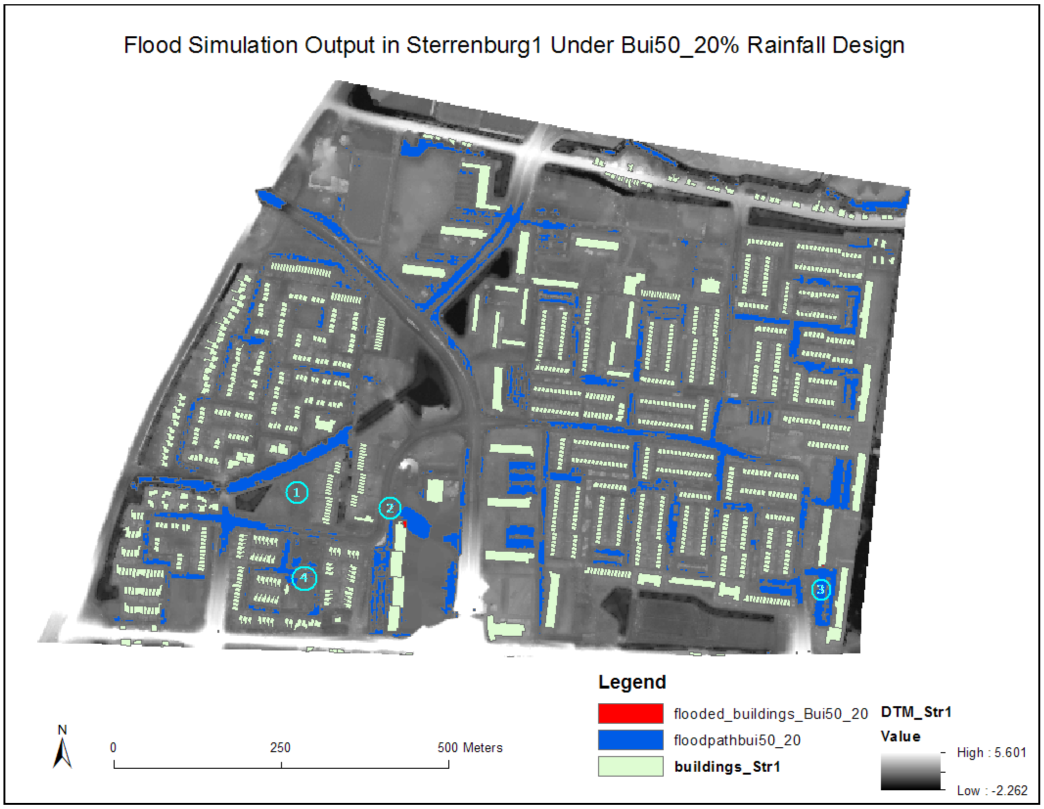

Figure 27 *Location of adaptation measures for the overland drainage system in Sterrenburg1*

ID number	Adaptation Measure
1	Use the park as retention area. Lower park grounds by ~ 25 to 30cm.
2	Build a speed bump with dimensions 12 cm x 4.8 m long . Increase street curb height by 10 cm along P.A. Koh-Plein and Planetenlaan (Dirkdebaan, 2012)
3	Build a street planter with dimensions 40 cm x 2m x 4 m on the south side of the building
4	Fill in side walk depression and increase curb height by 8 cm over 15 meters.

Table 5 *Description of adaptation measures for the overland drainage system in Sterrenburg1*

In Sterrenburg2, the digital terrain model was also modified at the areas shown in Figure 28. The numbered items correspond to the adaptation measures selected and are described in the legend of Figure 28.

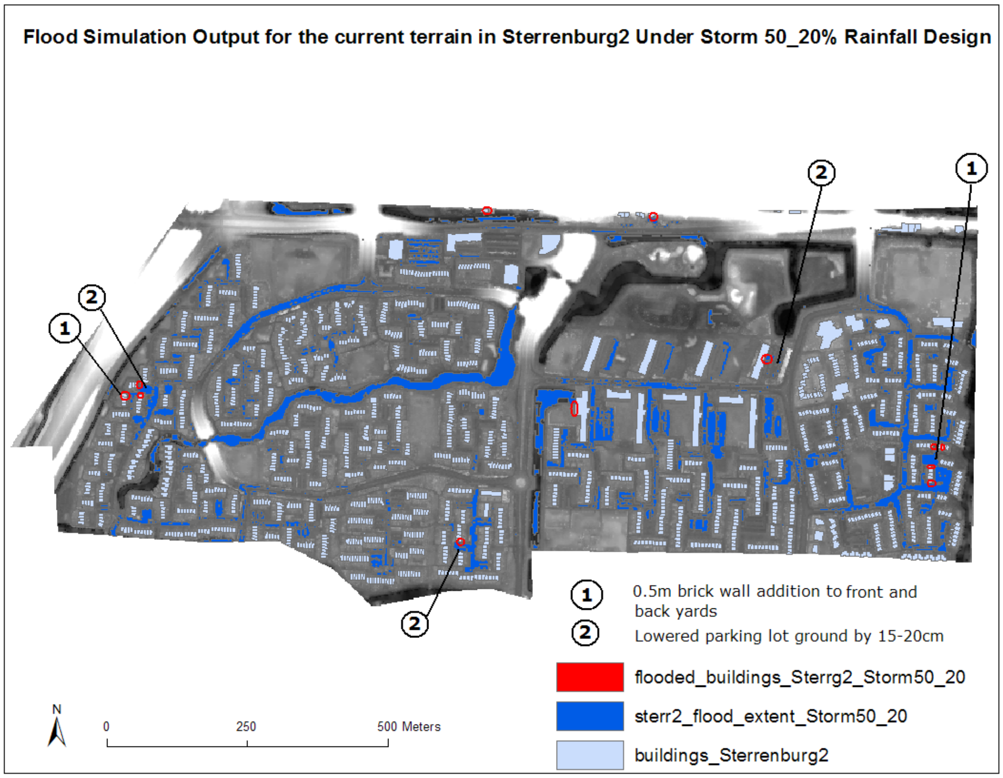

Figure 28 Location and description of adaptation measures for the overland drainage system in Sterrenburg2

In Sterrenburg3, the digital terrain model was also modified at the areas shown in Figure 29. The numbered items correspond to the adaptation measures selected and are described in Table 6.

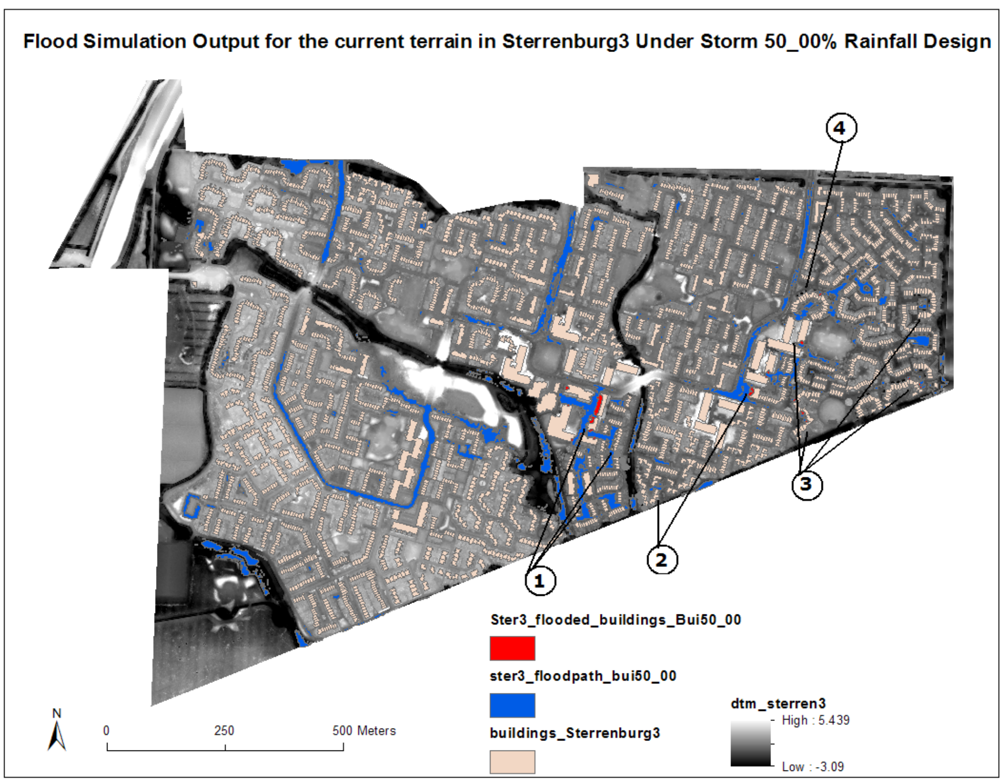

Figure 29 Location of adaptation measures for the overland drainage system in Sterrenburg1

ID number	Adaptation Measure
1	Lower road profile by 15-20 cm using a 0.5% gradient to drain the water towards adjacent canal.
2	Property dry-proofing.
3	Garage wet-prooding.
4	Create a swale on each side of the road with overpass for garage and house access. Alternatively, lower the road profile by 15-20 cm.

Table 6 *Description of adaptation measures for the overland drainage system in Sterrenburg3*

Adaptation measures 2 and 3 listed in Table 6 are dry-proofing and wet-proofing. Garage wet-proofing involves removing valuable items and placing electrical plugs above water level. That way, the water still flows into the garage but creates little damage. Property dry-proofing involves elevating a building from the ground, sealing building openings or perimeter shielding with barriers to prevent water from entering the building. An example of property dry-proofing is shown in Figure 30. This house is actually located in Sterrenburg3.

Figure 30 *Photo of an elevated house in Sterrenburg3 (Google, 2012)*

3.3 PHASE 3: Analysis of the modified drainage system's response to climate change

The following sections present the results of the 1D and 2D2D models for the adapted sewer system and the modified overland drainage system respectively.

3.3.1. The modified sewer system

The land use file was modified to simulate a 40% disconnection of open paved roads and flat roofs from the sewer system. The 1D model was then run to simulate the Bui 6 and Bui 8 synthetic design storm events over the modified urban area of Dordrecht. The output of the 1D model revealed the freeboard height of the 11,306 manholes. The percentage of overtopped manholes per rainfall intensity is presented in Figure 31, Figure 32, Figure 33, and Figure 34 for the four districts identified as most vulnerable in paragraph 3.1.1. Just as the histograms developed for the analysis of the current sewer system, the vertical axis represents the percentage of overtopped manholes, while the horizontal axis shows the rainfall intensity increase per 5% increments, along with the corresponding rainfall quantities shown below the increments. The increase in rainfall intensity shown on the horizontal axis represents climate change. For all four districts, the freeboard heights of the manholes decrease with increasing rainfall intensity, and as such, the number of overtopping manholes increases.

