Rainproof urban water management in the municipality of Heemskerk, The Netherlands

Designing adaptation pathways with D-Hydro Suite 1D2D modelling

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Summary

As a result of climate change, the intensity and frequency of extreme precipitation events is expected to increase. Decision-makers ask for resilient plans that protect cities against pluvial flooding and that increase the likelihood of success in a variety of plausible scenarios. The Dynamic Adaptive Policy Pathways (DAPP) approach is an integrated approach including transient scenarios, different measures, and adaptation pathways which show possible sequences of promising adaptation measures.

The municipality of Heemskerk experienced pluvial flooding after the extreme precipitation event of July 28th 2014. This research aimed to design adaptation pathways for resilient urban water management in the municipality of Heemskerk following the DAPP approach. The system analysis was conducted using beta modelling software D-Hydro Suite 1D2D. An integrated model with interaction between the 1D sewage system and the 2D overland flow was used to simulate the 2014 event. KNMI's 2014 climate scenarios G_L and W_H were used to predict water depth on streets in 2050 resulting from an event with the same return period as the 2014 event, 1-in-100 years. The additional rainwater storage that was needed to decrease the water depth to the allowed maximum of 10 cm on streets was set as Adaptation Tipping Point (ATP).

The results of the simulations in D-Hydro showed similarities with the Climate Impact Atlas (Klimaateffectatlas). However, only 44,5% of the actual reported flooding locations of the 2014 event had a simulated water depth of 10 cm or higher. This showed that a high water depth does not necessarily result in nuisance from flooding.

Eight adaptation measures were selected based on the possibilities and constraints in the municipality of Heemskerk. Three of these measures – 'Underground storage', 'Lowered roads' and 'Wadis' – were simulated in D-Hydro to estimate their efficacy. Complemented with literature all eight adaptation measures were evaluated on their costs, constraints, possible side effects and the contribution to the ATP. Finally, five different adaptation pathways were designed, each with a different theme.

The reliability of the results was influenced by the parameters of the model and data used. It was therefore recommended to improve the quality of the integrated model in future research. This study should be seen as an exploration of possibilities in the municipality of Heemskerk for formulating specific Dynamic Adaptation Policy Pathways and should be seen as a starting point towards resilient urban water management.

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Maureen van Rijn
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List of Acronyms

IPCC	Intergovernmental Panel on Climate Change
KNMI	Koninklijk Nederlands Meteorologisch Instituut (Dutch Meteorological Institute)
SRES	Special Report on Emission Scenarios
DAPP	Dynamic Adaptive Policy Pathways
ATP	Adaptation Tipping Point
HHNK	Hoogheemraadschap het Hollands Noorderkwartier
GUI	General User Interface
AHN	Actueel Hoogtebestand Nederland (Dutch current bed level registration)
DTM	Digital Terrain Model
DIMR	Deltares Integrated Model Runner
RLG	Representative Lowest Groundwater depth
RHG	Representative Highest Groundwater depth

1 Introduction

1.1 Uncertainties in urban water management

Cities are increasingly vulnerable to climate change (Babovic, 2018). The important economic activities, growing urban population and the increasing risk of heavy precipitation make urban systems prone to pluvial flooding (UN DESA, 2018; Babovic, 2018). Anthropogenically enhanced greenhouse gas concentrations and the related climate change are an expected cause of changes in the hydrological cycle (Hegerl et al., 2014). Considering a warming climate and more water vapor in the atmosphere (Trenberth et al., 2007), an increased precipitation intensity was one of the first climate model results regarding precipitation extremes (Pall et al., 2007). The special report of the Intergovernmental Panel on Climate Change (IPCC) on Managing the Risk of Extreme Events and Disasters to Advance Climate Change Adaptation (Seneviratne et al., 2012) states that it is *likely* (66–100% probability) that the frequency of heavy precipitation or the share of total rainfall from heavy precipitation will increase in the 21st century. Also, the Dutch Meteorological Institute's (KNMI) climate scenarios predict more extreme precipitation events throughout the year and a 12% increase in hourly precipitation intensity per degree of warming (KNMI, 2015). In addition, a 1-in-20 year annual maximum 24-hour precipitation rate is *likely* to become a 1-in-5 to 1-in-15 year event by the end of the 21st century in many regions following the Special Report on Emission Scenarios (SRES) A2, A1B and B1 emission scenarios (Seneviratne et al., 2012). The risk of pluvial flooding in cities due to the predicted increase in the frequency and intensity of heavy rainfall events is enhanced by the amount of paved area. Impervious paved area is directly connected to the sewage system and consequently overloads the sewage system during extreme events (EEA, 2012). Figure 1 shows the difference between discharge of rainwater towards the sewage system between urban and rural areas. Most sewage systems are designed such that only once every two years it cannot fully process the precipitation event and rainwater stays on the streets (Vergroesen et al., 2013).

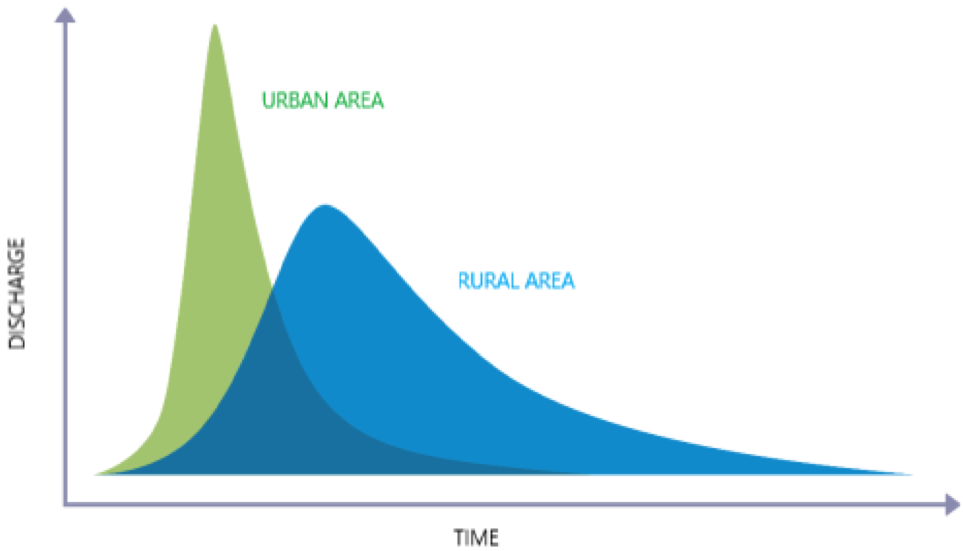


Figure 1: Peak discharge after precipitation in urban and rural area. (Edited from Langeveld et al., 2019). Urban areas have a quicker response, while the peak discharge in rural area is more evenly distributed over time.

Broadly, decision-makers in urban water management face uncertainties associated with the following external factors: climate change, urban population growth and economic development (Kwakkel et al., 2015). Coping with uncertainties in policymaking requires a plan that increases the likelihood of success in a variety of plausible scenarios. Dynamic adaptive plans that are robust to deal with these uncertainties are receiving more attention. One of many proposed adaptive planning approaches (Kwakkel et al., 2015) is the Dynamic Adaptive Policy Pathways (DAPP) approach (Haasnoot et al, 2013). The DAPP approach is based on two complementary approaches for designing adaptive plans: Adaptive Policymaking and Adaptation Pathways. Adaptive Policymaking is a structured approach consisting of five steps for designing a dynamic adaptive plan (Kwakkel et al., 2010). The first two steps analyze the existing conditions of the system and design a basic plan. In the third step this plan is made more robust by four types of actions: to reduce the likely adverse effects and the uncertain adverse effects of the plan, to seize likely opportunities and to reduce failure (or enhance success) of the plan. The fourth step focusses on monitoring the plan's performance. Lastly, step five describes different possible actions to refine the plan where necessary: defensive-, corrective-, capitalizing- or reassessing actions.

The Adaptation Pathways approach presents a sequence of possible actions after an Adaptation Tipping Point (ATP) (Haasnoot et al., 2012). The ATP is central to the Adaptation Pathways approach and is about the conditions under which an action no longer meets the specified objectives. As a result of the Adaptation Pathways approach, the different pathways are presented as alternative routes to the same desired point in the future in a map similar to that in Figure 2.

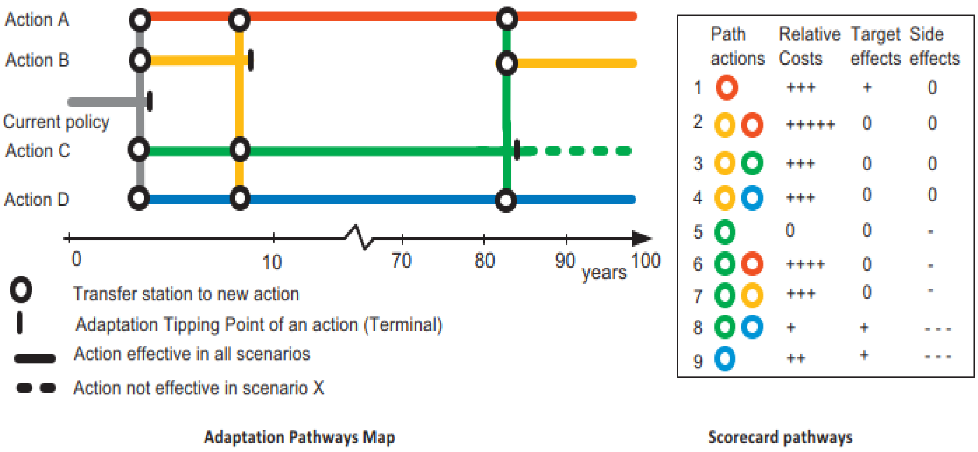


Figure 2: An example of an Adaptation Pathways map. Starting from the left, the current policy will reach its Adaptation Tipping Point after four years. Following the grey line, four adaptation measures or 'actions' can be chosen. Action A and D are sufficient for the coming 100 years, while Action B will delay reaching the Adaptation Tipping Point for the first five years, which means a shift to one of the other actions is necessary. (Source: Haasnoot et al. 2013).

DAPP is an integrated approach using the strengths of prior approaches, including: transient scenarios representing uncertainties and their development with time, different actions – or measures – to handle vulnerabilities, and adaptation pathways which show possible sequence of promising adaptation measures (Haasnoot et al., 2013).

Using transient scenarios, the DAPP approach tries to capture part of the uncertainty towards the future. The KNMI'14 climate scenarios translate the results from the 2013 IPCC report (IPCC, 2013) for the Dutch situation (KNMI, 2015). Within the scope of this research, two of the four climate scenarios are considered as scenarios for the DAPP approach: W_H and G_L. These are, respectively, the warmest and the least warm scenario (Figure 3) and correlate with the RCP8,5 and RCP4,5 respectively. These "Representative Concentration Pathways" (RCP) represent different pathways that lead to added radiative forcing (W/m^2) towards the end of the century due to increasing emissions and socio-economic development scenarios (Van Vuuren et al., 2011).

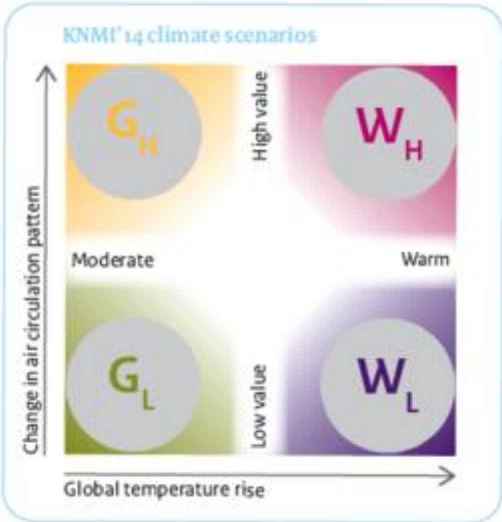


Figure 3: KNMI'14 climate scenarios (KNMI, 2015). The x-axis shows the rise in global temperature (moderate or warm) and the y-axis shows the change in air circulation pattern. The G_L-scenario is the most moderate scenario, while the W_H-scenario is the most extreme.

1.2 Problem Statement

One of the most recent extreme precipitation events in the Netherlands was on July 28th 2014. This event caused flooding in cities in the provinces Noord-Brabant, Zuid-Holland and Noord-Holland. The estimated return period was 1-in-100 years for Noord-Holland and 1-in-500 years for the province of Noord-Brabant (Beersma et al., 2019; De Boer, 2016). Indeed, the municipality of Heemskerk experienced flooding after the event of July 28th 2014 (the 2014 event). De Boer (2016) found maximum precipitation volumes of 54,1 mm per 60 min and 73,2 mm per 120 min for weather station Wijk aan Zee, which is closest to Heemskerk. Given that these intensities are likely to increase because of climate change, sewage systems and overland flow routes will likely be inundated more often. Controlling the relationship between the piped sewer network and the above-ground flow system has become more critical (Ghbn, 2016). Thus, against the backdrop of a changing climate and motivated by the need to increase flood resilience, the municipality of Heemskerk together with the municipality of Beverwijk and the water board, Hoogheemraadschap het Hollands Noorderkwartier (HHNK), formulated a water and sewer plan for the period 2017-2021. This plan extends the existing water management plan well into 2050. Central to this plan is the question on how to manage rain-, ground-, surface- and used (sewage) water, with a view to reducing the burden on the sewage system during heavy rain events and to enhance natural runoff and infiltration (Cruz et al., 2017).

Formulating and implementing adaptation measures that fit the objective of the municipality of Heemskerk – to unburden its sewage system and make it more resilient towards an uncertain future – requires a more dynamic and resilient adaptation strategy. Voskamp & van de Ven (2015) define resilience as "the ability of a system (the city) to adapt and adjust to internal or external processes". These authors suggest two aspects of resilience: continuous functioning and process of adaptation. The former relates to the ability to handle and recover quickly from unplanned, disruptive events. The latter reflects on the improved level of protection to future events. This dual definition for resilience to extreme weather events illustrates that adaptation measures can be focused on four different capacities of the urban system for decreasing its vulnerability: coping capacity (to handle disturbances when they take place), recovery capacity (to recover from disturbances after they have taken place), threshold capacity (to prevent damage by building a threshold resistance to disturbances) and adaptive capacity (to emphasize that the process of adaptation should be a continuous, long term process) (Voskamp & van de Ven, 2015).

The DAPP approach could give insights to possible implementation strategies or adaptation pathways, each with different strengths and weaknesses. It could also aid in protecting Heemskerk's community against pluvial flooding in the future. For this research, the DAPP approach provides a clear step-by-step method (from the Adaptive Policymaking approach) and an evident Adaptation Pathways map which can be presented to the municipality of Heemskerk.

Integrated sewage systems and overland flow models can provide municipalities with new insights into how the sewage system responds to increased rainfall events and how best to make the changes that will increase resiliency under more extreme climatic conditions (Ghbn, 2016). Thus, to investigate the effect of unburdening the sewage system and thereby increasing overland flow and infiltration during heavy rain events, an integrated model is required. D-Hydro Suite 1D2D is a new hydrodynamic simulation program, which can be used for simulating rainfall-runoff in urban environments (Deltares, 2019). Whilst potentially useful and powerful, the new model needs to be thoroughly tested and validated before it can be fully deployed. Hence, this research contributes to the development – testing and validation – of this new hydrodynamic modelling software, which could aid future decision-making in urban water management.

1.3 State of the art

Urban water management, specifically in the context of pluvial flooding, modelling and adaptation strategies, is at the frontier of contemporary water resources research and sets the framework of this study. Six studies especially relevant to this research are discussed below as well as how the findings have influenced the setup of this research.

Gersonius et al. (2012) conducted a case study in Dordrecht, the Netherlands, where they used ATPs to assess the adaptation potential of the stormwater system to climate change. They concluded that "quantifying the resilience of the existing stormwater system in terms of ATPs will improve the knowledge as to which responses and potential adaptations may be no-/low-regret, as it focuses the attention on the most urgent effects of climate change" (p. 6833). However, Gersonius et al. (2012) also stated that the adaptive potential will be different from the actual adaptive capacity, which includes socio-economic, political and physical factors.

Thus, this research will supplement the method of Gersonius et al. (2012) with the DAPP approach, which takes the social-economic, political and physical factors in consideration.

Previous research on pluvial flood risk within the management area of waterboard HHNK was conducted by Hoekstra Bonnema (2017). That study determined the extent to which retention of rainwater on private properties could reduce pluvial flooding in urban areas. Building upon Hoekstra Bonnema (2017), this research also includes municipal adaptation measures in the analyses. For both the adaptation pathways – where a distinction between public and private pathways can be made – and the municipality of Heemskerk, this adds valuable information regarding reduction of pluvial flood risk.

Arnbjerg-Nielson et al. (2015) compared the effect of implementing the Copenhagen municipality adaptation plan in different scenarios as well as the impacts of extreme precipitation in a business-as-usual scenario towards 2100. They concluded that business-as-usual was not an option, as the costs of damage in vulnerable areas would be too high. However, if the plan would be fully implemented, the city of Copenhagen would be well protected even in the high-end scenario. Building on the research of Arnbjerg-Nielsen et al. (2015), this research will compare the impact and effectiveness of multiple adaptation measures using integrated 1D2D-modelling. It will, however, not focus on whether adaptation measures are necessary given that this option was excluded by Arnbjerg-Nielsen et al. (2015).