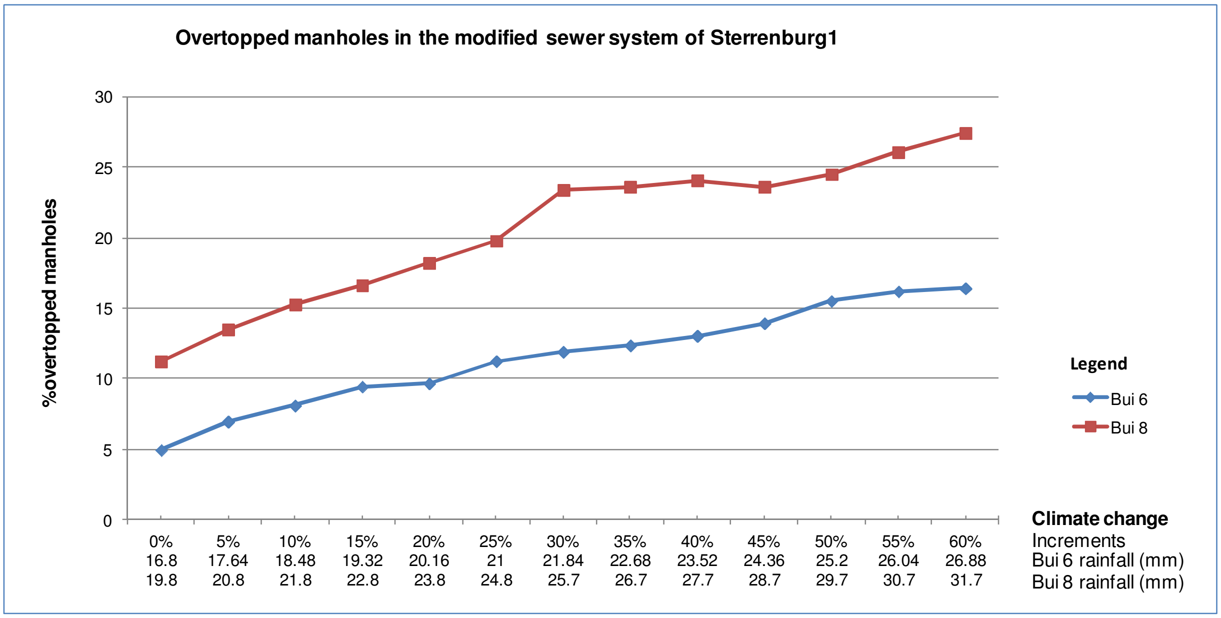

Figure 31 *Response of Sterrenburg1's modified sewer system to climate change*

Sterrenburg2 and Dubbeldam (Figure 32 and Figure 33) show a steep increase in the percentage of overtopping manholes as the rainfall intensity increases. Sterrenburg1 and Industriegebied West on the other hand, show a gradual gentle increase in the percentage of overtopped manholes as rainfall intensity increases. However, at 0% climate change, the percentage of overtopped manholes starts off higher in Sterrenburg1 and Industriegebied West then in Sterrenburg2 and Dubbeldam.

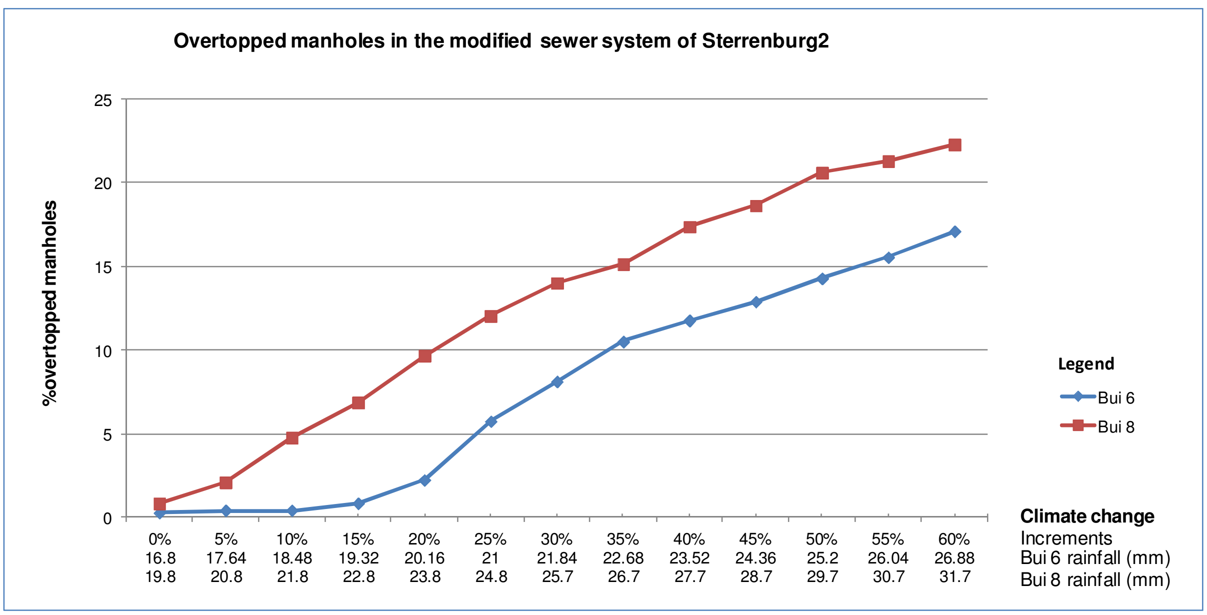

Figure 32 *Response of Sterrenburg2's modified sewer system to climate change*

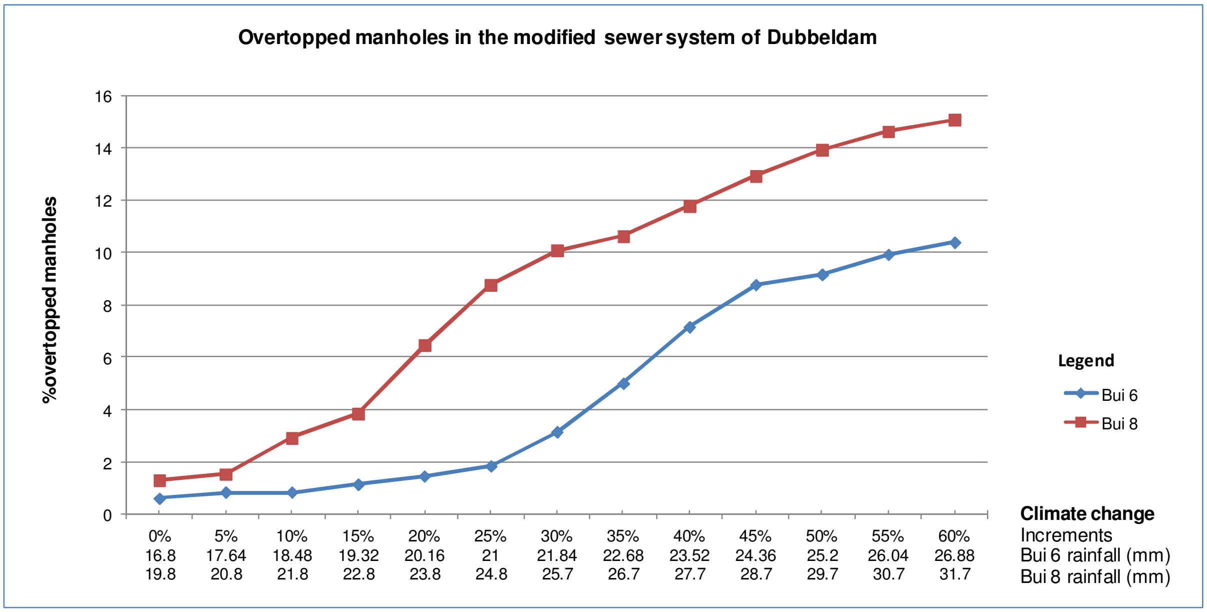

Figure 33 *Response of Dubbeldam's modified sewer system to climate change*

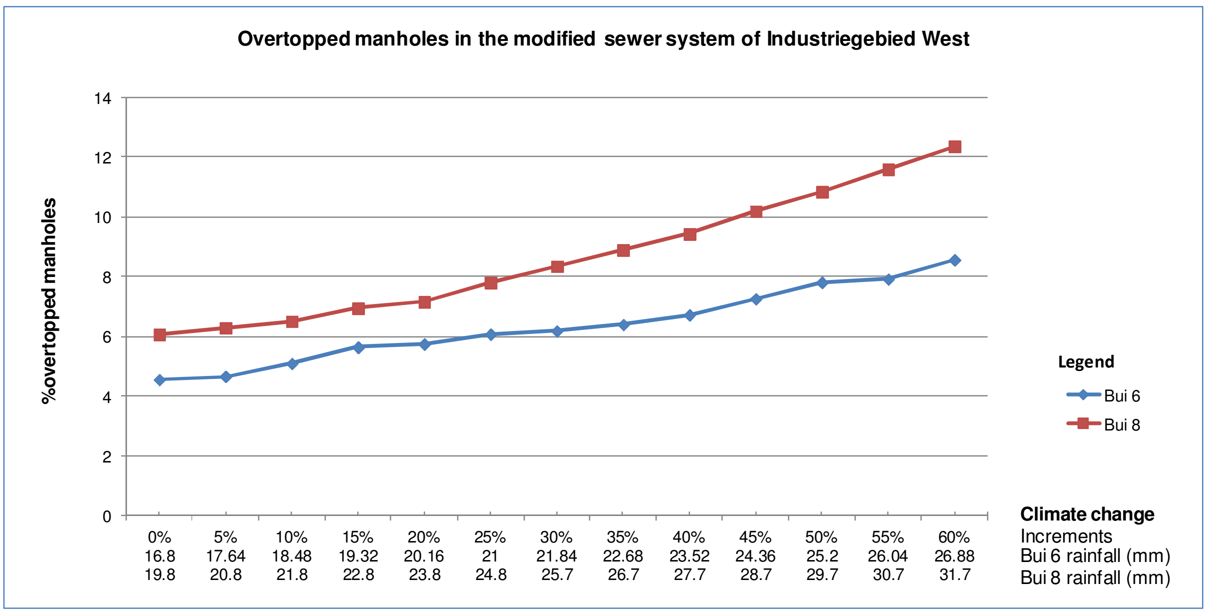

Figure 34 *Response of Industriegebied West's modified sewer system to climate change*

Just as for the current sewer system, the percentage of overtopped manholes is greater under Bui 8 conditions then Bui 6, and can be explained by the greater total rainfall quantity under Bui 8.