Fraga et al. (2017) computed a rainfall-runoff transformation in urban environments by using a 1D2D dual drainage model and found that rain events that exceeded the capacity of the sewer network were appropriate to analyze both the response of the overland flow and sewage network as well as the interaction between them. The conclusion of Fraga et al. (2017) supports the methodology of this research in using the 2014 event for testing and validating D-Hydro Suite 1D2D.

Similar to this research, Yu et al. (2016) simulated an extreme precipitation event, including flooding due to direct runoff. They compared the results with incidents of flooding reported by the public via an online emergency system. This research aims not only to use a similar method for testing the new D-Hydro Suite 1D2D, but also to use the validated model to determine the impact of implemented adaptation measures.

1.4 Research aim and questions

Set against the background of the aforementioned body of research, this study aims to answer the following overarching research question:

Which Dynamic Adaptive Policy Pathways can be formulated for the municipality of Heemskerk, with a view to making its urban water system resilient towards 2050?

Based on this research question, two objectives and corresponding sub-questions are formulated. These are summarized in Table 1 and are both related to the DAPP approach. In order to formulate these pathways using the DAPP approach, Heemskerk's urban water system needs to be described and analyzed in order to identify its strengths and weaknesses. This will be achieved by modelling the urban water system using the new hydraulic modelling software D-Hydro Suite 1D2D. The first objective is to test whether the D-Hydro Suite 1D2D software is able to provide a valid simulation of the 2014 event. The second objective is to formulate the adaptation pathways for the municipality of Heemskerk including adaptation measures that fit the vision of the municipality as proposed in the 2017 water management plan and considering the W_H- and G_L KNMI '14 climate scenarios towards 2050.

Table 1: Objectives and corresponding sub-questions.

	Objective	Sub-question
1.	Test D-Hydro Suite 1D2D on its capability to simulate the 2014 event and validate its performance.	How well does D-Hydro Suite 1D2D simulate the 2014 event compared to the locations of actual reported flooding in the municipality of Heemskerk after the 2014 event?
2.	Formulate 'Adaptation Pathways' towards resilient urban water management in the municipality of Heemskerk considering the W_H- and G_L KNMI '14 climate scenarios towards 2050.	How do the 'Adaptation Pathways' towards a resilient urban water management in the municipality of Heemskerk differ considering the W_H- and G_L KNMI '14 climate scenarios towards 2050?

For the first sub-question, it is hypothesized that the simulated flooding locations give a 80% or higher resemblance compared to the actual reported flooding locations. Yu et al. (2016) found an overall similarity of 91,6% after comparing the reported flooding incidents with the predicted regions with a water depth greater than 2 cm. Aiming for a similar correspondence between results, it must be taken into account that D-Hydro 1D2D Suite is still a beta-version of the software and it might not be realistic to expect that high of a resemblance.

With regard to the second sub-question, it is hypothesized that the adaptation pathway for the W_H-scenario will contain more extreme adaptation measures than the G_L-scenario in order to reach the same level of resilience for pluvial flooding in the municipality of Heemskerk. This hypothesis is informed by the findings of Kwadijk et al. (2010) and Gersionius et al. (2012). Kwadijk et al. (2010) defined ATPs "*as points where the magnitude of change due to climate change is such that the current management strategy will no longer be able to meet the objectives. This gives information on whether and when a water management strategy may fail and other strategies are needed.*" (p 730). The W_H climate scenario is introduced by KNMI (2015) as more extreme, presuming that the ATP is reached earlier and other strategies, or adaptation measures, are needed. An example of this was given by Gersonius et al. (2012). Their results showed that different adaptation strategies were able to push back the ATPs and make the system performance acceptable towards the chosen climate scenarios.

1.5 Reader's guide

In chapter two, the methodology applied in this research is explained. Thereafter, the results are presented followed by a discussion of these results. Finally, conclusions are drawn and the overarching research question is answered with recommendations for the municipality of Heemskerk.

2 Methodology

2.1 General setup of methodology

Following the overarching research question and the corresponding objectives stated previously, the setup of the methodology for this research is based on the DAPP approach. The steps of the DAPP approach are visualized in Figure 4 and form the structure for the methodology sections below, where each section will correspond with one of the steps of the DAPP approach. However, this research will only address steps one to five. Steps six to ten are not included in this research, but the municipalities of Heemskerk will be encouraged to finalize the approach outside the scope of this research. Figure 5 provides a schematic overview of the setup of the methodology.

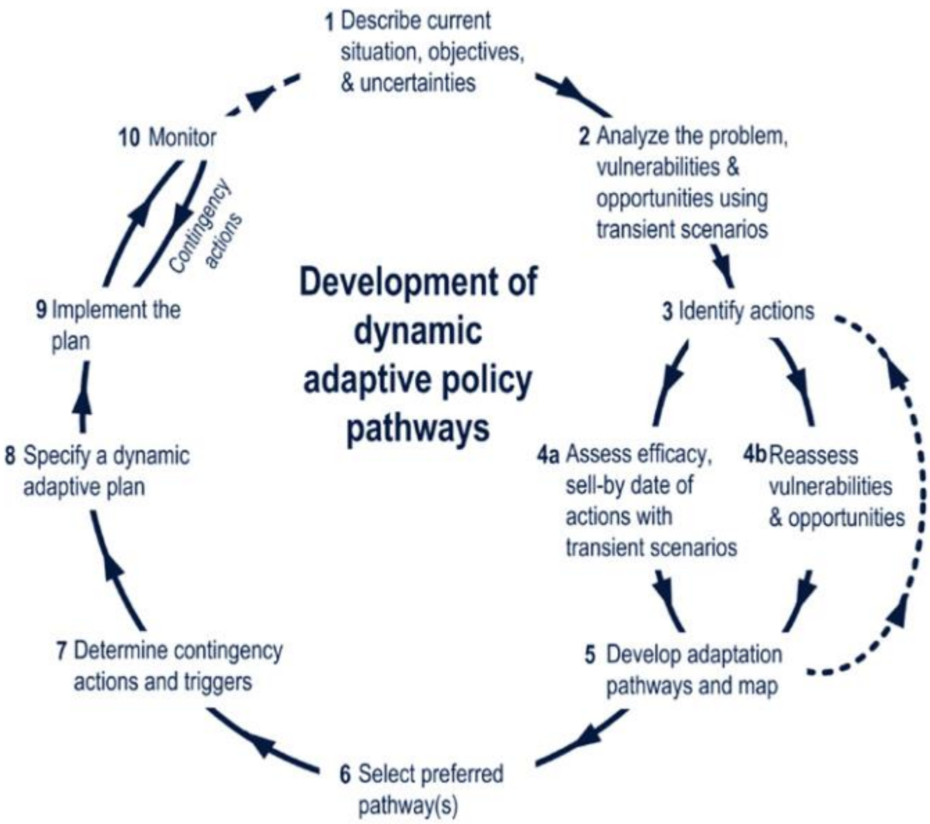


Figure 4: The Dynamic Adaptive Policy Pathways (DAPP) approach (Source: Haasnoot et al., 2013). Each step of the development of dynamic adaptive pathways is described. The arrows indicate the relation between the different steps.

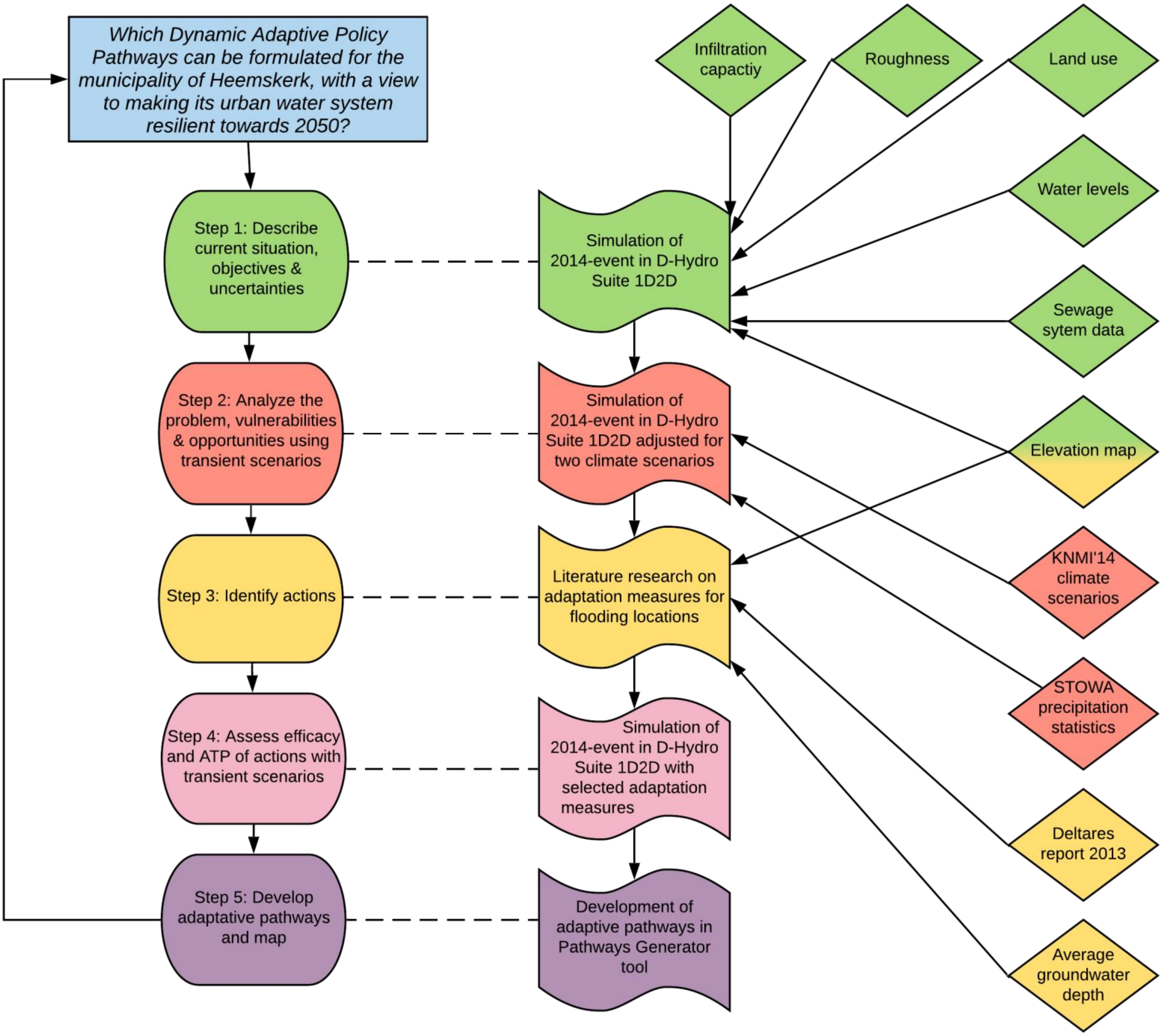


Figure 5: Setup of methodology. The round shapes show the first five steps of the DAPP approach. The flag shapes display the connected methods to the different steps. The diamond shapes show the required data. The different colors connect each step with its methodology and data.

2.2 Step by step methodology

2.2.1 Step 1: Describe current situation, objectives and uncertainties

"The first step is to describe the study area, including the system's characteristics, the objectives, the constraints in the current situation, and potential constraints in future situations. The result is a definition of success, which is a specification of the desired outcomes in terms of indicators and targets that are used in subsequent steps to evaluate the performance of actions and pathways, and to assess the 'sell-by dates' of the actions. The description of the study area includes a specification of the major uncertainties that play a role in the decision-making problem. These uncertainties are not restricted to uncertainties about the future, but can also cover uncertainties related to the data or models that are being used." (Haasnoot et al., 2013, p.489).

Model building

The description of the study area and the system characteristics were done by building an integrated 1D2D model in D-Hydro Suite 1D2D and simulating the 2014 event. D-Hydro Suite 1D2D, or D-Hydro, is currently in its beta development phase and additional testing and validation of the different modelling functions is necessary. D-Hydro claims to be able to provide an integrated 1D2D model (also called 2D-1D or 1D-2D+ model, see Figure 6), meaning rainfall on roofs is directly connected with the sewage system (0D), while the remainder of the rain is modelled as overland flow, either connected to the sewage system via gullies or drains, or leaving the system via infiltration or surface water (Stichting Rioned, 2019a). The sewage model is one dimensional, while the overland flow is modelled as 2D. This is the most extensive way of modelling urban water systems.

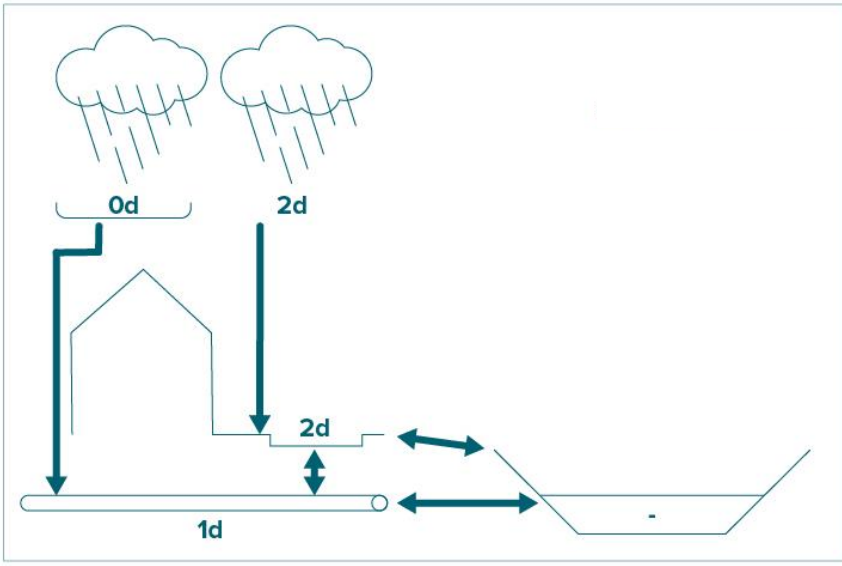


Figure 6: 1D-2D+ model without coupling with surface water (source: Stichting RIONED, 2019a). The figure shows how all components of the 1D-2D+ model are included. Rainfall is modelled both as 0D, meaning that rainfall on roofs is directly connected to the sewage system, and in 2D, which indicated flow over the grid. The sewage system is modelled in 1D. The arrows indicate interaction between the different components.

Other modelling software like InfoWorks ICM and 3Di also have options for this type of modelling, but D-Hydro may be preferred over these alternatives because of the software's more affordable and competitive pricing.

Building the model for the 2014 event simulation was divided in two parts: building the 1D sewage network and building the 2D grid for overland flow. Data for the 1D sewage network was provided by the municipality of Heemskerk as shapefiles of the manholes, pipes and special structures such as weirs, outlets and pumps. This data was acquired by the municipality from their management and maintenance program Obsurv. The shapefiles included information on the locations of manholes and pipes, depth of pipes, diameters of pipes and materials, as well as crest widths and crest heights of weirs. Since this research focusses on pluvial flooding, the wastewater pipes from the separated system, the connection with houses, large drainage systems (underneath sports fields) and culverts were taken out of the analysis. This adjusted selection of pipes, manholes and structures was imported into Sobek2.16 (Deltares, 2018) where the model was checked, adjusted if necessary and exported in the D-Hydro import format (GWSW).

The 2D grid was built in the D-Hydro general user interface (GUI) by shaping a polygon covering the research area and therein generating the grid with three meter by three meter grid cells. This 2D grid consisted of 1.594.973 cells and was linked to the 1D sewage network by links between the manholes at the start of each pipe and its overlying grid cell. A three meter resolution is very large for modelling urban water systems, since important details (mainly in bed level) are lost with the interpolation. For example, speed bumps and sidewalks are not distinguished, possibly underestimating the water depth on streets. Unfortunately, D-Hydro was not yet able to run this model with a smaller grid size.

The precipitation of the 2014 event peaked at 54,1 mm in one hour. This total amount of precipitation was divided per five minutes following the built-up of test event "Bui07" with a peak in the first half hour. Prior to this peak of 54,1 mm/hour it already had been raining (19,1 mm in one hour) (Meteobase, 2020) and thereby filling the sewage system. This was simulated in the model by adding the test event "Bui08", with a similar total volume, before the actual peak, as shown in Figure 7. "Bui07" and "Bui08" are both standardized precipitation events designed by Stichting RIONED used to test the hydraulic capacity of sewage systems (Stichting RIONED, 2019b). A more detailed table with precipitation data per five minutes is provided in Appendix F. The precipitation was modelled in both 1D and 2D, meaning that the precipitation on roofs was directly connected to the 1D sewage system, while the precipitation on the 2D grid (in mm/day) was modelled everywhere except the roof areas to prevent overestimation of the total precipitation volume. For the initial conditions temperature was set at 16°C, based on historical weather data (KNMI), and evaporation at 0,16 mm/hour.

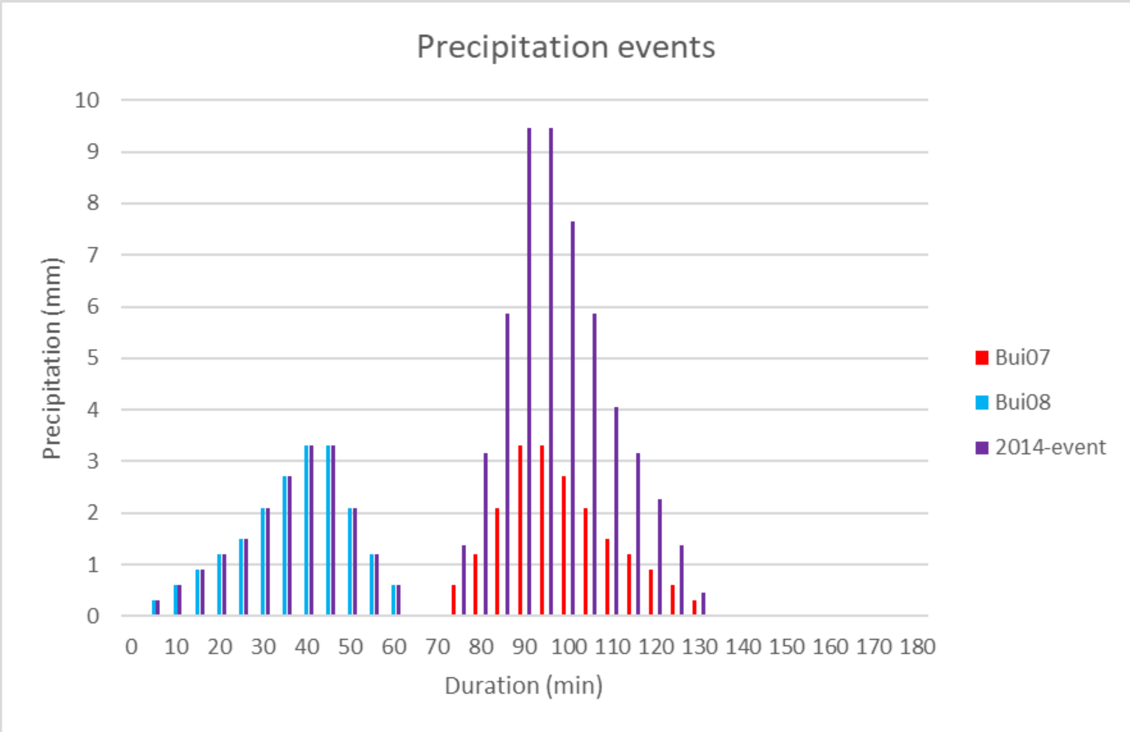


Figure 7: Precipitation events (Source: Stichting RIONED and Meteobase). This graphs shows how the total precipitation volume of the 2014 event was divided per five minutes based on the Bui07 and Bui08 standards. The first peak of the 2014 event is similar to Bui08, while the second peak has the same built-up as Bui07 but with a larger volume.

Other data that was attached to the grid includes bed level, roughness, infiltration capacity and initial water levels. Bed level was obtained from the Dutch digital elevation map – AHN (Actueel Hoogtebestand Nederland) or Dutch bed level registration – as a Digital Terrain Model (DTM), meaning that for example houses and trees were not included (see Figure 8). For the analysis, however, the elevation of buildings should be considered since these obstruct overland flow. Therefore buildings were elevated by 10 meters in QGIS 3.4 (QGIS Development Team, 2018). The map with the elevation levels in Heemskerk at a 0,5 m by 0,5 m resolution is attached in Appendix A.

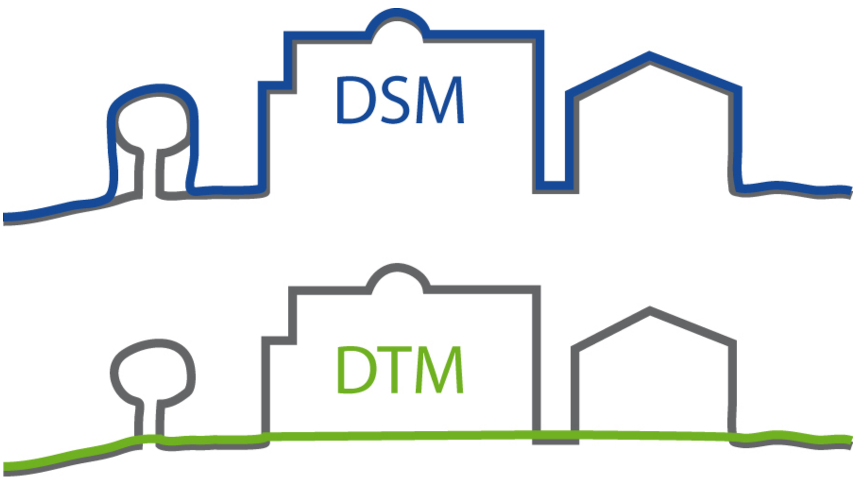


Figure 8: Difference between Digital Surface Model (DSM) and Digital Terrain Model (DTM). In a DSM, all objects and their elevation are included while DTM focusses on the bed level without objects. (Source: 3DMetrica, 2017).

Roughness data was based on land use maps and roughness constants with Manning unit (Stichting RIONED, 2019c). A distinction was made between fifteen classes of roughness such as, among others, unpaved, open paved, closed paved, grassland, forest and agricultural lands. The full table with all classes and corresponding values for roughness can be found in Appendix B. Data on infiltration capacity was provided by waterboard HHNK in mm per day, ranging from zero (closed paved) to 300 mm/day (forest) on a one by one meter resolution. A graphical overview of the infiltration capacity is attached in Appendix C.

Initial water levels were also provided by HHNK and are based on their target surface water level areas. A map of the initial water levels is included in Appendix D. These values determine to what extent the sewage system is able to discharge in surface water via external weirs. These values are constant over time, since there was no interaction with surface water included in this research. It is expected that the discharge was overestimated due to this assumption, because surface water levels are expected to rise during heavy rainfall.

In order to link all data sets to the three by three meter grid the data was interpolated using the averaging method for bed level, infiltration capacity and initial water level. For roughness the data set included some missing values and so the triangulation interpolation method was used. Since the D-Hydro GUI was not yet able to run the simulation including the data sets mentioned above, the model was run via the Deltares Integrated Model Runner (DIMR) export where all functionalities could be included. The model time was set to three hours with a calculation time step of one minute. The output was generated every five minutes.

System analysis

The results of the 2014 event simulation were validated by comparing them to both the actual reported flooding and the Climate Impact Atlas (Klimaateffectatlas). This atlas shows pluvial flooding in Heemskerk as a result of a 1-100 years event, based on a 2D overland flow model with constant sewage system storage and discharge capacity of 20 mm/h (Stichting Climate Adaptation Services, 2018). The comparison of the 2014 event simulation results with the actual reported flooding locations in 2014 was conducted in QGIS 3.14 (QGIS Development Team, 2020). 1475 random samples (five times five random samples per polygon) were taken from the polygons that indicate the flooding locations. For each of these samples was assessed whether water depth on this location was under or above the allowed water depth, or the definition of success (as part of the DAPP approach). The percentage of samples that were indicated as flooding locations in the simulation results was used to accept or deny the first hypothesis as stated in Section 1.4.

Validation of the results of the 2014 event simulation was used to identify strengths and weaknesses of the system as well as the model. The objectives for future situations are based on the water and sewage plan of the municipality of Heemskerk.

2.2.2 Step 2: Analyze the problem, vulnerabilities and opportunities using transient scenarios

"In this step, the current situation and possible future situations are compared to the specified objectives to identify whether there are any gaps. The possible future situations are 'reference cases' assuming no new policies are implemented, and consist of (transient) scenarios that span the uncertainties identified in step one. A gap indicates that actions are needed." (Haasnoot et al., 2013, p. 490).

As introduced in Section 1.1, this research used the KNMI W_H- and G_L-scenario in order to see how climate change will affect extreme events towards 2050. Three tables with precipitation statistics for the current climate and for the two climate scenarios are included in Appendix E (Beersma et al., 2019). The precipitation statistics show that a precipitation volume of 58 mm in one hour corresponds with a return period of one hundred years in the current climate. In order to calculate the precipitation events considering the two climate scenarios, the precipitation volume of the 2014 event was multiplied by a climate factor of 1,0345 for the G_L-scenario and 1,2069 for the W_H-scenario, both based on the predicted precipitation volume for 2050. The precipitation events can be found in Appendix F.

The results from the two climate scenario simulations were compared and used to define the ATP based on extra storage that is needed towards 2050 to prevent that similar events cause pluvial flooding. In order to more easily compare the three simulations three locations were chosen to zoom in to, based on the difference in elevation and groundwater depth and because these are all locations where flooding was reported after the 2014 event. The locations are shown in Figure 9 below.

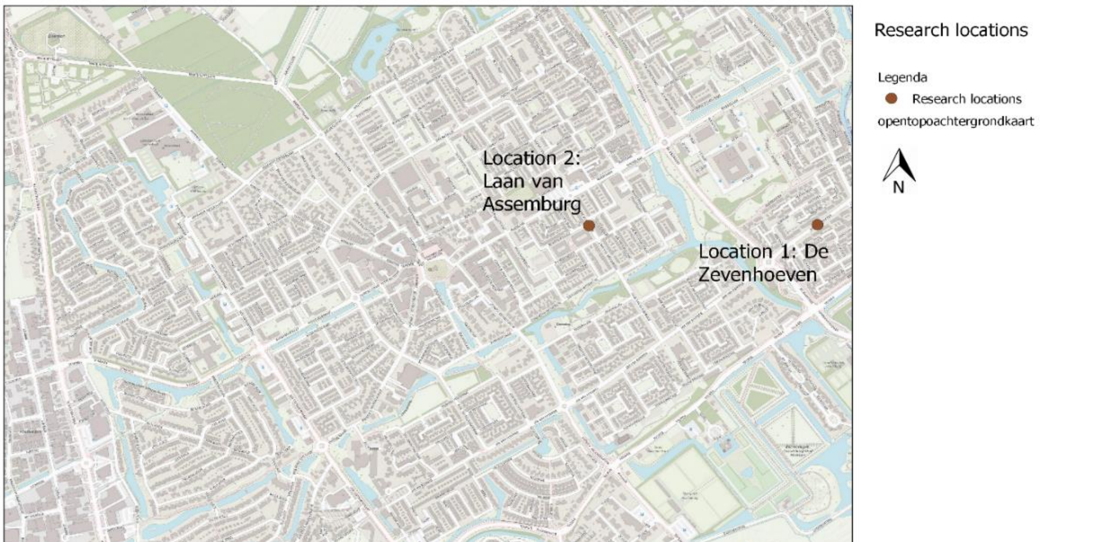


Figure 9: Research locations in the municipality of Heemskerk.

For each study location the catchment area was determined by looking into the flow velocity vectors over the grid. Maps of these catchments are included in Appendix G. The ATP was estimated by calculating the difference between the maximum water depth on each location and the allowed water depth towards 2050 (or the definition of success). This difference was then converted into a unit of millimeters extra storage per hectare, based on the area of the catchment. As defined by Vergroesen et al. (2013), 10 mm per hectare requires extra storage of 50 m^3 assuming that fifty percent of the area runs off (only paved area). This rule of thumb was used to define the amount of storage in m^3 needed for each location.

2.2.3 Step 3: Identify actions

"In the third step, one identifies possible actions that can be taken to meet the definition for success. These actions can thus be specified in light of the opportunities and vulnerabilities previously identified." (Haasnoot et al., 2013, p. 490).

A first selection of adaptation measures was made from a list of 44 measures in the 2013 Deltares report based on the possibilities and restrictions in Heemskerk (Vergroesen et al., 2013). Meaning, the measures should be implemented on small scale, such as home, street or neighborhood scale, the measures must be suitable for urban area, the adaptation measures should be able to be implemented in existing neighborhoods or during sewage maintenance constructions and finally, the adaptation measures selected can all be managed and maintained by private homeowners or the municipality. The second selection was location-based, meaning that slope and groundwater depth were taken into consideration. The slope was estimated from the bed level, where a division was made between no slope, top of the slope, flank of the slope and the foot of the slope. In the municipality of Heemskerk there is a clear zero meter sea level line, where the area east of this line is below sea level and the area west of this line is above sea level (see also Appendix A). Therefore, the east of Heemskerk was classified as no slope, around the zero meter sea level line is classified as foot of the slope, the highest parts of Heemskerk in the south-west are classified as top of the slope and the area between the zero meter sea level line and this top is seen as flank of the slope. The groundwater depth was obtained from previous groundwater research conducted by Wareco Ingenieurs for the municipality of Heemskerk. A map of these groundwater depths is included in Appendix H.

2.2.4 Step 4: Assess efficacy and ATP of actions with transient scenarios

"The fourth step is to evaluate the actions. The effects of the individual actions on the outcome indicators are assessed for each of the scenarios and can be presented using scorecards. The results are used to identify the sell-by date for each of the actions." (Haasnoot et al., 2013, p. 490).

Ideally all selected adaptation measures would be tested in D-Hydro to see the effect on the water depth. However, since not all functions were available in the D-Hydro GUI during this research, the possibilities to simulate adaptation measures were limited. Therefore three adaptation measures were tested in D-Hydro, while the efficacy of other adaptation measures was found in literature and based on the findings from simulations with adaptation measures. The simulation was used to test the efficacy of the measures by looking into the change in water depth on the three study locations and a change in pattern or redistribution of water. The tested adaptation measures were 'Underground storage', 'Lowered roads' and 'Wadis' on research locations De Zevenhoeven, Laan van Assemburg and De Veste, respectively. The selection for which adaptation measure was implemented on which location was conducted by looking at the characteristics of each research location and the requirements for implementing the adaptation measure. Groundwater depth and relief were the most defining characteristics in this study.

The measure 'Underground storage' was simulated by adding an extra rectangle pipe to the 1D sewage system with dimensions of 35,68 m by 9 m by 0,8 m, which resulted in additional storage of 256 m^3. The pipe had a weir with a height of 1 m and also 9 m width to make sure the storage pipe was filled by the connected system, but the water would not be able to return into the system. Since this research is less interested in the depletion of the system, no pump was added to this storage which is common for this measure. All other components of the model were similar to those of the 2014 event simulation. The 'Lowered roads' were simulated by adjusting the bed level with ten centimeters over an area of 4942 m^2 resulting in 480 m^3 extra storage. The amount of storage was deliberately overestimated, since it was expected that the actual storage would decrease due to the interpolation towards three by three meter grid cells. Lastly, the 'Wadis' were simulated by lowering the bed level with twenty centimeters on three locations, creating three wadis with each dimensions of 30 m by 15 m and a total additional storage of 270 m^3. Also, pipes were attached to the 1D system to simulate depletion of the wadis.

In order to estimate the contribution of each simulated adaptation measure to the ATP, the change in water depth on the research locations was converted into a unit of volume (m^3) with a similar method as explained in Section 2.2.2. The efficacy was based on the change in water depth in the entire catchment. Costs, constraints and side effects were found from literature. The other adaptation measures that could not be tested by a simulation were scaled with the three tested adaptation measures, meaning that based on their functionality and approach (infiltration, storage on or below surface etc.) the contribution to ATP and efficacy were estimated by making an educated guess.

2.2.5 Step 5: Develop adaptation pathways and map

"The fifth step is the assembly of pathways using the information generated in the previous steps." (Haasnoot et al., 2013, p.490).

For the fifth step the ATPs of the adaptation measures are combined in one adaptation pathways map to provide an overview of possible implementation pathways towards resilient urban water management in the municipality of Heemskerk in two different climate scenarios. The scope of this research did not allow to include a temporal variation in adaptation pathways, like the example of Figure 2, and are based on their contribution to the ATP as extra storage. Deltares' Pathways Generator tool was used to design this map (Deltares, 2017). These maps provide the information to reject or accept the second hypothesis and by translating the aim of the municipality of Heemskerk to make the urban water system resilient towards 2050 into the adaptive pathway that is most suitable for the municipality, the overarching research question was answered.

3 Results

3.1 Setup of results

Following the steps of the DAPP approach as described in the previous Sections 2.2.1 to 2.2.5 the results are presented in a similar structure: starting with the system analysis, followed by the transient scenarios, selected adaptation measures and their efficacy and concluding with the adaptation pathways map. How these results relate to the research question is assessed in the discussion.

3.2 System analysis

Figure 10.A shows the results of the 2014 event simulation in D-Hydro after 180 minutes, after two hours of rain and one dry hour, with water on streets throughout the municipality. The darker colors show that some neighborhoods experience higher water depths than others. Figure 10.B shows the Climate Impact Atlas with water on streets after a 1-100 years precipitation event with two hours of rain and four dry hours. Comparing the two figures shows a similar pattern, but overall Figure 10.B estimates more water on streets. An additional overview map from 60 minutes into the 2014 event is included in Appendix I.

Figure 11.A shows the results of the 2014 event simulation after 120 minutes, just after the highest precipitation peak. The red patches in Figure 11.B indicate where flooding was reported in 2014. Although more locations show water on streets than the reported flooding locations, most reported locations are also simulated with significant water depth. In the municipality water and sewage plan it is stated that the municipality wants to be prepared for events similar to that of 2014, meaning they want to prevent flooding in the future. As Figure 11 points out, there is more water on streets than is actually considered nuisance by flooding. For the formulation of success this means that there can be some inundation, but there is a maximum of 10 cm of water on streets as a result of events with the same return period as the 2014 event (1-in-100 years). This value is similar to the value in the analysis of Arnbjerg-Nielsen et al. (2015).