3.3.2. The modified sewer systems' tipping points

The final output of phase 3 is the computation of the modified system's tipping point with respect to climate change. The threshold is kept to 1% of total manholes "allowed" to overtop. Figure 35 and Figure 36 show the tipping point chart for Bui 6 and Bui 8 rainfall events respectively. Again here, the vertical axes represent the districts of the urban area, while the horizontal axes represents climate change as a function of the rainfall events Bui 6 and Bui 8. Figure 35 shows that the historic district, Indische en Volgebuurt, Sterrenburg1, and Industriegebied West reach the tipping point at 0% climate change for Bui 6. Meanwhile, the district of Dubbeldam reaches a tipping point at 10%, Sterrenburg2 at 15% and Sterrenburg3 at 20% rainfall intensity increase, which would occur after the occurrence of the G scenario developed by the IPCC, which is forecasted to occur in 2050. All the other districts would reach the tipping point after the occurrence of the W scenario developed by the IPCC. This result shows that in the occurrence of a Bui 6 rainfall event, the modified sewer system would fail to meet its intended function in three areas of Dordrecht. The 40% disconnection strategy is therefore effective in some districts and ineffective others.

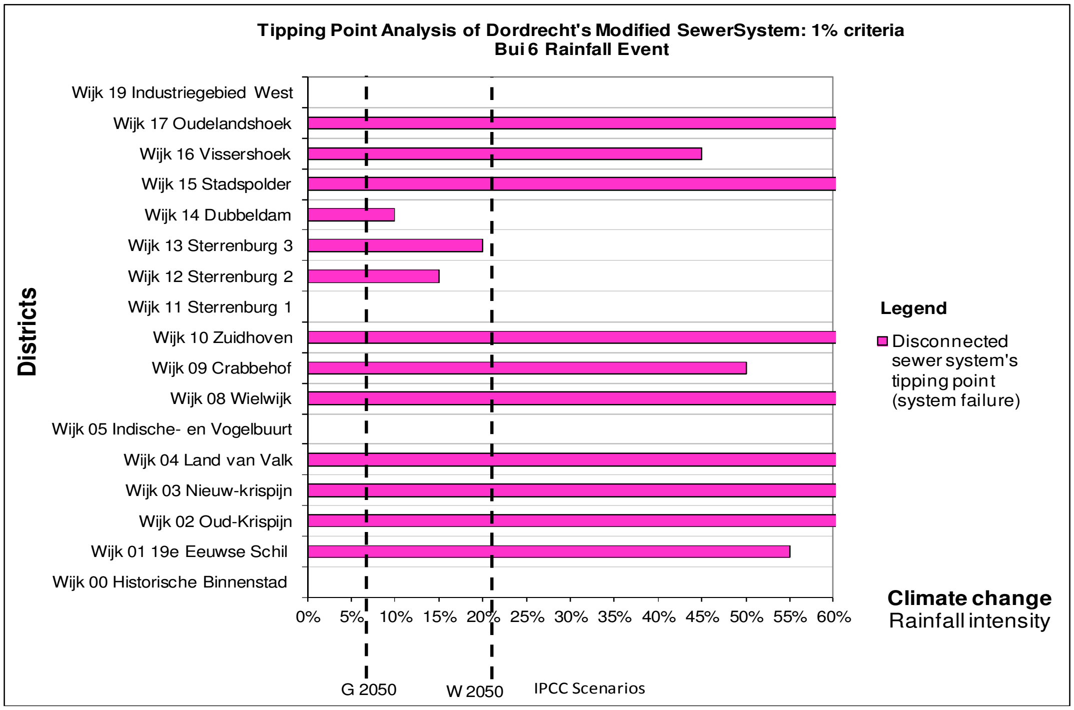

Figure 35 *Tipping point of the modified sewer system under Bui 6*

Figure 36 shows the tipping point chart for the modified sewer system under Bui 8 rainfall conditions. The historic district, Indische en Volgebuurt, Sterrenburg1, Sterrenburg2, Dubbeldam, Visserhoek, and Industriegebied West reach a tipping point at 0% climate change. Sterrenburg3 reaches a tipping point at 5% increase in rainfall intensity, so just before the occurrence of the G scenario. All the other districts would reach the tipping point after the occurrence of the W scenario developed by the IPCC. This result shows that in the occurrence of a Bui 8 rainfall event, the modified sewer system would fail to meet its intended function in seven areas of Dordrecht. The 40% disconnection strategy is therefore effective in some districts and ineffective others.

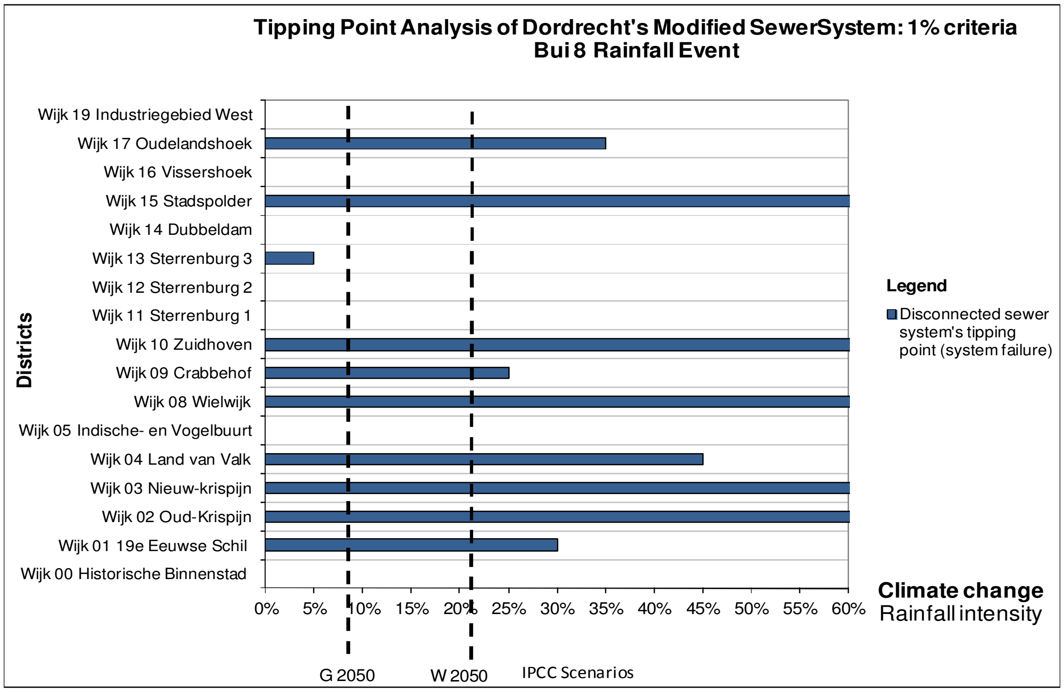

Figure 36 *Tipping point of the modified sewer system under Bui 8*

3.3.3. The modified overland drainage system

In Sterrenburg1, the overland drainage system was adapted as per the modifications described in Table 5. The response of the adapted system was simulated using the same rainfall event Storm 50. The flood extent for a 20% increase in rainfall intensity of the event Storm 50 is shown in Figure 37 (in blue). The large blue triangular area represents the accumulation of water at a depth exceeding 5cm in the park located on the corner of Venuslaan and Komentenlaan.

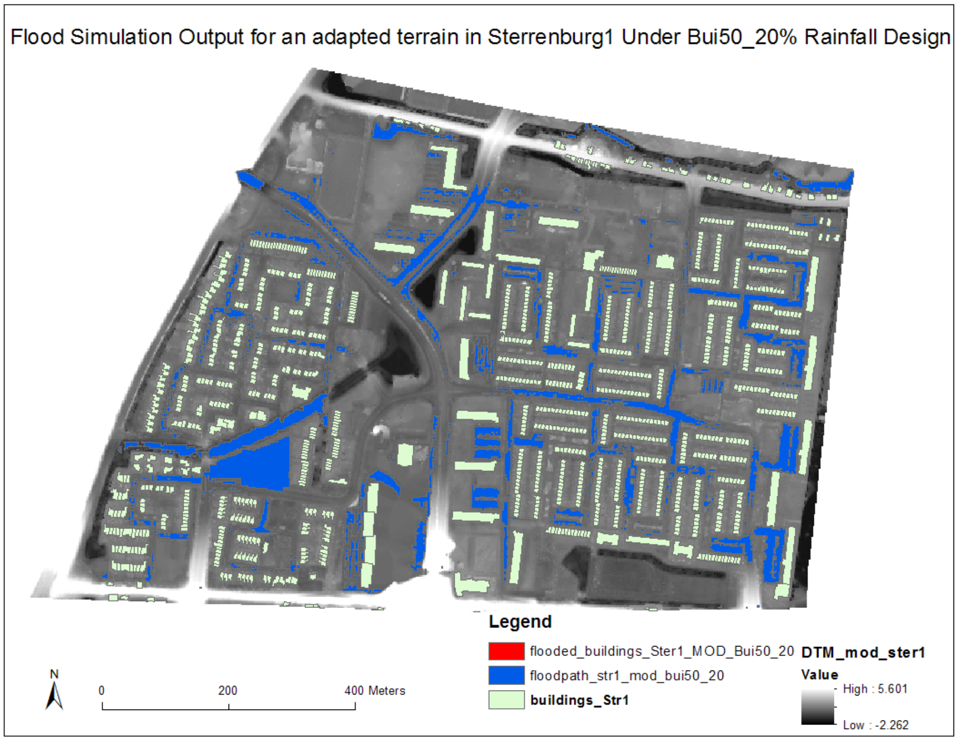

Figure 37 *Flood extent for adapted overland drainage system in Sterrenburg1 under Storm 50 rainfall event with a 20% intensity increase.*

In Sterrenburg2, the overland drainage system was adapted as per the modifications described in Figure 28. The response of the adapted system was simulated using the same rainfall event Storm 50. The flood extent for a 20% increase in rainfall intensity of the event Storm 50 is shown in Figure 38.

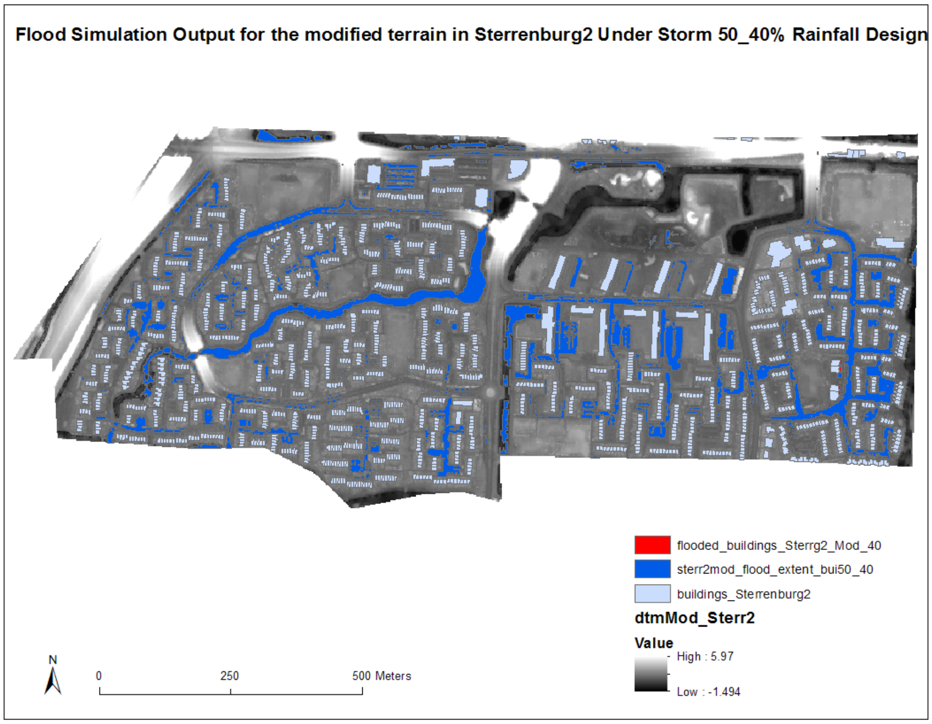

Figure 38 *Flood extent for adapted overland drainage system in Sterrenburg2, Storm 50 rainfall event with a 20% intensity increase.*

In Sterrenburg3, the overland drainage system was adapted as per the modifications described in Table 6. The response of the adapted system was simulated using Storm 50. The flood extent for the event Storm50 without rainfall intensity increase is shown in Figure 39.

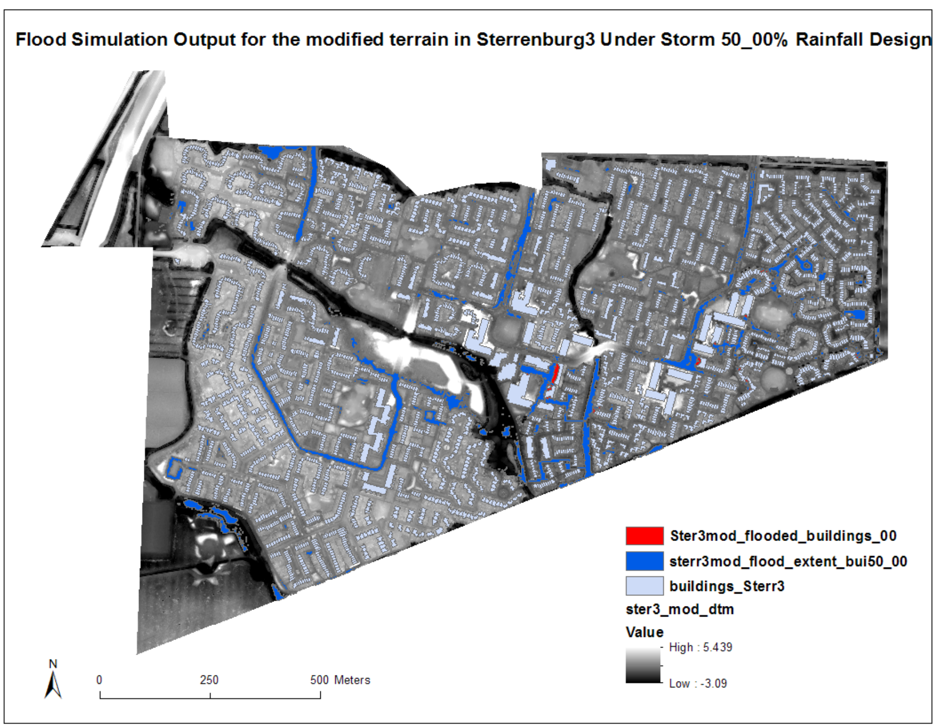

Figure 39 *Flood extent for adapted overland drainage system in Sterrenburg3 under the standard Storm 50 rainfall event.*

Figure 40 shows the tipping point graph of the adapted overland drainage system. For Sterrenburg1 and Sterrenburg2 the tipping point occurs at a 30% increase in rainfall intensity for the Storm 50 event. Whereas for Sterrenburg3, the tipping point occurs at Storm50 with no increase in rainfall intensity.

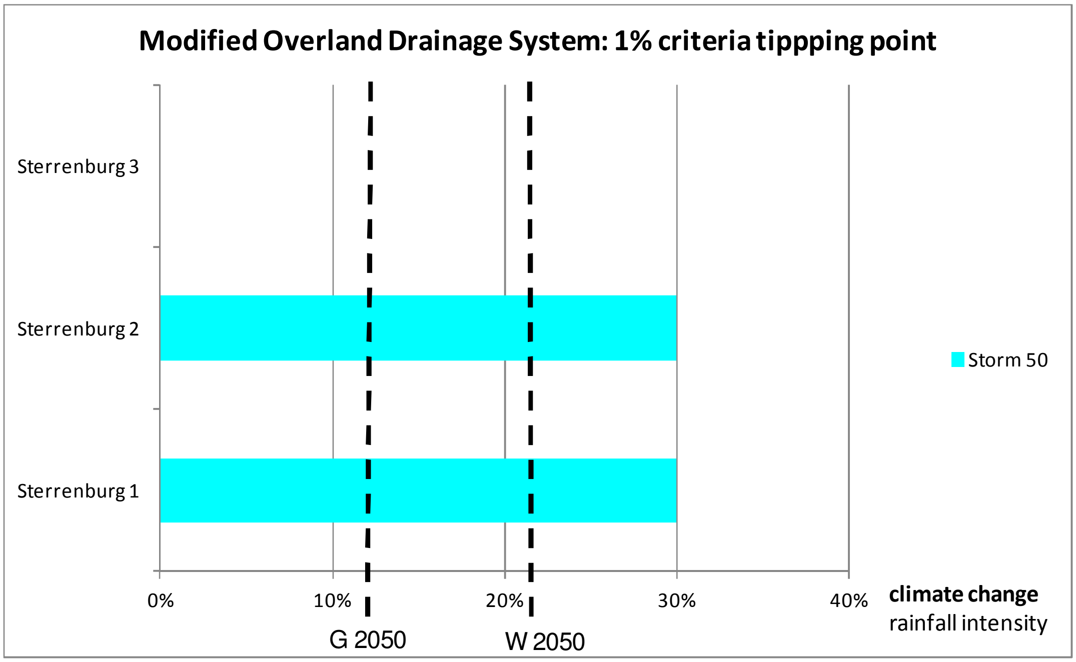

Figure 40 *Tipping point analysis of the modified overland drainage system*

3.4 PHASE 4: Evaluation of the adaptation strategies' effectiveness

The ultimate purpose of the adaptation strategies presented in this study was to improve the urban drainage system so that the system as a whole could cope with the effects of climate change, and particularly with increased rainfall quantities. Section 3.4.1 will present a comparison in system's resilience between the current and modified sewer systems. Section 3.4.2 will present a comparison in system's resilience between the current and modified overland drainage system, and section 3.4.3 will compare the incremental strategy to the transformational strategy.

3.4.1. Effectiveness of the modified sewer system

The tipping point of the current system is compared to that of the modified system in Figure 41 and Figure 42, and is used here as an indicator of improvement. A shift in tipping point from low rainfall intensity for the current system to higher rainfall intensity for the modified system means that the modified system will fail when subjected to higher rainfall intensities then that of the current sewer system. In other words, it means that the disconnection strategy improves the resilience of the sewer system to climate change. Figure 41 shows the tipping point comparison of the current and modified sewer systems under Bui 6 conditions. There is no shift in tipping point, and so no noticeable improvement for the historic district, Indische en Volgebuurt, Sterrenburg1, and Industriegebied West. There is no improvement for Zuidhoven either; however, Zuidhoven has a tipping point that occurs much later in time in terms of climate change. The shift in tipping point for the other districts is remarkable.