The quantitative analysis of the actual reported flooding locations compared to the simulation results of the 2014 event found that 44,5% of the random samples on flooding locations had a water depth of minimal 10 cm.

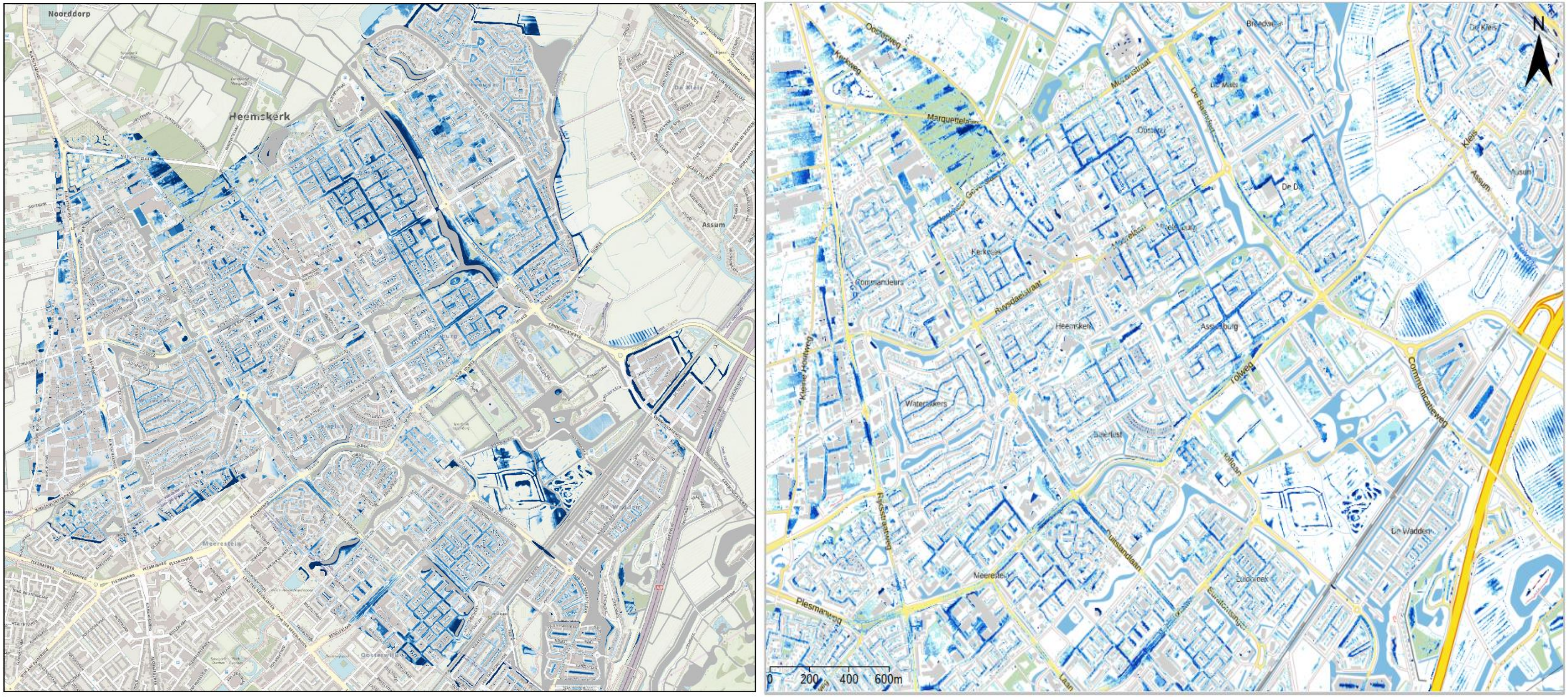


Figure 10: Map A (left) is the results of the 2014 event simulation after the full simulation period of three hours. Map B (right) is the Climate Impact Map. Both maps use the same legend.

Water depth at pressure points (m)

- 0
- 0.05
- 0.1
- 0.15
- 0.2
- 0.3

N

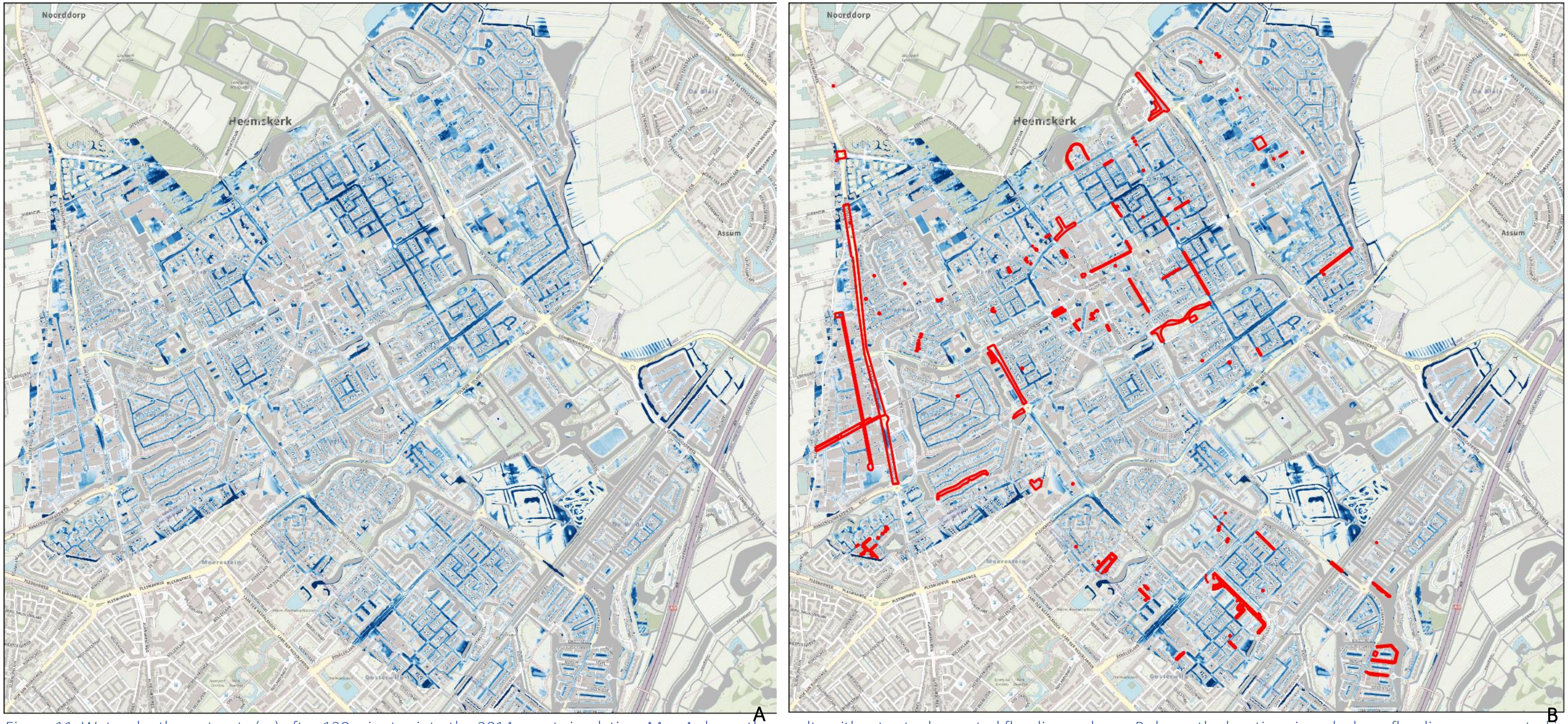


Figure 11: Water depth on streets (m) after 120 minutes into the 2014 event simulation. Map A shows the results without actual reported flooding and map B shows the locations in red where flooding was reported in 2014.

Legenda

2014_event

Water depth at pressure points (m)

- 0
- 0.05
- 0.1
- 0.15
- 0.2
- 0.3

Reported flooding locations

N

0 0,5 1 km

3.3 Transient scenarios

In this section the two climate scenarios, G_L and W_H, are compared to each other as well as to the performance of the current system. Based on the results the ATP, in terms of extra storage that is needed in order to prevent nuisance due to pluvial flooding, is determined. Figure 12 shows the difference between the water depths in the W_H-scenario and the G_L-scenario. Although differences are generally small, overall water depth in the W_H-scenarios was higher than in the G_L-scenario. The pattern of water on streets is considered similar in both scenarios.

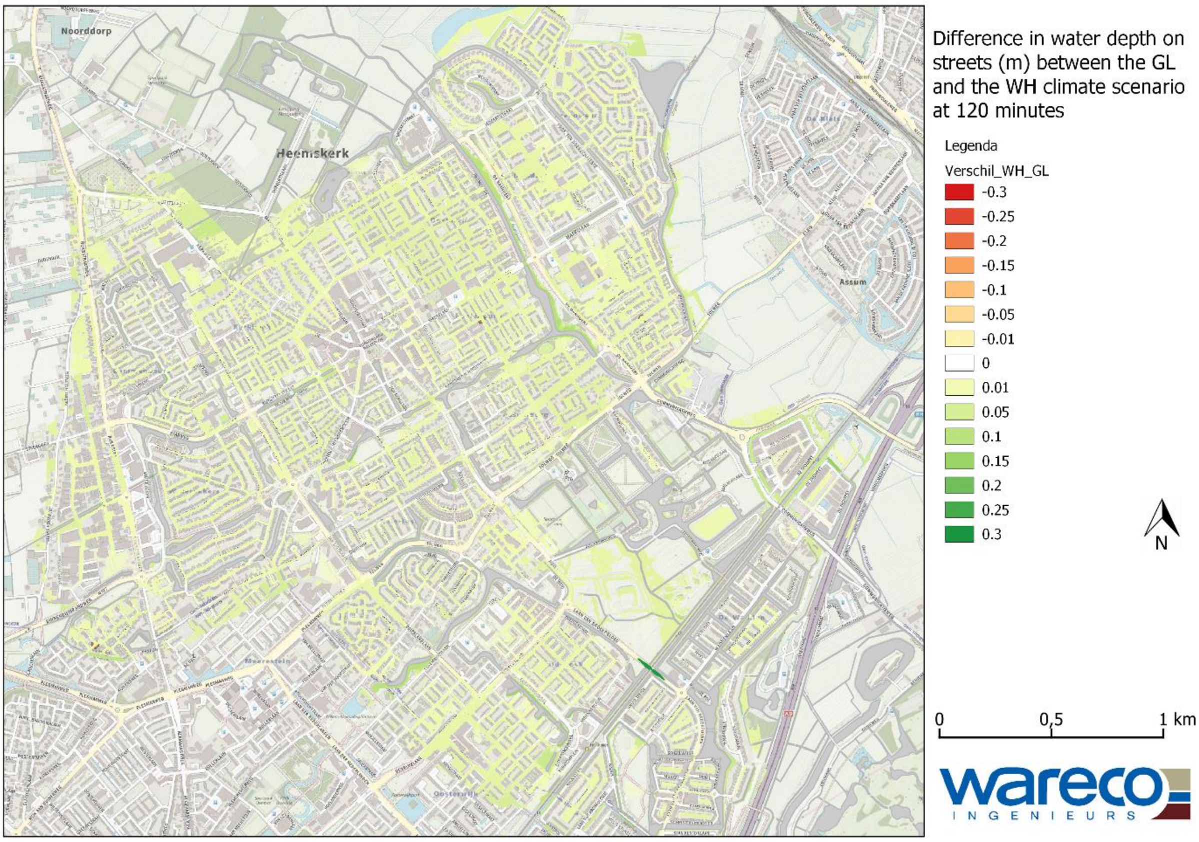
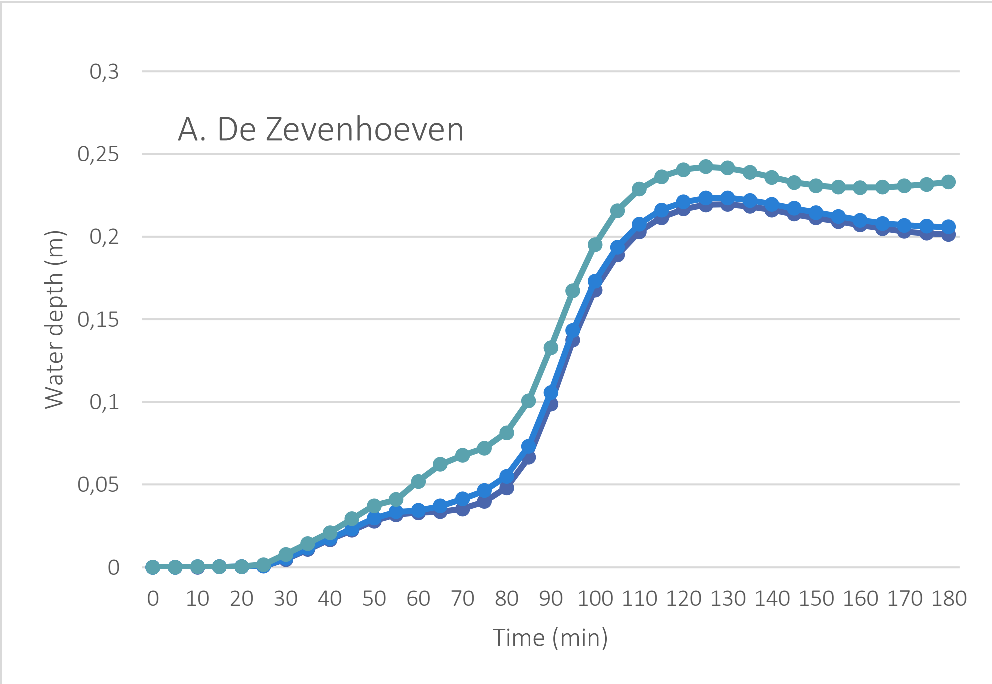
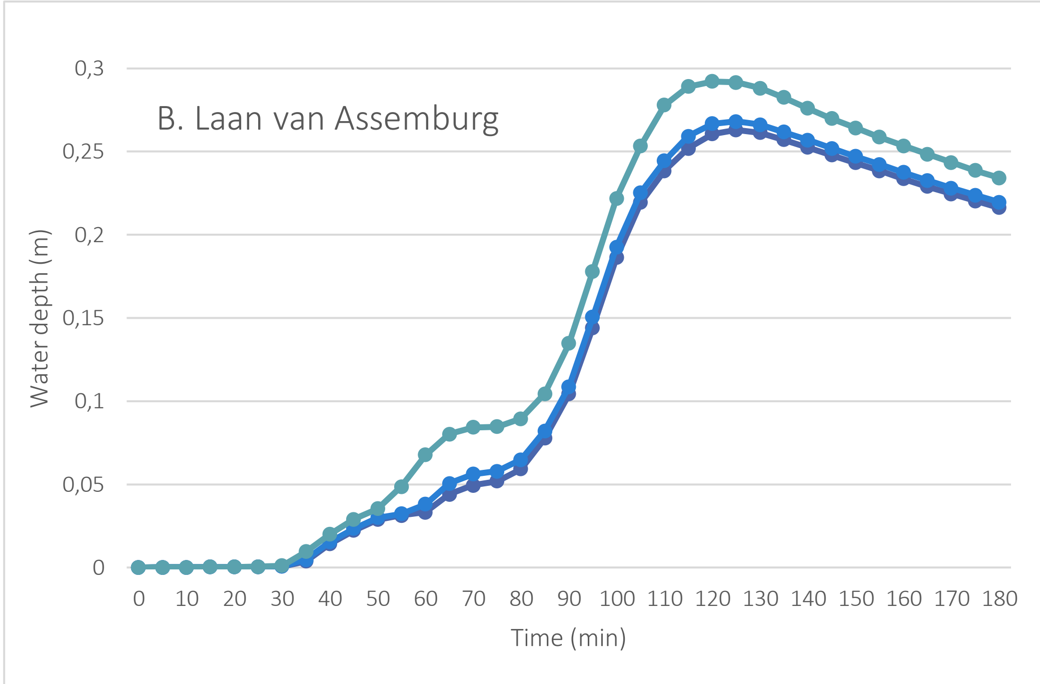


Figure 12: Difference in water depth on streets (m) between the G_L- and the W_H-climate scenario after 120 minutes of the simulation. Red colors indicate a negative difference, meaning that the G_L-scenario simulation calculated a higher water depth. Green colors indicate a positive difference, meaning that the W_H-scenario simulation calculated higher water depth.

In order to see the difference between both the two climate scenarios and the simulation of the 2014 event, the water depths of the three research locations introduced in Section 2.2.2 are shown over time in Figure 13. All three locations show that the G_L-scenario does not differ much from the 2014 event. However, the W_H-scenario shows both higher water depths as well as a different pattern over time.

Based on the difference between the simulated water depth and the allowed water depth on streets of 10 cm for the formulation of success, the ATPs for the current situation and towards 2050 are shown in Table 2.