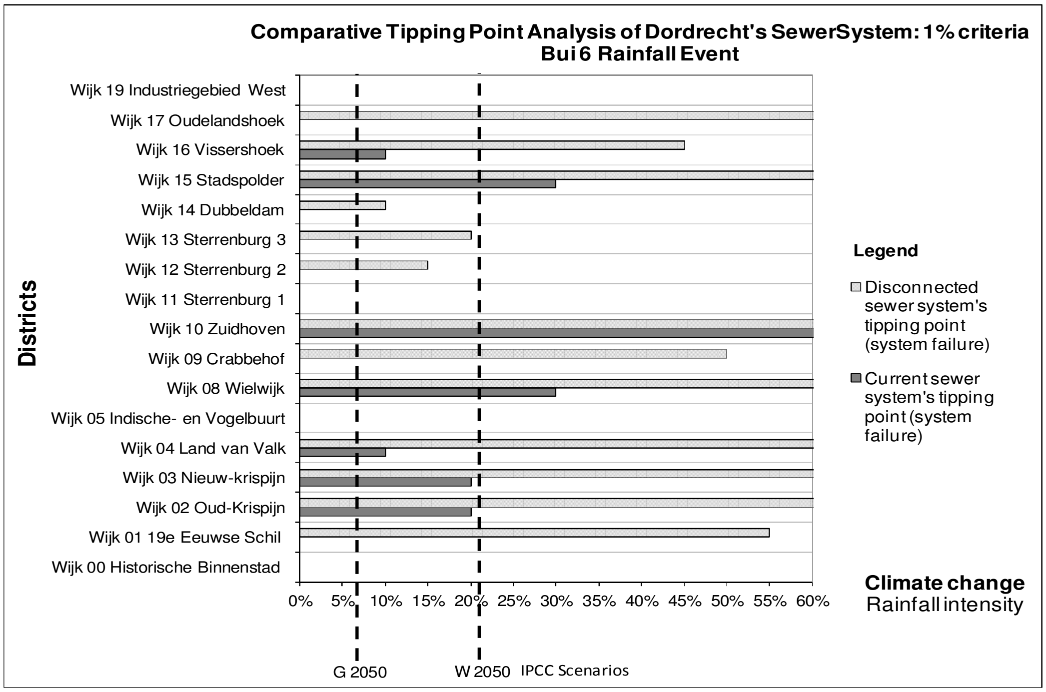

Figure 41 *Comparative analysis of the sewer system's tipping point under Bui 6*

Overall, the disconnection strategy was effective in increasing the systems' resilience for only 65% of the districts. Figure 42 shows the tipping point comparison of the current and modified sewer systems under Bui 8 conditions. There is no shift in tipping point for the historic district, Indische en Volgebuurt, Sterrenburg1, Sterrenburg2, Dubbeldam, Visserhoek, and Industriegebied West. There is a slight improvement for Sterrenburg3, and a great improvement for the nine other districts.

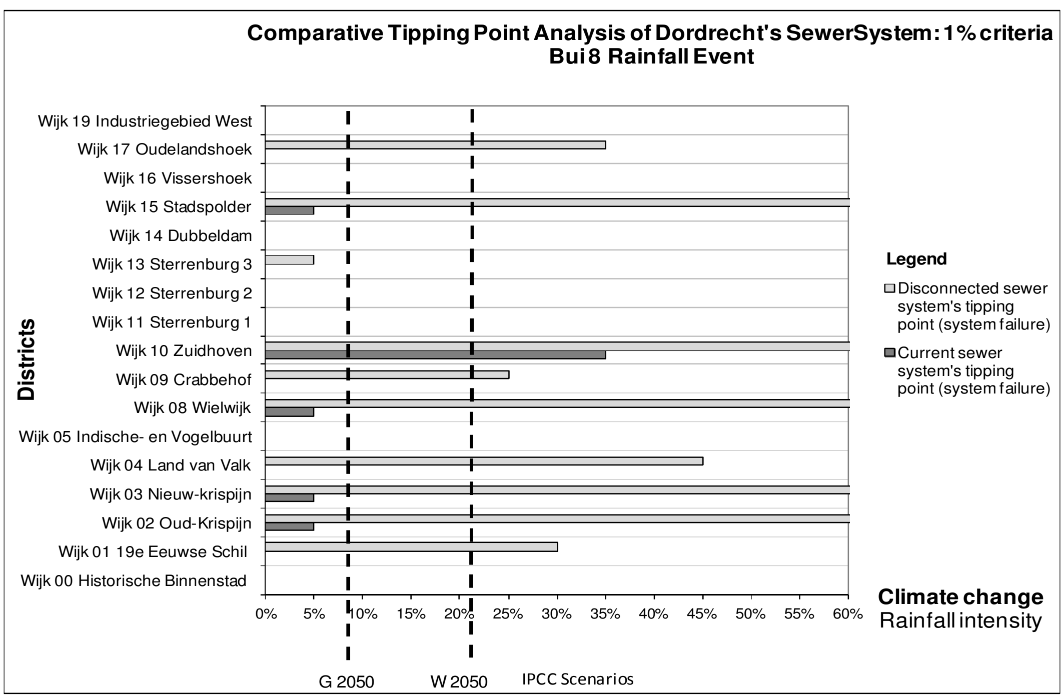

Figure 42 *Comparative analysis of the sewer system's tipping point under Bui 8*

Overall, the disconnection strategy is effective in increasing the system's resilience in only 60% of the districts.

3.4.2. *Effectiveness of the modified overland drainage system*

Figure 43 shows the comparison in tipping point for the current and modified overland drainage systems. For Sterrenbugr1, there is a clear improvement in system's resilience to climate change, expressed by the shift in tipping point from 20% rainfall intensity for the current system to 30% rainfall intensity for the modified system. The overland drainage system could therefore cope with more rainfall quantities with the retrofits suggested in Table 5. This transformational strategy is thus effective in Sterrenburg1. Similar conclusions can be drawn for Sterrenburg2; there is a shift in tipping point from 10% to 30% increase in rainfall intensity. On the other hand, Sterrenburg3 shows no improvement, since the tipping point remains the same even with the adaptation measures suggested in Table 6. The transformational change strategy is therefore not effective in Sterrenburg3 with the measures selected here.

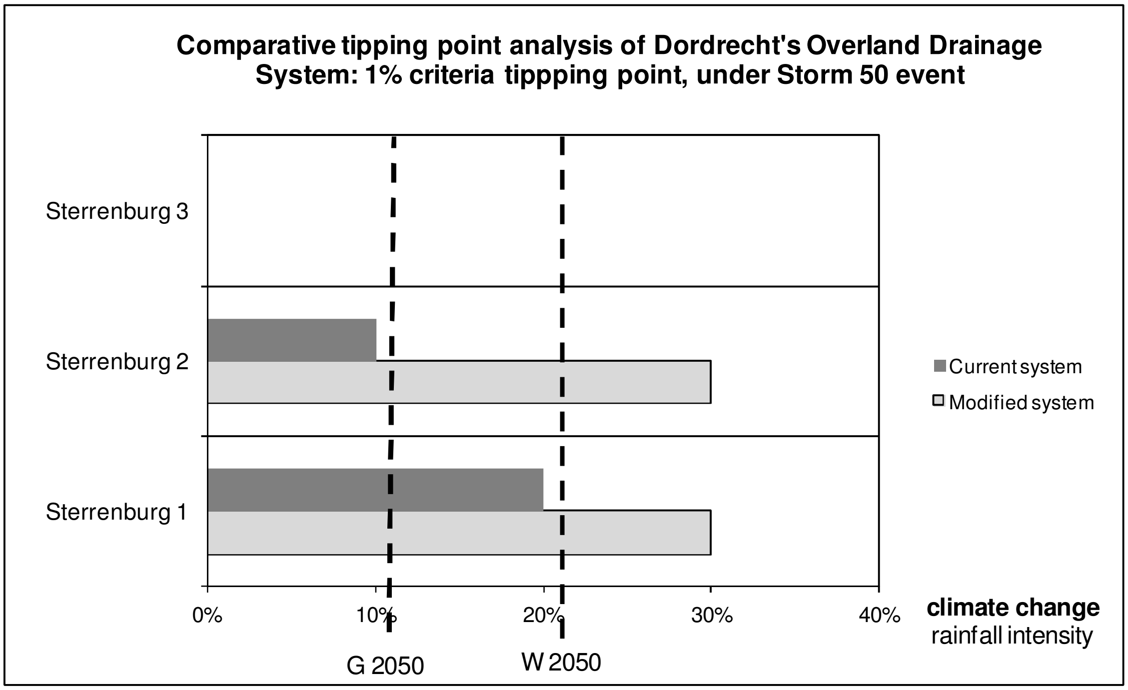

Figure 43 *Comparative analysis of the overland drainage system's tipping point, Storm 50 rainfall event*

3.4.3. *Comparison between incremental change and transformational change strategies*

Table 7 provides a summary of the effects of the disconnection strategy in each district, for both Bui 6 and Bui 8. Column two provides information on the risk of flooding from the current sewer system; this information is based on the percentage of overtopped manhole. Column three provides information on the occurrence of a tipping point shift. Column four provides an estimate of the effectiveness of the disconnection strategy in each district. A red cross means that the disconnection strategy was ineffective in improving the resilience of the sewer system to climate change. A single green check mark means a moderately effective disconnection, two green check marks means an effective disconnection, and three green check marks mean a highly positive disconnection.

Incremental change: Sewer System - Bui 6			
Districts	Will the current system be resilient until 2050?	Will the adapted system be resilient until 2050?	Effectiveness of disconnection strategy
Historische Binnenstad	unlikely	unlikely	X
19e Eeuwse Schil	unlikely	very likely	✓✓✓
Oud-Krispijn	likely	very likely	✓✓✓
Nieuw-krispijn	likely	very likely	✓✓✓
Land van Valk	likely	very likely	✓✓✓
Indische- en Vogelbuurt	unlikely	unlikely	X
Wielwijk	very likely	very likely	✓✓
Crabbehof	unlikely	very likely	✓✓✓
Zuidhoven	very likely	very likely	-
Sterrenburg 1**	unlikely	unlikely	X
Sterrenburg 2	unlikely	likely	✓
Sterrenburg 3	unlikely	likely	✓
Dubbeldam	unlikely	likely	✓
Stadspolder	very likely	very likely	✓✓
Vissershoek	likely	very likely	✓✓✓
Oudelandshoek	unlikely	very likely	✓✓✓
Industriegebied West	unlikely	unlikely	X

Incremental change: Sewer System - Bui 8			
Districts	Will the current system be resilient until 2050?	Will the adapted system be resilient until 2050?	Effectiveness of disconnection strategy
Historische Binnenstad	unlikely	unlikely	X
19e Eeuwse Schil	unlikely	very likely	✓✓
Oud-Krispijn	unlikely	very likely	✓✓✓
Nieuw-krispijn	unlikely	very likely	✓✓✓
Land van Valk	unlikely	very likely	✓✓✓
Indische- en Vogelbuurt	unlikely	unlikely	X
Wielwijk	unlikely	very likely	✓✓✓
Crabbehof	unlikely	very likely	✓✓
Zuidhoven	very likely	very likely	✓✓
Sterrenburg 1**	unlikely	unlikely	X
Sterrenburg 2	unlikely	unlikely	X
Sterrenburg 3	unlikely	unlikely	✓
Dubbeldam	unlikely	unlikely	X
Stadspolder	unlikely	very likely	✓✓✓
Vissershoek	unlikely	unlikely	X
Oudelandshoek	unlikely	very likely	✓✓✓
Industriegebied West	unlikely	unlikely	X

** Highly problematic districts
- current system already performs very well
X not effective
✓ moderately effective
✓✓ effective
✓✓✓ highly effective

Table 7 *Evaluation of the effectiveness of the disconnection strategy per district*

Table 8 presents a summary of the effectiveness of the transformational change strategy in Sterrenburg1, Sterrenburg2, and Sterrenburg3. Column two provides information on the risk of flooding from the current overland drainage system; this information is based on the percentage of flooded buildings. Column three provides information on the occurrence of a tipping point shift. Column four provides an estimate of the effectiveness of the overland drainage system strategy in the three districts of interest. The transformational change strategy proved to be effective in Sterrenburg1 and Sterrenburg2, but not in Sterrenburg3.