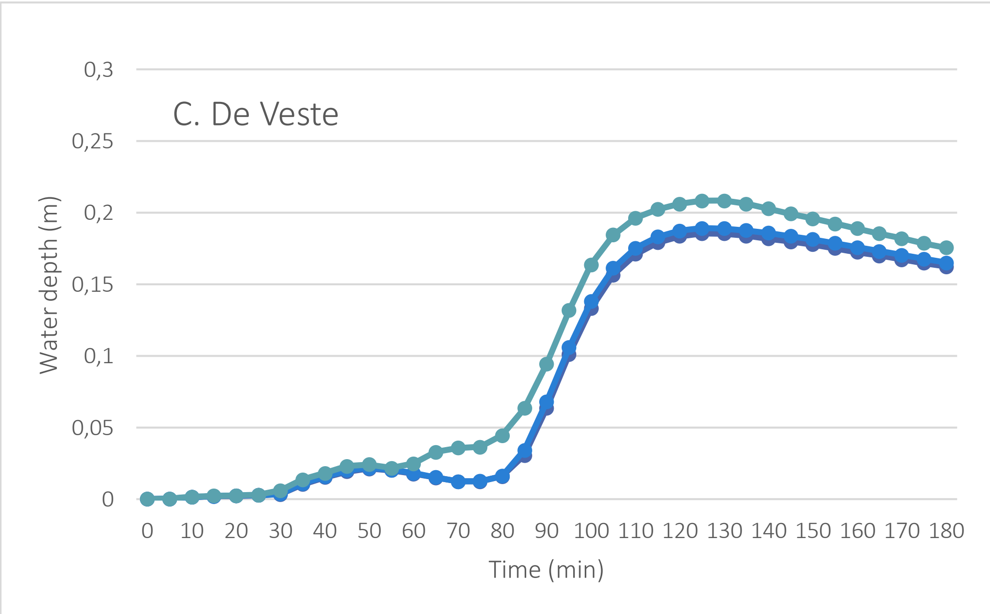


Figure 13: Water depth on streets (m) over time on three research locations in the 2014 event compared to two climate scenarios.

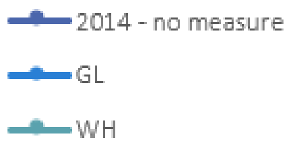


Table 2: ATPs for the current situation and towards 2050 based on two climate scenarios (G_L and W_H) for the three research locations.

Location	ATP (current)	ATP (G_L-scenario)	ATP (W_H-scenario)
De Zevenhoeven	250 m^3	260 m^3	300 m^3
Laan v. Assemburg	230 m^3	235 m^3	270 m^3
De Veste	280 m^3	295 m^3	355 m^3

3.4 Adaptation measures

The municipality of Heemskerk describes in their 2017-2021 policy that they want to process rainwater in the most natural way, meaning that water is retained or, when necessary, discharged with delay to natural low areas (Cruz et al., 2017). Voskamp & van de Ven (2015) refer to adaptation measures that make use of natural processes as green or blue adaptation measures. These green or blue measures can produce significant co-benefits, such as a cooling effect or be combined with other land use functionalities, while grey measures (concrete structures, pumping stations) tend to be effective but mono-functional. Considering the preference of the municipality for green or blue adaptation measures, physical constraints and the maintenance party, a selection of eight adaptation measures was made. A table of the selected adaptation measures together with their score on preferred conditions is included in Appendix L. The description of the adaptation measures below was based on Vergroesen et al. (2013).

3.4.1 Underground storage

Although many forms of underground storage are possible, this research will focus on a storage of rainwater in an underground tank (Figure 14). The volume of such tanks can vary between several cubic meters to ten thousand cubic meters.

Figure 14: Underground storage tank. (Source: Vergroesen et al., 2013)

3.4.2 Lowered roads

Precipitation can be stored in lowered streets in a controlled way between the sidewalks. Speed bumps can make sure the water does not flow away to naturally lower areas too fast, but this measure works best in non-sloping areas. The road can either be lowered over the total width – limited by the maximum height of the sidewalk for the safety of pedestrians –, or in a v-profile creating water flow in the center of the road, see Figure 15. This decreases nuisance by splashing water and keeps the road better accessible for cars.

Figure 15: Lowered road with v-profile. (Source: Amsterdam Rainproof, 2020a)

3.4.3 Storage under roads

Below permeable pavements precipitation can be stored in a coarsely porous medium or infiltration crates (Figure 16). Emptying of this underground storage is based on infiltration. An advantage over the measure of storage on the roads is that the streets are well accessible and that there is no nuisance of gushing water. Similarly, this measure is preferably implemented in non-sloping area.

Figure 16: Storage under roads with infiltration crates. (Source: Vergroesen et al., 2013)

3.4.4 Rain barrels

Rain barrels can be used to store rainwater coming from roofs, see Figure 17. While individual storage is limited, it can unburden the sewage system when used on greater scale. Also, rain barrels can provide local irrigation water, but preferably the rain barrel should be empty prior to heavy rain events. Rain barrels can also help to increase awareness about pluvial flooding and droughts (Klimaatklaar, n.d.).

Figure 17: Rain barrel. (Source: Vergroesen et al., 2013)

3.4.5 Infiltration transport pipes

Infiltration transport pipes are perforated pipes which causes a part of the water to infiltrate into the groundwater along the way (Figure 18). In contrast to normal sewage pipes, these pipes lay horizontally to increase infiltration. During heavy precipitation part of the water will end up in surface water too, because flow velocity is too high to infiltrate. An advantage of this measure is that there is no above ground disturbance.

Figure 18: Infiltration transport pipe. (Source: Vergroesen et al., 2013)

3.4.6 Wadis

A wadi is a wide, shallow depression in a grass field where precipitation is collected (Figure 19). Here it will infiltrate into the ground and discharged by underlaying drainage into nearby surface water. A direct connection between the drain and the top layer functions as emergency spillway in case the wadi is full.

Figure 19: Wadi. (Source: Amsterdam Rainproof, 2020b)

Figure 20: Permeable paved surface. (Source: Vergroesen et al., 2013)

Figure 21: Rainwater tiles for controlled overland flow (Source: Struyk Verwo Infra, n.d.)

3.4.7 Permeable paved surface

Permeable paved surface is meant to increase infiltration of precipitation through the grouts of tiles and road bricks. Open asphalt can be effective during both high and low intensity precipitation, while permeable pavement is mostly effective during lower intensity rainfall. The infiltration decreases the total runoff into the sewage system. Figure 20 is an example of permeable paved surface.

3.4.8 Parks and green strips

Parks and green strips can store runoff from streets and roofs. Although variations of this measure are possible, this research will consider disconnection of roofs from the sewage system and controlled overland flow in designated rainwater tiles with a notch (see Figure 21) into a local green strip or wadi.

3.5 Efficacy and ATP of adaptation measures

The selected adaptation measures from Section 3.4 were evaluated on their efficacy, costs, constraints, contribution to the ATP and possible side effects. The results of this evaluation will be discussed in the following sections and are summarized in Table 3.

As described in Section 2.2.4 evaluating the efficacy of the adaptation measures was done by looking into the results of the simulated adaptation measures with respect to the redistribution of water and the actual change in water depth on the research locations. The adaptation measures that were not tested in a D-Hydro simulation are scaled between the three tested measures, based on literature findings and the simulation results of the three measures. The change in water depth was converted into the contribution to the ATP with a similar method as the calculation for the overall ATP. The costs, constraints and possible side effects are based on literature findings.

3.5.1 Underground storage

Figure 22 shows the three research locations, De Zevenhoeven, Laan van Assemburg and De Veste (see Figure 9), where 'Underground storage', 'Lowered roads' and 'Wadis' were implemented, respectively. Figure 23 shows the water depth on each of these locations over time with and without the adaptation measure. For the first location, De Zevenhoeven, Figure

22.A without adaptation measure and Figure 22.B with underground storage show overall a very similar pattern and also Figure 22.C does not show much difference between the two maps. However, Figure 23.A, which shows the water depth over time, shows that although after 120 minutes there is indeed little difference in water depth, the first peak results in lower water depth (decrease of 0,009 m). Considering this, it can be said that underground storage can indeed lower water depth on streets by taking water out of the system, but placement and timing of the storage are important. Looking at the results in Figure 23.A, it could be possible that the underground storage was already full after the first peak, meaning it did not have any effect during the second peak. Costs for underground storage consist, among others, of the costs for the material and construction and for the excavation and are estimated at €420/m^3 (Stichting RIONED, 2015a). For the underground storage considered in this research initial costs without maintenance would be estimated at €107.805,-. Since the storage is underground there is no conflicting land use, but also no positive side effects to this measure.

3.5.2 Lowered roads

On the second location, Laan van Assemburg, Figure 22.D, 22.E and 22.F show the results of the implementation of the lowered roads measure. Figure 22.F shows that in the lowered roads there is a redistribution of the water: the difference is positive in the middle where the change in bed level was implemented, while on the sides the difference in water depth is negative, meaning that it decreased compared to the simulation without adaptation measure. However, there is a small difference in water depth (0,007 m) on the research location itself, see also Figure 23.B, which shows that in this case the adaptation measure was only effective where it was implemented, without affecting the water depth on other locations. For this adaptation measure the following constraints should be considered: a minimal groundwater depth is necessary and in a sloping area this measure could cause uncontrolled discharge (Vergroesen, et al., 2013). The costs of this measure consist of excavation costs and repaving of the street and are estimated at €26,33/m^2. However, with a depth of 10 cm, still a surface of 2500 m^2 is necessary to reach the aimed 250 m^3 of extra storage (Table 2). Total costs would be estimated at €65.825,-.

3.5.3 Wadis

At the third location (De Veste, Figure 22.G, 22.H and 22.I) wadis were implemented and the maps show how the wadis are filled with water, while the water depth decreased downstream in the neighborhood. This decrease in water depth due to the extra storage in the wadi is also visible in Figure 23.C, which shows a lower water depth on the research location over the total time frame with a maximum decrease of 0,02 m. The costs for implantation of wadis are estimated at €53/m^3 and include replacing old materials with more permeable material and all labor that is involved, such as excavation (Stichting RIONED, 2015b). For 250 m^3 extra storage the total costs would be estimated at €13.250,-. Important to consider is the minimum groundwater depth that is required for this adaptation measure. On the other side is groundwater recharge one of the positive side effects of this measure, as well as possible combined land use and cooling of the urban area.

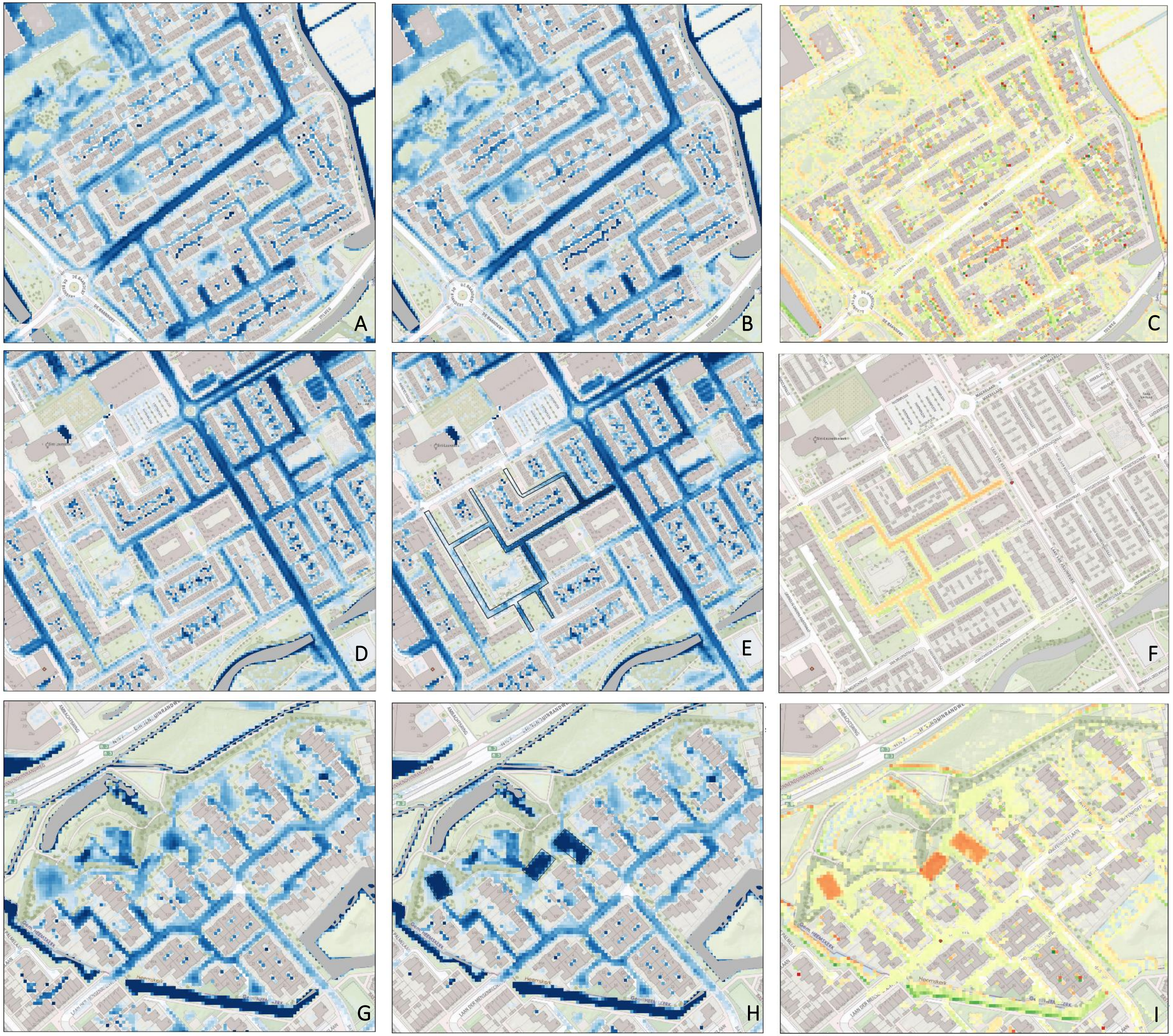
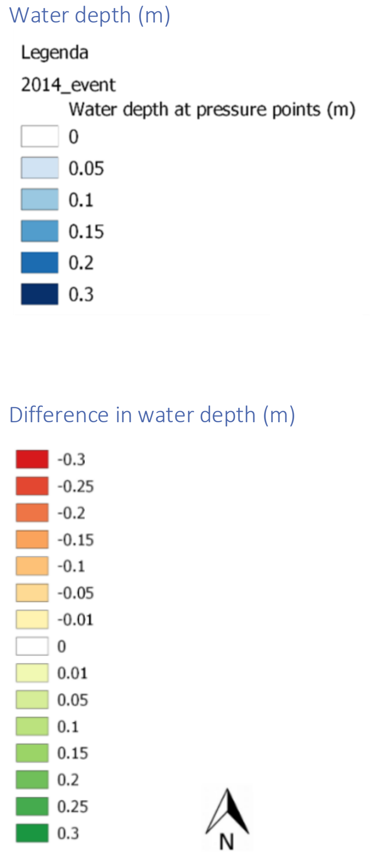
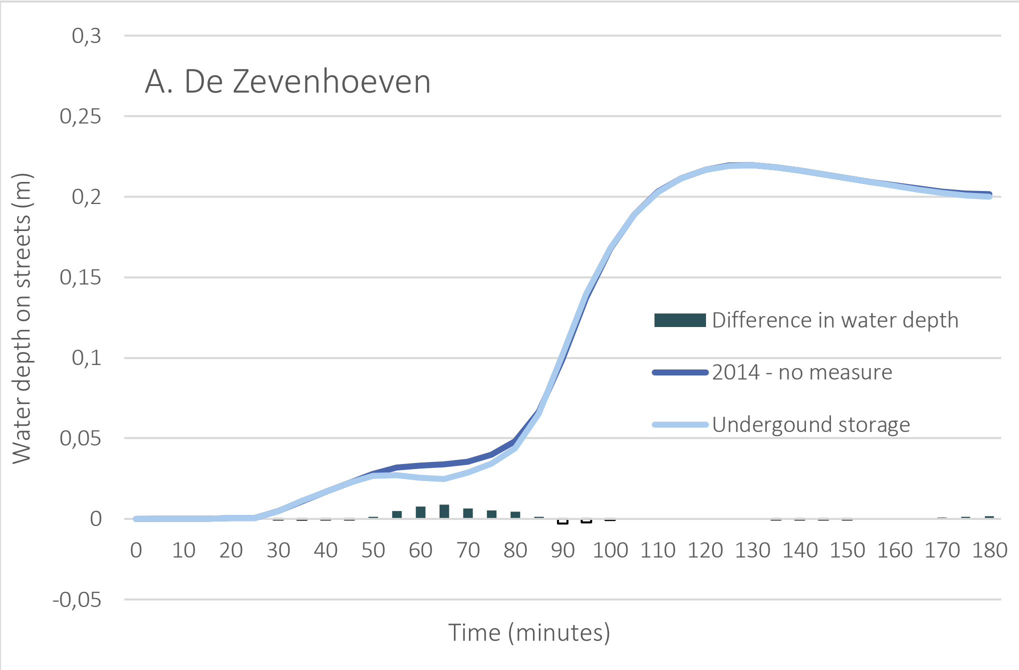
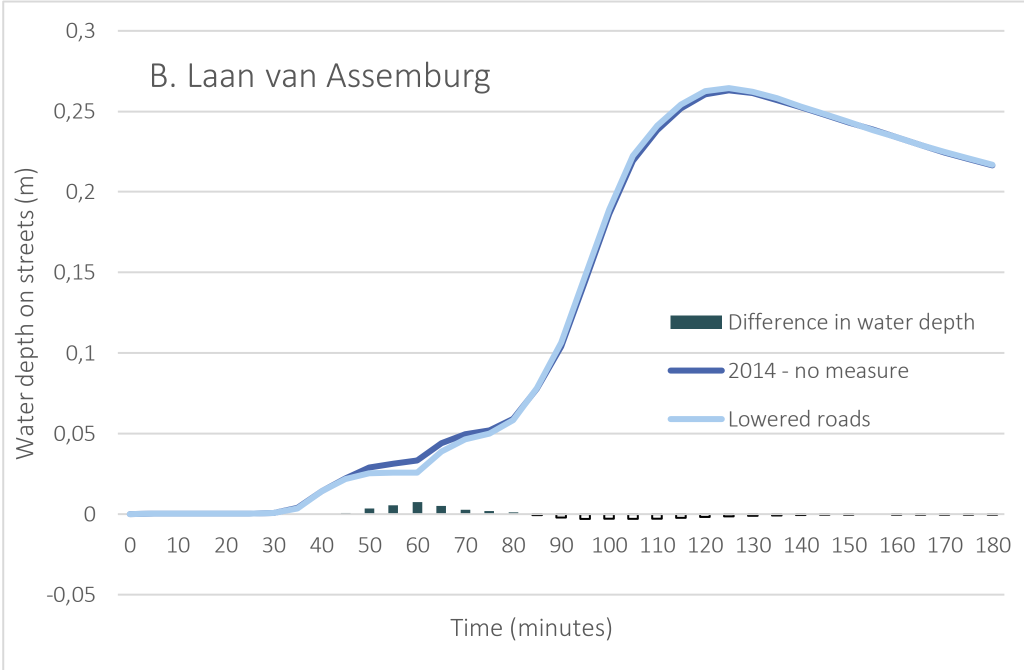


Figure 22: The effect of three adaptation measures on water depth at 120 minutes into the simulation. Each row shows a different research location: the upper row is the location De Zevenhoeven, the middle row the location Laan van Assemburg and the bottom row is location De Veste. Maps A, D and G show the water depth after 120 minutes of the 2014 event. Maps B, E and H show the 2014 event with the implementation of adaptation measures: underground storage in map B, lowered roads in map E and wadis in map H. The right column shows the difference between the maps in the left and middle column.







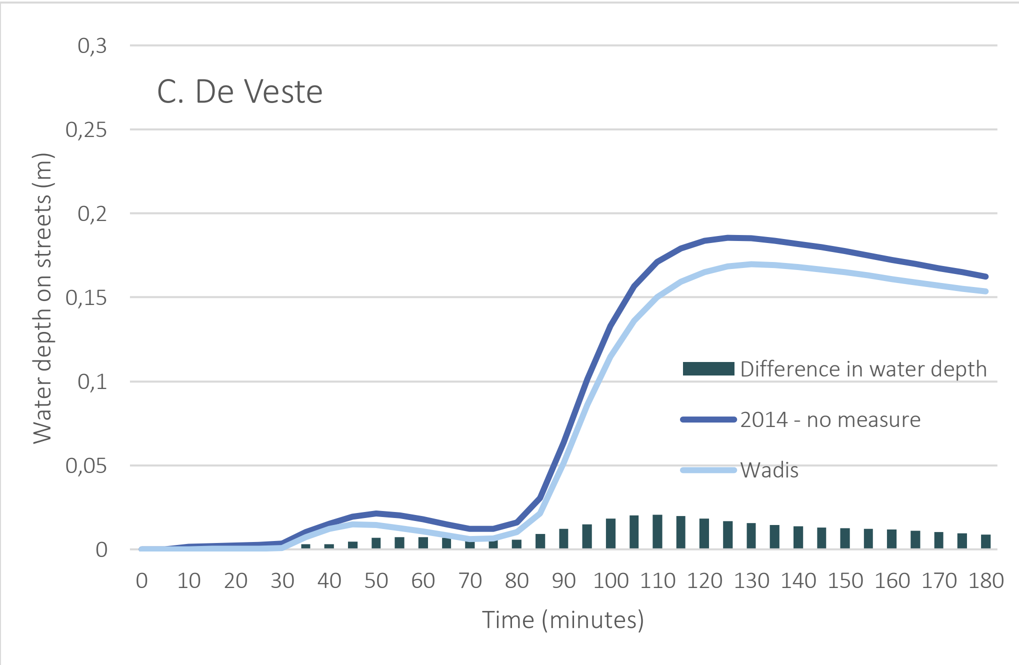


Figure 23: Effect of different adaptation measures on three research locations over time. The dark blue line indicates the water depth resulting from the initial 2014 event simulation without adaptation measures. For each location a different adaptation measure was implemented: underground storage on location 1, lowered roads on location 2 and wadis on location 3. The light blue line shows the water depth on each location resulting from the simulation where these measures were implemented. The dark green bars show the difference between the 2014 event without measure and the simulation with adaptation measure. A positive bar thus means a decrease in water depth.

Table 3: Results of the simulation and analysis of the eight selected adaptation measures. The stars in the 'Contribution to ATP' column indicate the values that were estimated by an educated guess.

Adaptation measure	**Efficacy**	**Costs**	**Constraints**	**Contribution to ATP**	**Side effects**	**Private/Public**
Underground storage	+/- Timing and place in the system are important for its performance	€420/m^3	Interference with underground infrastructure	45,1 m^3 (18%)	No conflicting land use, but also no positive side effects due to underground implication	Public
Lowered roads	+ Only effect at the location where the measure is implemented	€26,33/m^2	Only in non-sloping area, minimal groundwater depth	37,6 m^3 (10,7%)	Combined land use possible	Public
Storage under roads	++	€456/m^2	Minimum groundwater depth, non-sloping	125 m^3 (50%)*	Combined land use possible and groundwater recharge	Public
Rain barrels	--	€266/m^3	Space requirement in small garden	5 m^3 (2%)*	Create awareness and can be used for garden irrigation purposes	Private/Public
Infiltration transport pipes	+/- Expected to be less efficient during peak events	€870-1200/m	Minimum groundwater depth	15 m^3 (6%)*	Groundwater recharge	Public
Wadis	++ Efficient redistribution of rainwater	€53/m^3	Minimum groundwater depth	103,8 m^3 (41,5%)	Combined land use possible, groundwater recharge and cooling effect	Public
Permeable paved surface	+	€95/m^2	Porous soil underneath pavement	20 m^3 (8%)*	Groundwater recharge and combined land use possible	Public/Private
Parks and greens strips	++	€36/m^2	Less effective when soil is saturated	50 m^3 (20%)*	Groundwater recharge, combined land use possible and cooling effect	Public

3.5.4 Storage under roads

Storage under roads could be seen as a combination of underground storage (with infiltration crates) and permeable pavement. However, unlike underground storage this measure aims to prevent rainwater to enter the sewage system, instead of adding storage to the sewage system. From the underground storage simulation in D-Hydro it was found that the placement was very important, which is not applicable for storage under roads. For this method the effect, when looking at placement, could be compared with lowered roads where the decrease in water depth was most effective on the location where it was implemented. Important for infiltration into the road is that there is no slope and there is a minimum groundwater depth. An advantage of storage under roads compared to lowered roads is that there is no nuisance of splashing water (Vergroesen et al., 2013). Also, storage under roads has a larger storage capacity than above ground storage such as wadis (Waterschap Hollandse Delta, n.d.). Constraining the applicability of storage under roads is that the crates decrease the load-bearing capacity, meaning less heavy vehicles are able to use the road after implementing the infiltration crates. Costs for this measure are composed of the costs for permeable paved surface and the installation of infiltration crates and are estimated at €456/m^2 (SBRCUR-net, 2014; Stichting RIONED, 2015c). For 250 m^3 extra storage and 50 cm deep infiltration crates, the total costs are estimated at €228.000,-.

3.5.5 Rain barrels

Rain barrels are known as an easy water storage measure, but unfortunately their efficacy is low, especially compared to the other adaptation measures considered in this research. In theory, the rain barrel can efficiently unburden the sewage system by storing (part of the) rainwater falling on roofs. However, when used for garden irrigation rain barrels are not empty during heavy rainfall, decreasing its storage capacity. Also, the costs are quite high: €266/m^3 plus an additional €75 per house for disconnecting the rain pipe from the sewage system (Stichting RIONED, 2015d; SBRCUR-net, 2014) which adds up to total costs of €191.525,-. In order to reach the aimed amount of extra storage roughly 1667 rain barrels of 150 L are needed. This is an underestimation, since it is unlikely that all the storage will be available during heavy rainfall. On the other side, installation of rain barrels can increase awareness among Heemskerk's citizens and engagement in other adaptation measures.

3.5.6 Infiltration transport pipes

Infiltration transport pipes can be installed under roads where they do not interfere with other land use. The location where these pipes can be implemented is restricted by the minimal groundwater depth and the slope. Also, the efficacy is expected to be higher during rain events with a longer time span compared to short high intensity rainfall events. Infiltration transport pipes contribute to groundwater discharge. The costs for this adaptation measure is €870/m for a 800 mm diameter concrete infiltration pipe and €1200/m for PVC material (Stichting RIONED, 2015e). Since a 800 mm diameter pipe can store 0,503 m^3 per meter, a total of 500 m of infiltration transport pipes is necessary to meet the aimed amount of storage. The total costs for PVC infiltration pipes are therefore estimated at €435.000,-.

3.5.7 Permeable paved surface

Replacing closed paved surfaces with permeable paved surface can unburden the sewage system by intercepting rainwater on its way to the gully. This measure contributes to groundwater recharge and can be easily combined with other land use. However, its efficacy is expected to be less during peak events, as noted in Section 3.4.7. In order to meet the storage aim of 250 m^3 and considering a 20 cm deep sandy infiltration layer with 25% effective porosity, a surface of 5000 m^2 is needed. The costs of implementing permeable paved surface are estimated at €95/m^2 and the total costs are estimated at €475.000,-(SBRCUR-net, 2014).

3.5.8 Parks and green strips

Redirecting water from roofs into parks and green strips is one of the least drastic measures, while the effect could be significant. The costs consist mainly of repaving the street or sidewalk with water tiles and disconnecting the roofs from the sewage system, which is estimated at €36/m^2 (SBRCUR-net, 2014; Struyk Verwo Infra, n.d.). Of course when no proper green strip of park is near, it could be considered to implement a wadi too. This adaptation measure can be combined with other land use and contributes to groundwater recharge. A constraint of this measure is that it is less effective when the soil is already saturated from previous rain events. Also, only rainfall from roofs can be redirected, declining its total contribution to the ATP.

3.6 Adaptation pathways map

In Figure 24 below, all adaptation measures and five different pathways are shown in the adaptation pathways map. Each pathway was composed by combining measures under a certain theme. This section will describe the five different pathways and this analysis is also summarized in Table 4.

The first pathway was themed ‘Storage above ground’ and includes the measures ‘Lowered roads’, ‘Wadis’, ‘Parks and green strips’ and ‘Rain barrels’. All measures combined, this pathway has a contribution to the ATP of 196,4 m^3, which is the third highest of the five pathways. The aforementioned measures from this pathway, except for the rain barrels, can be used for other land use purposes when not in use for water storage.

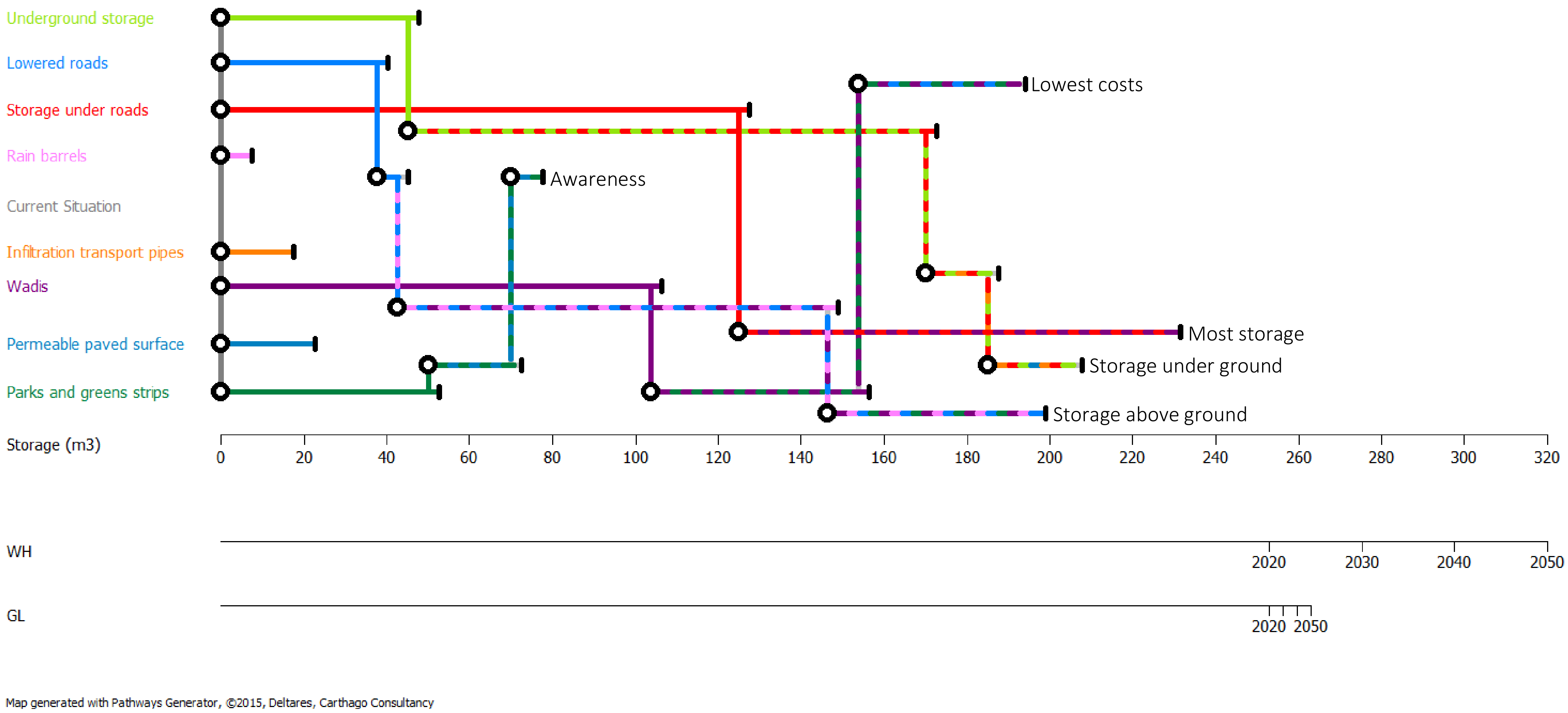


Figure 24: The adaptation pathways map with adaptation measures for resilient urban water management in the municipality of Heemskerk. This map should be read from left to right. Horizontal lines indicate the contribution to the ATP in storage (m³), vertical lines show the connection to other measures. Lines with multiple colors show the combination of two or more measures.

Table 4: Scoring card of adaptation pathways. The target effects indicate to what extent that pathway contributes to the target, which in this research is considered the contribution to the ATP in extra storage (m^3). The (+) symbol for target effects indicate a relatively large contribution to the ATP compared to the other pathways, while the (-) symbol indicates a smaller contribution to the ATP compared to the other pathways. The column with costs illustrate the total costs of each pathway. The (+) symbol here means that the pathways has low costs compared to others. The (-) symbol indicated a negative score and thus high costs. In the last column, side effects, the score for each pathway concerning possible negative side effects (-), for example conflicting land use, or positive side effects (+), such as groundwater recharge.

Pathway	**Target effects**	**Costs**	**Side effects**
Storage above ground	+	+	+
Lowest costs	+	++	++
Awareness	--	-	+\-
Most storage	++	-	+
Storage under ground	++	--	+

The theme of the second pathway is 'Lowest costs'. The adaptation measures included in this pathway are similar to the storage above ground pathway, but minus the rain barrels since that measure is not one of the cheapest measures. Table 4 also shows that the characteristics of the pathways are similar, because the rain barrels do not contribute to the ATP much like they do to the costs.

The third pathway's theme links the adaptation measures that could contribute to the awareness of citizens about climate change, and the effects on the urban environment. These smaller adaptation measures do not contribute much to the ATP, but do increase awareness among citizens which could contribute to acceptation for other, more drastic measures (Claessens et al., 2012).

The fourth pathway is themed 'Most storage' and combines the two adaptation measures with the highest contribution to the ATP, being 'Storage under roads' and 'Wadis'. Since storage under roads is a costly measure, this pathway is relatively costly. However, compared to the pathway 'Storage underground' the amount of storage is similar, but the costs much lower.