Transformational change: overland drainage system - Storm 50			
Districts	Will the current system be resilient until 2050?	Will the adapted system be resilient until 2050?	Effectiveness of overland drainage strategy
Sterrenburg1	unlikely	very likely	✓✓
Sterrenburg2	likely	very likely	✓
Sterrenburg3	unlikely	unlikely	X

Table 8 *Evaluation of the effectiveness of the overland drainage system strategy*

4. Discussion

4.1 Summary of findings

This study, while focusing on the case of Dordrecht, demonstrated that the RFA is applicable to the adaptation of urban drainage systems to climate change. Using a hydrodynamic-hydraulic model, it was shown that it is possible to quantify the response of a drainage system to climate change in terms of system tipping points. The system's response was quantified for disturbances of different magnitudes. The response of Dordrecht's sewer system to climate change was obtained in terms of percentage of overtopped manholes for two synthetic rainfall designs: Bui 6 and Bui 8. The socially acceptable performance criteria selected (or threshold) for the sewer system was 1% of manholes overtopped. The response of Dordrecht's overland drainage system to climate change was also obtained in terms of percentage of flooded buildings for one synthetic rainfall design; Storm 50. The threshold selected for the overland drainage system was 1% of buildings flooded.

For the sewer system, it was found that under Bui 6 rainfall conditions, ten out of the seventeen districts of Dordrecht already reach a tipping point under no influence of climate change. Whereas under Bui 8 conditions, twelve out of the seventeen districts reach a tipping point under no influence of climate change. Some of the other districts have a tipping point occurring just around the G2050 scenario, and others well after the W2050 scenario. These results are in accordance with the study conducted by the firm Tauw "Optimalisatie Watersysteem Dordrecht" [Optimisatie Water System in Dordrecht]. The study which was based on the same model DORD_BAS, revealed similar flood results (Meijer et al., 2006). The municipality of Dordrecht however, affirmed no knowledge of overtopped manholes in the recent past, and concluded that the model should be calibrated and validated. Recording of such events (overtopped manholes) are usually performed when citizens report the incidents. Thus if no incident of overtopped manhole is reported, the municipality is likely to be unaware of system failure.

For the overland drainage system the case study focused on Sterrenburg1, Sterrenburg2 and Sterrenburg3, three districts of Dordrecht that are to undergo urban renewal in a near future. The use of the overland drainage system was in itself an adaptation measure since this strategy would be new in Dordrecht. The tipping point of this system was found to occur at a 20%, 10% and 0% increase in the basic rainfall design Storm 50 for Sterrenburg1, Sterrenburg2 and Sterrenburg3 respectively.

Sub-hypothesis 1, which states that the tipping point of the current drainage system is expected to occur prior to the year 2050, is therefore only partly verified; since some of the districts reach a tipping point past 2050.

In order to increase the resilience of Dordrecht's drainage system to climate change, an adaptation strategy involving incremental changes and/or transformational change was applied. The incremental changes applied to the system involved disconnecting 40% of open paved roads and flat roofs from the sewer system, and this by 2045. Here, urban renewal and development were considered and used as windows of opportunity to perform the retrofits. The transformational change tested in this study consisted of using the streets and open water ways to direct excess runoff that the sewers could not accommodate for to lower lying areas for temporary storage or infiltration. The adaptation measures selected are "no-regret" solutions that are meant to solve existing flooding management problems while enhancing the adaptive capacity of the drainage system to a range of climate change scenarios (Laaser et al., 2009).

4.2 Effectiveness of the adaptation strategy

The response of the adapted or modified drainage system was quantified again in terms of system tipping point and for the same synthetic rainfall designs as for the current drainage system. This method allowed determining whether a shift in tipping point occurs when retrofitting the drainage system with the proposed adaptation strategy. A shift in tipping point translates into an improvement in resilience of the drainage system to intensifying rainfall events. For the sewer system, nine districts showed a substantial shift in tipping point under both Bui 6 and Bui 8 rainfall designs. Five districts showed no shift in tipping point, and thus no quantifiable improvement under Bui6 conditions, and seven under Bui 8. These results show that spatial planning and land use involving the disconnection of a portion of the roads and roofs from the sewer system can be effective in reducing the amount of runoff that reaches the sewers. In most districts, the disconnection strategy is therefore effective in increasing the resilience of the sewer system to climate change. These results are in accordance with results found in the literature. For example, the city of Portland in the USA has since 1993, introduced down-pipe disconnection of 56,000 commercial and residential properties in order to deal with sewer flooding backing up into basements and on roads. A 2011 study performed by the Portland Bureau of Environmental Services estimates that the 56,000 disconnections remove 4.5 billion liters of surface water from the sewer system annually. More tests performed by the Bureau in 2010 on a set of specific green infrastructure components, including green roofs, bioretention and disconnections, showed that these measures could reduce flows and runoff volume substantially (p.165 in Digman et al., 2012). However, the disconnection strategy proved to be ineffective in some districts; this could be due to the lack of data available to perform road disconnections, or to a bottleneck in the sewer system at some locations. Nevertheless, other incremental and no-regret measures such as rainwater harvesting, water re-use, tree planting, or the construction of a separate sewer system, should be investigated and tested in lieu of the 40% disconnection strategy presented in this study.

The terrain of Dordrecht was modified to simulate no-regret strategies such as speed bumps, lowered park areas that would direct excess runoff away from buildings. With a modified terrain, the tipping point shifted from 20% to 30% increase in the basic rainfall design Storm 50 for Sterrenburg1, from 10% to 30% for Sterrenburg2, and remained at 0% for Sterrenburg3. These results compare to case studies found in the literature, such as the "Urban flooding retrofit" project of Devonshire Park in Keighley, Yorkshire. The project was initiated in 2002 to prevent annual flooding of properties caused by increased rainfall and by a 20% increase in impervious surfaces over three decades. The solutions employed there, consisted of disconnections along with controlled path for excess runoff to Devonshire Park. No incidents of flooded properties were reported since the retrofit in 2002 (Digman et al., 2012). The overland drainage system strategy was deemed effective in Sterrenburg1 and Sterrenburg2 only, which means that using the overland drainage system can be effective in controlling the amount of runoff that reaches the sewer system, however the terrain must be adapted differently in Sterrenburg3 than was done in this study. Property flood-proofing may be the way to go forward in Sterrenburg3; home owners would however have to carry the cost of retrofit as opposed to municipalities.

Sub-hypothesis 2, which states that incremental changes and long-term transformations performed alongside (re)development plans should improve the resilience of Dordrecht's drainage system, is partially correct. First, plans for (re)development in Dordrecht were cancelled, or put on hold, due to budget cuts. Second, the incremental changes and long-term transformations suggested and tested in this study only improved the resilience of the drainage system in some of the districts.

The disconnection strategy proved to be effective in most districts, as shown in Table 7. However, the strategy was ineffective in some districts such as the Historic district, Indische en Vodelbuurt, Industriegebied, Sterrenburg1 , and Sterrenburg2, Dubbeldam, Visserhoek for Bui 8. The effectiveness of the overland drainage system could not be tested for each district due to software and time constraints. As explained in section 3.4.1., the incremental change strategy involving road and roof disconnections from the sewer system proved to be ineffective in Sterrenburg1. Whereas, the transformational change involving the use of a modified overland drainage system proved to be quite effective in increasing Sterrenburg1's overland drainage system's resilience to climate change. Sub-hypothesis 3, which states that the tipping point of the modified drainage systems should be pushed back decades after that of the current systems, while continually being pushed back in time as new information becomes available, is therefore partially verified. Only certain districts showed a tipping point shift from before 2050 to after 2050. Moreover, it is impossible to determine yet whether or not the tipping point will continually be pushed back in time due to the theoretical flexibility of the RFA. In order to confirm this hypothesis, the drainage system should first be retrofitted according to the adaptation measures suggested here, and retrofitted further as new information on climate change becomes available; at which point the tipping point analysis should be repeated for the newly modified drainage system. Finally, sub-hypothesis 4, which states that road and roof disconnection from the sewer system as well as the use of the overland drainage system would be effective in improving Dordrecht's drainage system is only partially true at the district level.

4.3 Benefits and shortcomings of the RFA and its relevance for decision makers

As Dessai and Hulme (2004) explain, bottom-up approaches such as the RFA, accept uncertainty of events, whereas traditional top-down approaches seek to reduce uncertainty. The approach selected should depend on the application and context. In this case, the application of the RFA to Dordrecht's drainage system is deemed useful in answering some of the basic questions decision makers have: *what is the first problem we will have to face as a consequence of climate change, and when will that happen?* (Kwadijk et al., 2009). The results obtained thus allow presenting managers and policy makers with improved information on risks of flooding and on risk of delaying management activities. Decisions about investments in drainage systems subject to thresholds can be rigorously analyzed that way (Whitten et al., 2012). Kwadijk et al. (2009) found that it was more effective and easier for policy makers and water managers to understand the effects of climate change when climate change was directly related to the current water management system (i.e. when a tipping point is reached for the current system). They generally found the approach practical in easing the dialogue between scientists and decision makers. Moreover, the application of the RFA to drainage systems is useful and valuable in 1) understanding the dynamics of the system and its response to a range of rainfall events, 2) widening the range of flood risk adaptation measures, 3) promoting incremental changes over time which allows for flexibility in reviewing appropriate measures as climate change information becomes available and refined, 4) promoting long-term objectives, and 5) evaluating future feedback.