The last theme is 'Storage underground' and includes all the measures that are based on storing water below surface: 'Underground storage', 'Storage under roads', 'Infiltration transport pipes' and 'Permeable paved surface'. The fact that the storage is implemented underground makes the measures within this theme more costly and thus also the most expensive theme.

4 Discussion

4.1 Summary and reliability of results

In this section the results for each sub-question will be discussed, as well as the reliability of these results. The reliability is determined by assessing the uncertainties and limitations with regard to the used methodology, data and assumptions.

4.1.1 D-Hydro Suite 1D2D

How well does D-Hydro Suite 1D2D simulate the 2014 event compared to the locations of actual reported flooding in the municipality of Heemskerk after the 2014 event?

This sub-question was answered by building an integrated model in D-Hydro Suite 1D2D, including the 1D sewage system and interaction with the 2D overland flow. Surface waters were not considered as a component of this integrated model. Parameters and data that were included are bed level, roughness, infiltration capacity and initial water levels. The simulation results were compared to both the Climate Impact Atlas (Klimaateffectatlas) and the actual reported flooding of the 2014 event in the municipality of Heemskerk. A quantitative analyses was used to find the correspondence between the reported flooding locations and simulated flooding locations with a minimal water depth of 10 cm.

The comparison of the 2014 event simulation with the atlas (Figure 10) showed that, even though the atlas had a longer depletion time after the precipitation event, the simulation results showed in general less water on streets. This could have two possible explanations that are considered in this research. Either the uniform sewage storage and discharge capacity used for the atlas (20 mm/h) is an underestimation and depletion of this system is faster in reality, or the water depth in the simulation is underestimated due to the constant initial water levels and the lost details in the bed level as a result of the large grid size (as explained in Section 2.2.1). Comparing the results of the 2014 event simulation and the actual reported flooding (Figure 11) shows that the actual reported flooding are both found at locations with large water depth (0,25 m/0,3 m), as well as locations with none to 5 cm water depth. The quantitative analysis showed that 44,5% of the random samples had a water depth of 10 cm or more. This difference shows that there is no one-to-one relation between water depth and nuisance from flooding, or that a high water depth does not necessarily result in nuisance that would be reported to the municipality.

In order to answer this sub-question, the quality of the 2014 event simulation results should be assessed first. The most impactful assumption for the reliability of the results is the three by three meter 2D grid that was used in this research. The interpolation from the 0,5 m resolution elevation map to the 3 m resolution grid caused a loss in detail that is essential for modelling pluvial flooding, since small difference in elevation – such as speed bumps and sidewalks – could influence the overland flow and thus the nuisance due to pluvial flooding. Elevating the bed level of the houses and buildings helped to increase the detail between streets and buildings. The second assumption is the exclusion of surface waters. Without culverts and pumping stations the surface water filled due to overland flow, but were not able to discharge water, creating unrealistic high water depths. This distorted image was not taken into account, while some of the surface waters are actually reported flooding locations. Other assumptions that were made in the process of the simplification of the 1D sewage system that should be considered are the omission of drains and the rural area in the west of the municipality with many greenhouses that was not part of this model. The former is expected not to have had much impact on the results, since these drains work on a longer timeframe than the peak event considered in this research. However, the greenhouses that were not connected in this model could have underestimated the water depth in nearby locations, since the greenhouses collect high volumes of rainwater which discharges into the urban system.

Answering the sub-question, D-Hydro Suite 1D2D does show promising results for simulating water on streets, however the missing detail due to the large grid cells makes the finesse between water on streets and flooding difficult. Based on the quantitative analysis Hypothesis 1 cannot be accepted. However, the research of Yu et al. (2016) on which this hypothesis was based, used measurements of water depth throughout the city that were compared to the model results. Future research should turn out whether the model simulations are a better fit when compared to measured water depths.

4.1.2 Dynamic Adaptive Policy Pathways

How do the 'Adaptation Pathways' towards a resilient urban water management in the municipality of Heemskerk differ considering the W_H- and G_L KNMI '14 climate scenarios towards 2050?

This sub-question was answered by following the steps of the DAPP approach. The transient scenarios, W_H en G_L, were used to establish the ATP in terms of extra storage that is needed to prevent pluvial flooding during 1-in-100 years event. Based on the possibilities and constraints in the municipality of Heemskerk eight adaptation measures were selected, of which three were simulated in D-Hydro to test the efficacy. The adaptation measures were combined in five different adaptation pathways with the five themes 'Storage above ground', 'Storage underground', 'Lowest costs', 'Most storage' and 'Awareness'. These five pathways were scored in the categories 'Costs', 'Contribution to the ATP' and 'Side effects'. The scorecard (Table 4) showed that the most effective adaptation measure is not necessarily the most expensive.

As explained in the previous section the 2014 simulation includes some assumptions that impact the reliability of the results. Since the simulations of the two climate scenarios were based on the same model – with different precipitation events – these assumptions also hold for the climate scenario simulations. The results do show that, as hypothesized, in the W_H-

climate scenario the water depth is generally higher than in the G_L-scenario (Figure 10), meaning that the model does respond as expected.

For the assessment of the ATPs the catchment for each research location was determined. This was, however, based on the flow velocity vectors from one output timestep of the 2014 event simulation. It should be taken into account that this time step might not have been representable for the flow during the whole event. Also, the modelling of the adaptation measures required some more drastic assumptions, since not all functionalities were available in D-Hydro. First of all, the simulations for the adaptation measures were also executed with the same 3 m grid size as the 2014 event simulation, which caused the depressions in the bed level for the wadis and the lowered roads to be smaller than anticipated and restricted the possibility to create a v-profile in the lowered roads. Furthermore, the underground storage did not include a weir or pump, limiting its realistic implementation in the model.

Even though, the contribution to the ATP per adaptation measure might not be reliable as a result, the decision to scale the other adaptation measures to the simulated measures does keep them proportional to each other. Knowing that all of the measures could, in theory, be expanded in storage until they meet the required ATP. This, however, is not realistic since there are many constraining factors such as, among others, costs, maximal load-bearing capacity of roads, relief and groundwater depth. Because the possibilities of expanding the adaptation measure with these constraints taken into account laid outside of the research scope, this research focused on deviating different pathways instead of aiming to find the combination of adaptation measures that could fulfill the ATP.

Answering the sub-question, there is a difference in ATP between the G_L- and the W_H-climate scenario. However, how the ATPs could be reached was not included in this research since the results of the adaptation measure simulations did not meet the reliability to base this conclusion on. Therefore, Hypothesis 2 cannot be accepted.

Recommendations on future research for both this and the first sub-question are almost all related to increasing the quality of the model. This could be done by decreasing the grid size, including a surface water model and connecting this model to an integrated model of the municipality of Beverwijk. Since these systems are connected, this will increase the quality and reliability of the results. Also, for future research it is recommended to conduct expert interviews with the municipality in order to give insight into the preferences in possible adaptation pathways which could then be worked out in more detail to give a concrete interpretation of how to reach the ATP. The adaptation pathways could be further developed in future research by including a temporal component that distinguishes the moment of implementation for each adaptation measure.

4.2 Comparison with results of others

In this section the results from the previous section will be compared with findings from similar studies in order to put them in perspective. Babovic and Mijic (2019) found a logical combination of adaptation strategies from individual options, which let to pathways that represented the simplest adaptations to the adaptation with the highest ATP. The approach and the results of Babovic and Mijic (2019) have resemblance with the findings from this study, however Babovic and Mijic (2019) stated that the total ATP of and adaptative pathway is *"not simply the sum of the strategy component's ATP"* (p. 10), which is how the total ATP of the adaptive pathways in this research are estimated. It would be recommended for future research to find the influence of the approach of Babovic and Mijic (2019) compared to that of this study.

Haasnoot et al. (2013) concluded that the analytical basis of the DAPP approach – for determining ATPs and developing pathways – can be supported with computational scenario-based approaches. Haasnoot et al. (2013) also stated that more complex models can be used to obtain more detailed information about the performance of the most promising actions from an initial exploration. This research was now limited to this initial exploration of actions, while the development of D-Hydro is promising for it to be used for obtaining and testing the performance of adaptation measures in the future.

Similar to this research, Ke et al. (2016) concluded with multiple options for adaptive strategies and the consideration between the most effective measures to reach the ATP, financial capacity of the city and additional measures that provide a nicer environment for residents. The selection of preferred pathways under different perspectives can assist to frame the long-term plan from different ways.

4.3 Implications of the results

Based on the results discussed in Section 4.1 and the perspective of similar studies it can be concluded that the DAPP approach is fitting to explore different adaptation strategies for urban water management. The computational analysis with D-Hydro showed to be able to assess the system's ATP, despite the limitation of the beta software. Also, this research contributed to further development of D-Hydro. Recommendations for further research are focused on a similar analysis when D-Hydro has more advanced modelling options and to evaluate the preferences of the municipality of Heemskerk with respect to the possible adaptation pathways proposed in this research.

5. Conclusion

This research focused on improving the urban water system of the municipality of Heemskerk with regard to pluvial flooding due to extreme precipitation events – like that of July 28^{th} 2014 – using the DAPP approach and aimed to answer the following research question:

Which Dynamic Adaptive Policy Pathways can be formulated for the municipality of Heemskerk, with a view to making its urban water system resilient towards 2050?

Based on the findings of this research five adaptation pathways with different themes – 'Storage above ground', 'Storage underground', 'Awareness', 'Most storage', and 'Lowest costs' – were composed for the municipality of Heemskerk. Since the results regarding the contribution to the ATP were not reliable and the constraints to the scale of implementation were not included within the scope of this research, none of these pathways, unfortunately, is able to meet the ATP necessary to prevent pluvial flooding due to extreme precipitation events in the future. However, even though this research did not result in one optimal adaptive pathway that could be recommended to the municipality of Heemskerk, this exploration of possibilities within the municipality should be seen as a starting point for future research where constraints and opportunities can be combined into one dynamic adaptive policy pathway towards resilient urban water management in the municipality of Heemskerk.

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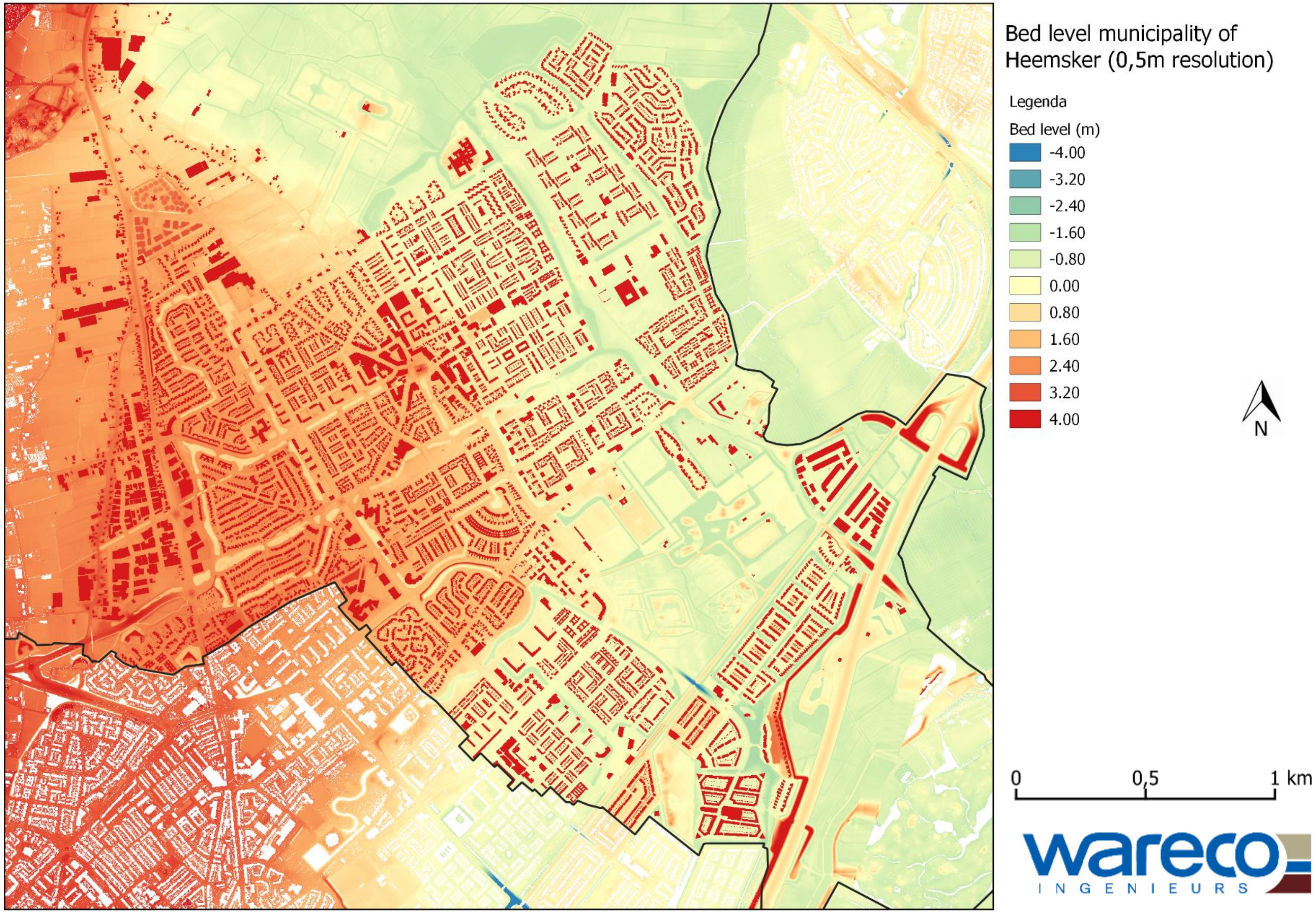
Appendix A – Bed level



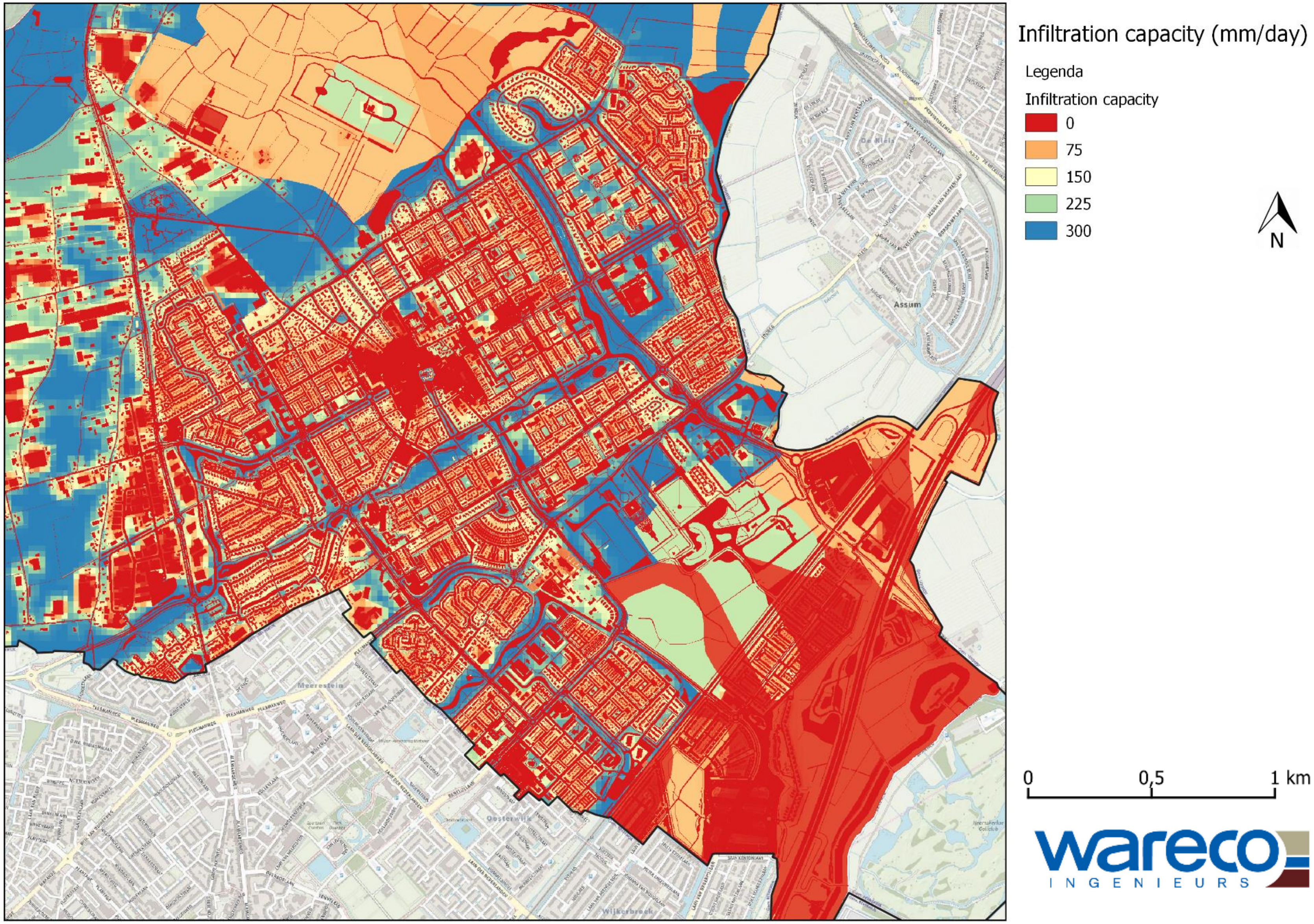
A 1: Elevation (m NAP) on 0,5m resolution.