4.4 Relevance of research findings for the Netherlands and beyond

The findings of this research are relevant for several municipalities across the Netherlands. A survey on pluvial flooding approaches of 203 Dutch municipalities was published by RIONED in January 2012, where almost all municipalities reported having to deal with pluvial flooding (RIONED, 2012). Moreover, the Dutch "National Program on Spatial Planning and Adaptation to Climate Change" (Nationaal Programma Adaptatie Ruimte en Klimaat) was established in 2006 to coordinate the efforts of a national adaptation strategy to meet the challenges of climate change to spatial planning and development in the Netherlands (Dessai and van der Sluijs, 2007). The RFA has now been tested on the drainage system of Dordrecht. With more research on the effectiveness of the overland drainage system, the RFA could be added to the CPT of the MARE group. In so doing, the tool would become available to members of the LAA in Bergen, Hanover, and Sheffield. Worldwide, municipalities facing pressures from climate change on their drainage systems can make use of this approach to assess the resilience of their drainage system to climate change. This approach is especially useful for local authorities, urban planners and water managers. Insurance companies may also be interested in the results of such studies; such results could give insurance companies guidance in establishing flood risk zones and in reviewing their premium rates.

4.5 Relevance of findings for storm water managers and the scientific community

The RFA, as described in the introductory paragraphs of this thesis, is a novel approach to storm water management that combines aspects of already existing approaches like the bottom-up and effect-based approaches, as well as decision support systems like the minimax strategy and the Bayesian decision theory. The novelty of the RFA basically lies in its capacity to cope with uncertainty, as well as its flexibility to adapt to future changing climate, but also in its use of windows of opportunity in the development of adaptation strategies. In contrast to the top-down and cause-based approaches, the RFA offers a dynamic dimension to the process of adaptation. It also highlights how adaptation measures are linked to feedback mechanisms across various spatio-temporal scales; that is, decisions of today will affect the flexibility of future storm water management. In this regard, the RFA facilitates the development of responses and adaptation measures that are appropriate at the right time and place (Gersonius, 2012).

The RFA has proven to be effectively applicable to drainage systems under intensifying pressures from climate change. However, the RFA should not limit itself to hydraulic systems and threats from climate change. The RFA has great potential for testing the limits of ecological systems as well. A good example is the eutrophication of water bodies, where a pristine lakes' tipping point is reached when excessive amounts of nutrients are loaded (by nearby farming for example). The water body's response is characterized by increasing turbidity, oxygen depletion and algal bloom. The tipping point of such systems can be evaluated by simulating the system's response to varying concentrations of phosphates and nitrates. Adaptation measures should be discussed with multi-disciplinary stakeholders, such as water boards, farmers, municipalities, policy makers, and scientists.

4.6 Some drawbacks

The RFA was rather straightforward to apply to Dordrecht's drainage system, and conveyed important results that decision makers may want to take into consideration when planning for the future. One of the major drawbacks of this study was the use of the software Sobek to simulate pluvial flooding. Particularly for the overland flow module, Sobek uses a very high volume of a computer's virtual memory and can only use one processor at a time. This limited the amount of information that could be processed to areas of 100 hectares to 400 hectares, with a resolution or cell size of 2 m x 2m. The non-linear processing time took between 1 to 10 days per simulation. This software limitation and the time restrictions resulted in analyzing only three districts of Dordrecht, when the initial plan was to perform the analysis for the entire city. Breaking up the 1D2D simulations per district gives invalid results at the district boundaries, on which one cannot conclude, because the flow of water at the boundaries acts as a waterfall. Another drawback regarding the analysis performed is the assumption that houses have a doorstep height of 5cm. This assumption is rather conservative; however, results could certainly change according to building construction type. In addition, the data used was simple but somewhat incomplete and a lot of assumptions had to be made. For example, the database containing information on the year of construction of the roads was rather incomplete. For that reason, it was impossible to use several windows of opportunities (every decade or so) to introduce adaptation measures; instead, it was assumed that over the next 30 years, roughly 40% of all roads and buildings eligible for maintenance would undergo retrofit. Besides, the factor chosen to make roads eligible for retrofit was the material in which they were built. Assumptions like these influence the precision of the results. However, in bottom-up approaches like the RFA, precision is not the objective per se. What matters more, is to have an idea of a system's response to certain drivers, and what changes can be effective in increasing the resilience of such systems.

5. Conclusion and recommendations

5.1 General conclusions

The results of this thesis show that the RFA can contribute to the adaptation of urban drainage systems to climate change. The RFA can be considered as an alternative or complementary approach to already existing approaches in storm water management under climate change. The results show that the main hypothesis stating that "*The resilience framework approach can be used to assess the current flood risks associated with Dordrecht's drainage system, to establish desired levels of drainage system performance, and to develop and test a set of adaptation measures that will increase its resilience to flooding",* is correct, except that the adaptation measures tested here do not increase the entire system's resilience to flooding, but only parts of it. The RFA was in itself valuable in partially developing a climate change adaptation strategy to Dordrecht's drainage systems; other sets of adaptation measures should be tested that would ideally increase the entire system's resilience to flooding. Finally, the overall objective of the research was to use the findings of this research in the decision process and design of future spatial planning and storm water management. To date, this objective has not yet been reached. This project is still on-going; however the results provided in this thesis already provide insight into the adaptive capacity and flexibility of Dordrecht's drainage system.

5.2 General recommendations

Some recommendations are presented here. First, the effectiveness of the overland drainage system should be tested for all urban districts of Dordrecht. Second, a cost-benefit analysis of the adaptation strategies should be performed in order to weight the environmental, monetary, social and technical costs and benefits of each measure. This cost-benefit analysis should be performed at the district level, since the effectiveness of the incremental and transformational change varies per district. Third, a threshold should be selected and agreed upon in order to design or retrofit drainage systems accordingly. In addition, an array of existing no-regret adaptation measures should be tested individually and simultaneously in order to evaluate their effects on the resilience of the system.

5.3 Recommendations to the LAA of Dordrecht

Table 7 is copied again below for the sake of summarizing the analysis performed in this research; refer to Table 9. The LAA of Dordrecht, and more specifically the municipality and the water board, should pay particular attention to the districts of Sterrenburg1, Sterrenburg2, Dubbeldam and Industriegebied West. Thoughtful planning is required in these districts if pluvial flooding of the streets is to be avoided. While these districts were found to already be susceptible to flooding, no substantial improvement was found when simulating road and roof disconnections from the sewer system. It is therefore advised to test the strategy of the overland drainage system and to conduct more research into ways of increasing local infiltration, retention, and/or evaporation.

Incremental change: Sewer System - Bui 6			
Districts	Will the current system be resilient until 2050?	Will the adapted system be resilient until 2050?	Effectiveness of disconnection strategy
Historische Binnenstad	unlikely	unlikely	X
19e Eeuwse Schil	unlikely	very likely	✓✓✓
Oud-Krispijn	likely	very likely	✓✓✓
Nieuw-krispijn	likely	very likely	✓✓✓
Land van Valk	likely	very likely	✓✓✓
Indische- en Vogelbuurt	unlikely	unlikely	X
Wielwijk	very likely	very likely	✓✓
Crabbehof	unlikely	very likely	✓✓✓
Zuidhoven	very likely	very likely	-
Sterrenburg 1**	unlikely	unlikely	X
Sterrenburg 2	unlikely	likely	✓
Sterrenburg 3	unlikely	likely	✓
Dubbeldam	unlikely	likely	✓
Stadspolder	very likely	very likely	✓✓
Vissershoek	likely	very likely	✓✓✓
Oudelandshoek	unlikely	very likely	✓✓✓
Industriegebied West	unlikely	unlikely	X

Incremental change: Sewer System - Bui 8			
Districts	Will the current system be resilient until 2050?	Will the adapted system be resilient until 2050?	Effectiveness of disconnection strategy
Historische Binnenstad	unlikely	unlikely	X
19e Eeuwse Schil	unlikely	very likely	✓✓
Oud-Krispijn	unlikely	very likely	✓✓✓
Nieuw-krispijn	unlikely	very likely	✓✓✓
Land van Valk	unlikely	very likely	✓✓✓
Indische- en Vogelbuurt	unlikely	unlikely	X
Wielwijk	unlikely	very likely	✓✓✓
Crabbehof	unlikely	very likely	✓✓
Zuidhoven	very likely	very likely	✓✓
Sterrenburg 1**	unlikely	unlikely	X
Sterrenburg 2	unlikely	unlikely	X
Sterrenburg 3	unlikely	unlikely	✓
Dubbeldam	unlikely	unlikely	X
Stadspolder	unlikely	very likely	✓✓✓
Vissershoek	unlikely	unlikely	X
Oudelandshoek	unlikely	very likely	✓✓✓
Industriegebied West	unlikely	unlikely	X

** Highly problematic districts

- current system already performs very well

X not effective

✓ moderately effective

✓✓ effective

✓✓✓ highly effective

Table 9 *Evaluation of the effectiveness of the disconnection strategy per district*

As for the other districts, the set of adaptation measures tested in this study shows promising results. The recommendation here is to proceed to testing the strategy of road and roof disconnection on a small scale, and to monitor its effects. Should precise results be required, it is advised to refine the data pertaining to the maintenance schedule of specific roads and public buildings.

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ANNEX 1: Tipping point analysis for 0% and 5% criteria

Comparative analysis of the tipping point for the current and modified sewer system for the 0% criteria, under Bui 6 rainfall conditions.

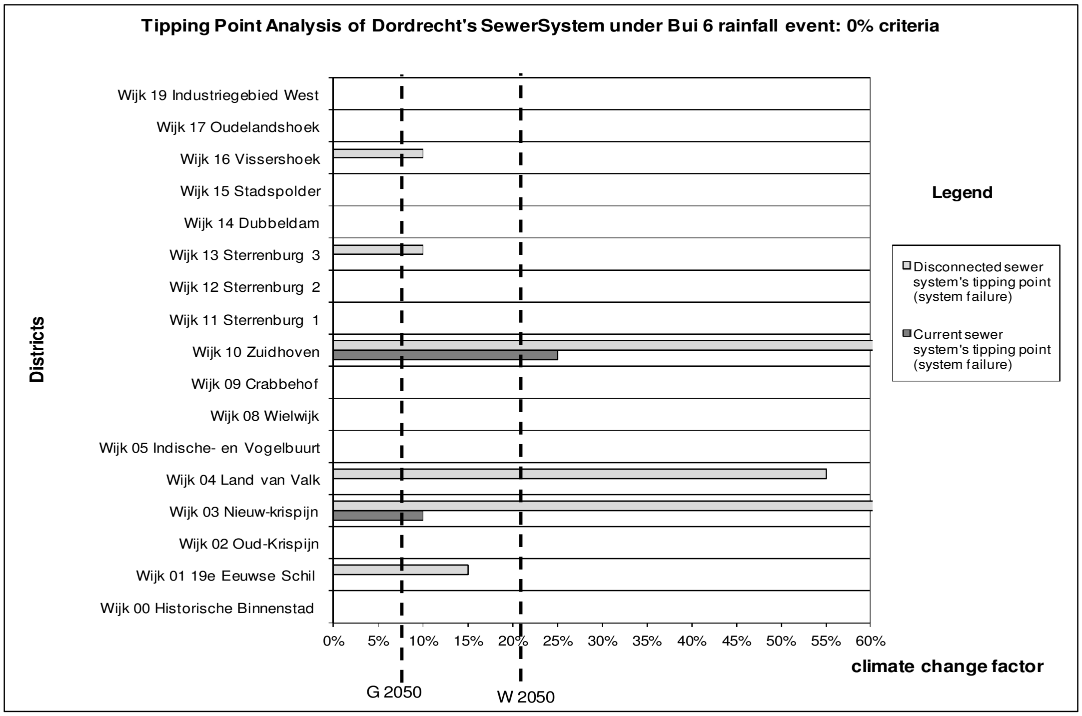

Figure 44 *Tipping point comparison for 0% threshold under Bui 6*

Comparative analysis of the tipping point analysis for the current and modified sewer system for the 5% criteria, under Bui 6 rainfall conditions.

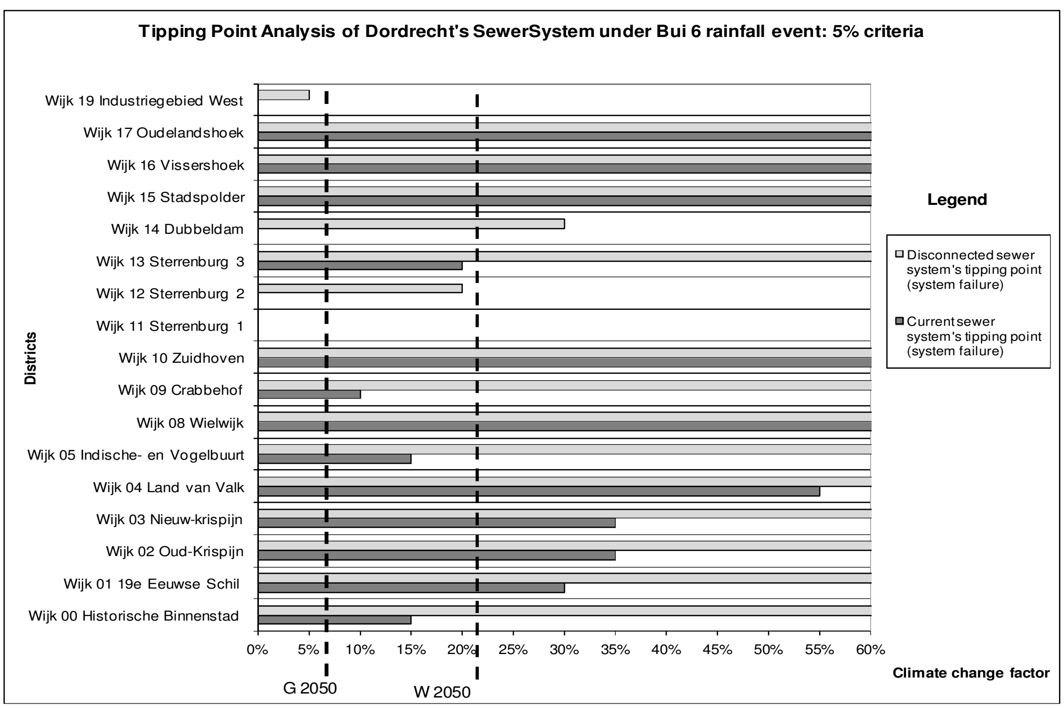

Figure 45 *Tipping point comparison for 5% threshold under Bui 6*

Comparative analysis of the tipping point analysis for the current and modified sewer system for the 0% criteria, under Bui 8 rainfall conditions.

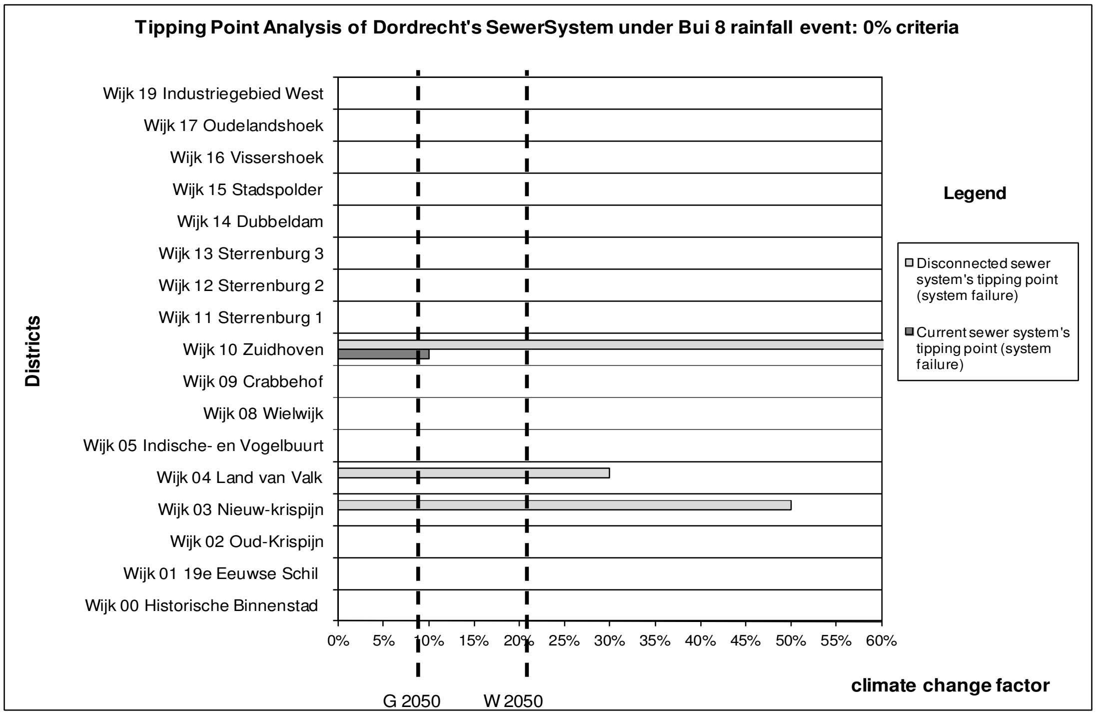

Figure 46 *Tipping point comparison for 0% threshold under Bui 8*

Comparative analysis of the tipping point analysis for the current and modified sewer system for the 5% criteria, under Bui 8 rainfall conditions.

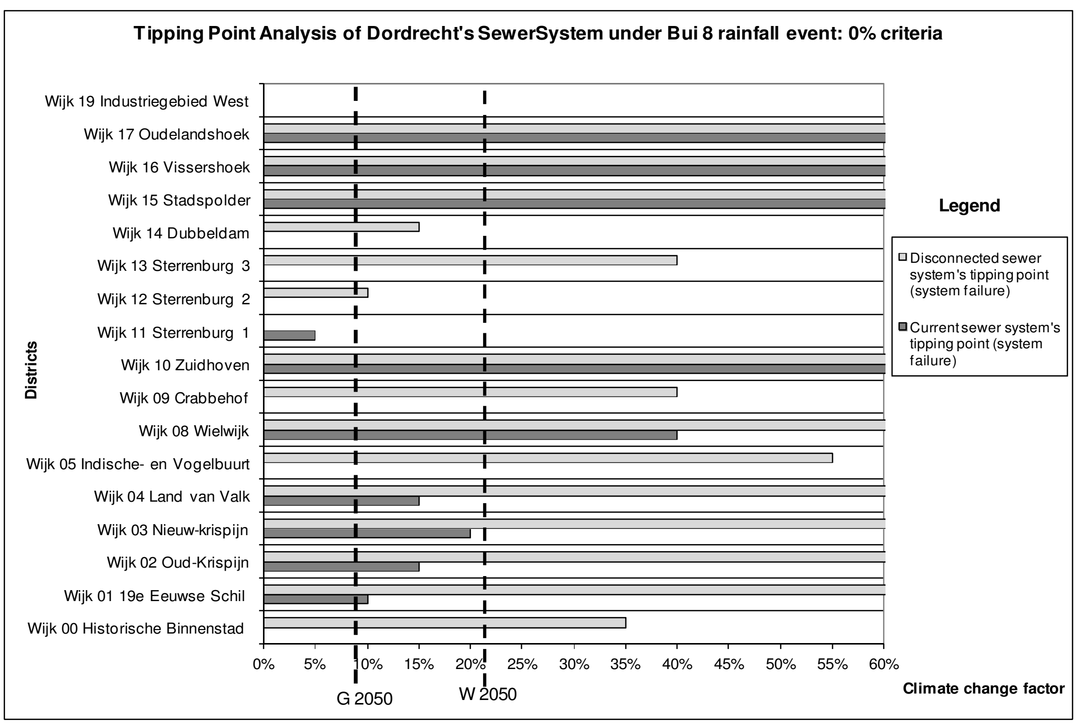

Figure 47 *Tipping point comparison for 5% threshold under Bui 8*

ANNEX 2: Statement of Originality

Utrecht University
Faculty of Geosciences
Department of Innovation and Environmental Sciences
Programme Science and Innovation Management
Programme Sustainable Development

Statement of Originality

Student's name: Nadia Koukoui

Student's ID: 3561526

Title report/thesis: Climate Change Adaptation of Urban Drainage Systems Using the Resilience Framework Approach – Case study in Dordrecht, Netherlands

I declare that:

-this is an original thesis and is entirely my own work.

-where I used the ideas of other writers, I acknowledge the source in every instance.

-where I used any diagrams or visuals, I acknowledge the source in every instance.

-the thesis (or part of it) was not and will not be submitted as assessed work in any other academic course.

☐ This thesis is confidential and cannot be placed on the internet.

☒ This thesis can be placed on the internet.

Date of signature:____________________

Student signature:____________________