Appendix B – Roughness

B 1: Rougness values per land use.

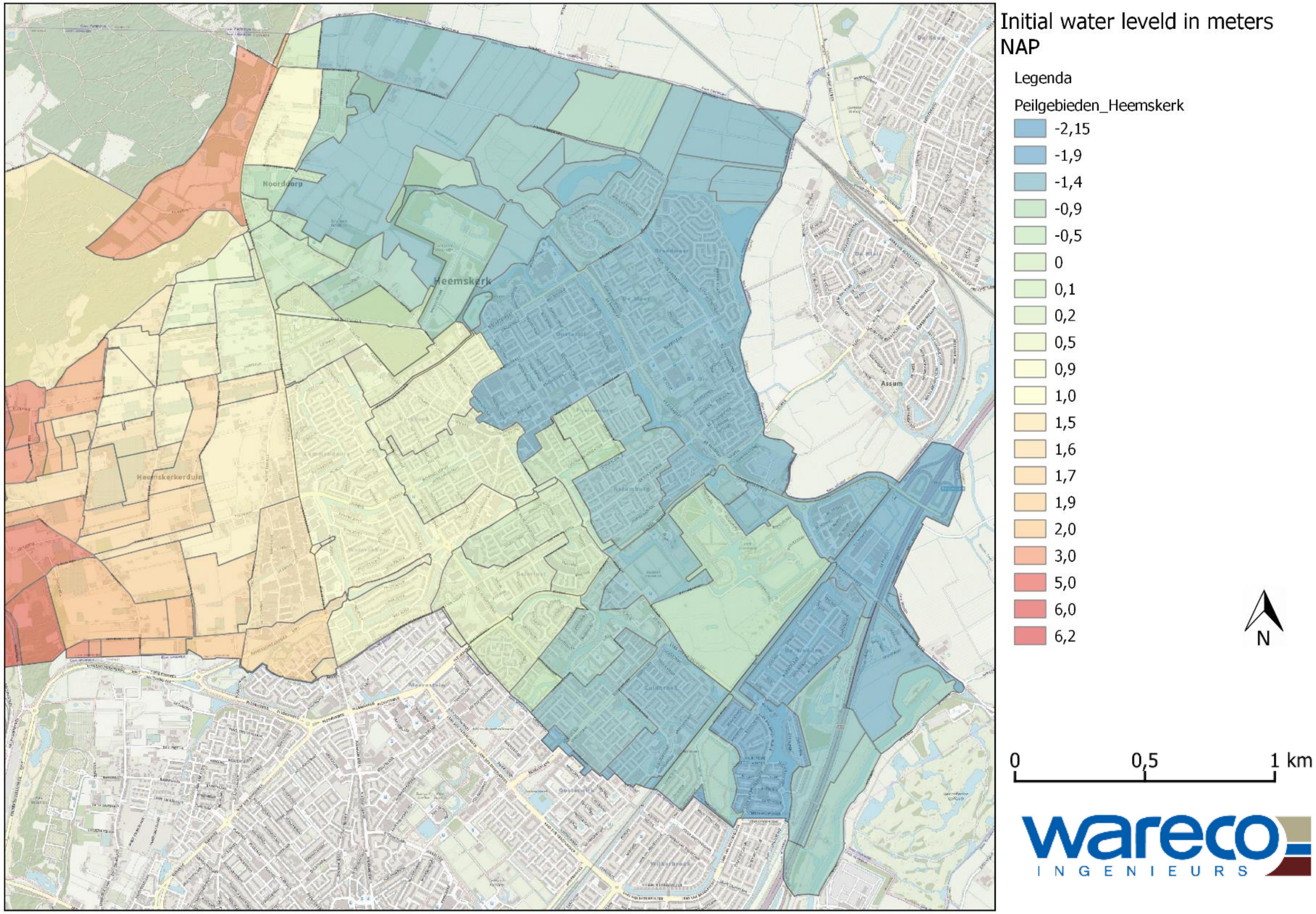
Land use	Roughness (Manning)
Open paved	0.013
Closed paved (including roofs)	0.011
Unpaved	0.200
Transition (base soil)	0.013
Transition (overgrown)	0.200
Arboriculture	0.500
Arable land	0.200
Mixed forest	0.500
Agricultural grassland	0.100
Remaining grassland	0.100
Deciduous forest	0.500
Reed land	0.500
Bushes	0.500
Greening	0.200
Courtyard	0.200

Appendix C – Infiltration capacity



C 1: Infiltration capacity in mm/day.

Appendix D – Initial water levels



D 1: Initial water levels in m NAP

Appendix E – Precipitation statistics

E 1: Precipitation statistics for the current climate, the G_L- and the W_H-climate scenarios. The cells marked yellow indicate the return period and precipitation volume used in this research.

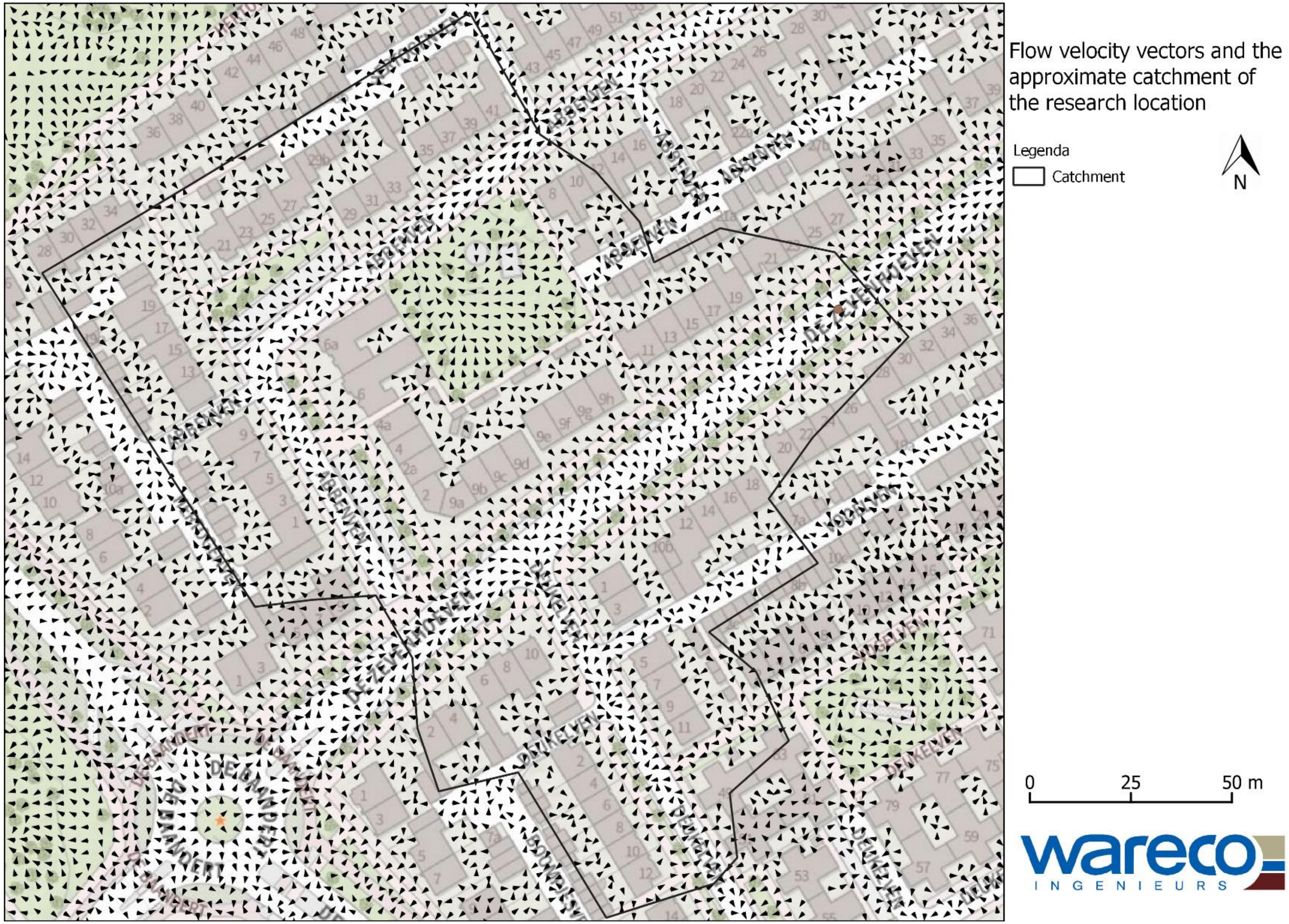
	Current											
Duration (hour)	0,17	0,5	1	2	4	8	12	24	48	96	192	216
Return period (year)	Precipitation volume (mm)											
0,5	8	10	13	15	19	22	25	30	39	50	68	72
1	10	13	16	20	23	28	31	37	46	59	79	84
2	12	17	20	24	28	33	36	44	54	69	90	95
5	15	21	26	31	36	42	45	54	66	81	105	110
10	18	25	31	37	43	49	53	63	75	92	116	121
20	20	30	37	44	51	58	62	73	85	102	127	132
25	21	32	40	47	54	61	65	76	88	106	131	136
50	25	38	48	57	65	72	77	87	100	117	141	147
100	29	46	**58**	68	78	86	90	99	111	128	152	158
200	33	55	70	81	89	95	98	112	124	140	163	168
250	35	58	75	87	94	100	103	117	128	144	167	172
500	41	70	91	105	112	117	120	132	142	156	178	182
1000	48	85	111	128	134	138	139	148	157	169	188	193
	2050 (G_L)											
Duration (hour)	0,17	0,5	1	2	4	8	12	24	48	96	192	216
Return period (year)	Precipitation volume (mm)											
0,5	8	11	13	16	19	23	25	31	39	51	70	74
1	11	14	17	20	24	29	31	37	46	60	81	85
2	13	17	21	25	29	34	37	44	54	69	92	97
5	16	22	27	32	37	43	46	54	66	82	106	111
10	18	26	32	38	44	50	54	63	75	92	117	122
20	21	31	39	46	53	60	63	73	85	103	128	133
25	22	33	41	49	56	63	67	76	89	106	132	137
50	26	40	50	59	67	74	78	87	100	117	142	148
100	30	48	**60**	71	81	89	92	99	112	129	153	159
200	35	57	73	84	92	98	100	112	124	141	164	169
250	36	61	77	90	97	103	105	116	129	145	168	173
500	42	73	94	109	116	121	122	131	143	157	178	183
1000	49	88	115	133	139	142	142	148	158	170	189	193
	2050 (W_H)											
Duration (hour)	0,17	0,5	1	2	4	8	12	24	48	96	192	216
Return period (year)	Precipitation volume (mm)											
0,5	10	13	15	19	22	26	29	34	43	56	75	79
1	12	16	20	24	28	33	36	42	52	66	88	92
2	15	20	24	29	34	40	43	50	61	77	100	105
5	18	26	31	37	43	50	54	62	75	92	117	122
10	21	31	38	45	52	59	63	73	86	104	130	135
20	25	37	45	54	62	69	74	84	98	116	142	148
25	26	39	48	57	65	73	78	88	102	120	146	152
50	30	46	58	69	78	87	91	101	115	133	158	164
100	35	56	**70**	83	94	103	108	116	129	147	171	176
200	40	67	85	99	107	114	117	132	144	160	183	188
250	42	71	90	105	113	120	123	137	149	165	187	192
500	50	85	110	127	136	141	143	155	166	180	200	204
1000	58	103	134	155	163	166	167	175	184	195	212	216

Appendix F – Precipitation events

F 1: Precipitation events in mm per 5 minutes.

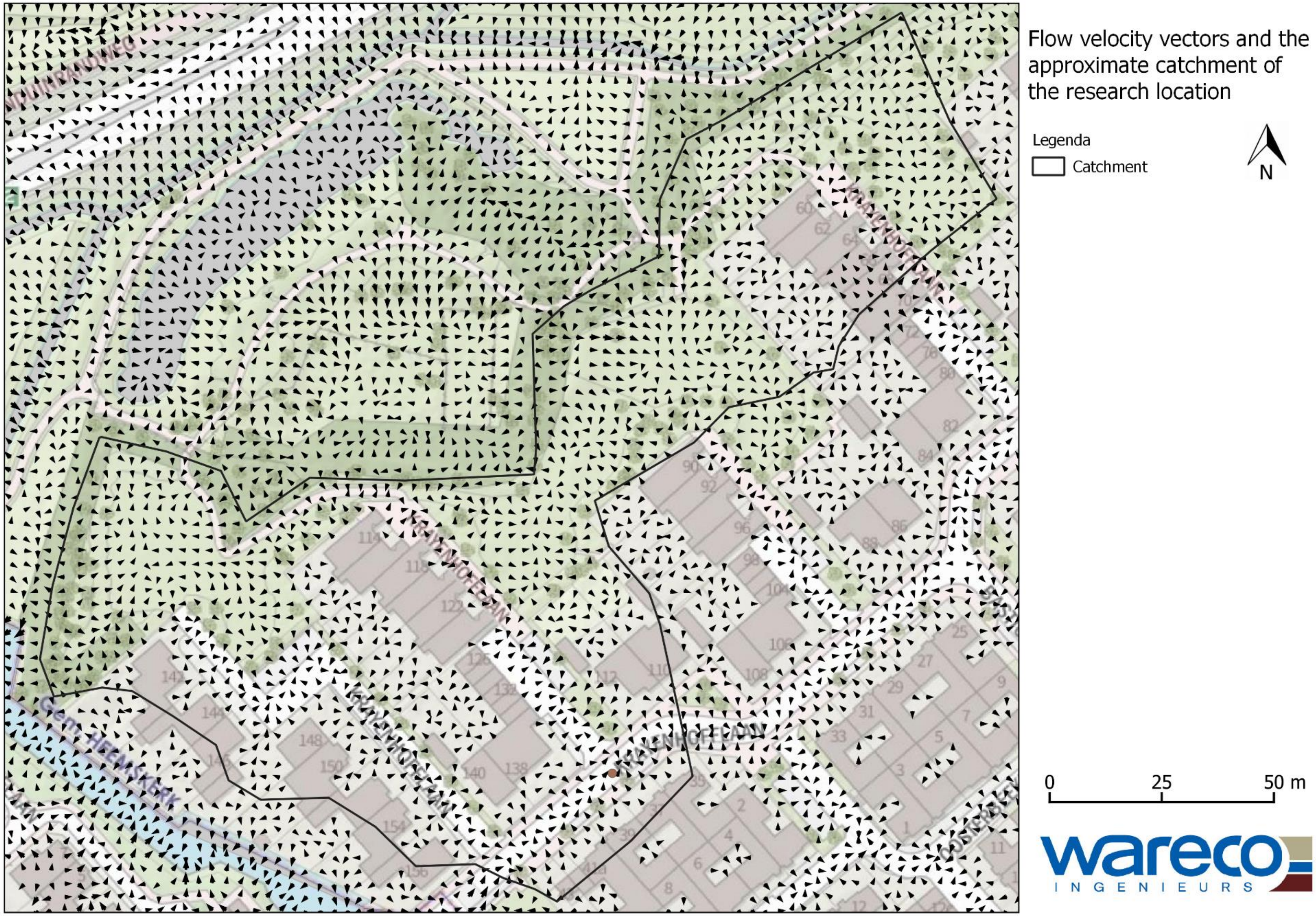
Precipitation event	Bui07	Bui08	2014 event	2050 (G_L)	2050 (W_H)
Duration (min)					
0	0	0	0	0	0
5	0,6	0,3	0,3	0,31035	0,36207
10	1,2	0,6	0,6	0,6207	0,72414
15	2,1	0,9	0,9	0,93105	1,08621
20	3,3	1,2	1,2	1,2414	1,44828
25	3,3	1,5	1,5	1,55175	1,81035
30	2,7	2,1	2,1	2,17245	2,53449
35	2,1	2,7	2,7	2,79315	3,25863
40	1,5	3,3	3,3	3,41385	3,98277
45	1,2	3,3	3,3	3,41385	3,98277
50	0,9	2,1	2,1	2,17245	2,53449
55	0,6	1,2	1,2	1,2414	1,44828
60	0,3	0,6	0,6	0,6207	0,72414
65			0	0	0
70			0	0	0
75			1,36	1,40692	1,641384
80			3,16	3,26902	3,813804
85			5,86	6,06217	7,072434
90			9,46	9,78637	11,41727
95			9,46	9,78637	11,41727
100			7,66	7,92427	9,244854
105			5,86	6,06217	7,072434
110			4,06	4,20007	4,900014
115			3,16	3,26902	3,813804
120			2,26	2,33797	2,727594
125			1,36	1,40692	1,641384
130			0,46	0,47587	0,555174
135			0	0	0
140			0	0	0
145			0	0	0
150			0	0	0
155			0	0	0
160			0	0	0
165			0	0	0
170			0	0	0
175			0	0	0
180			0	0	0

Appendix G – Catchments per research location



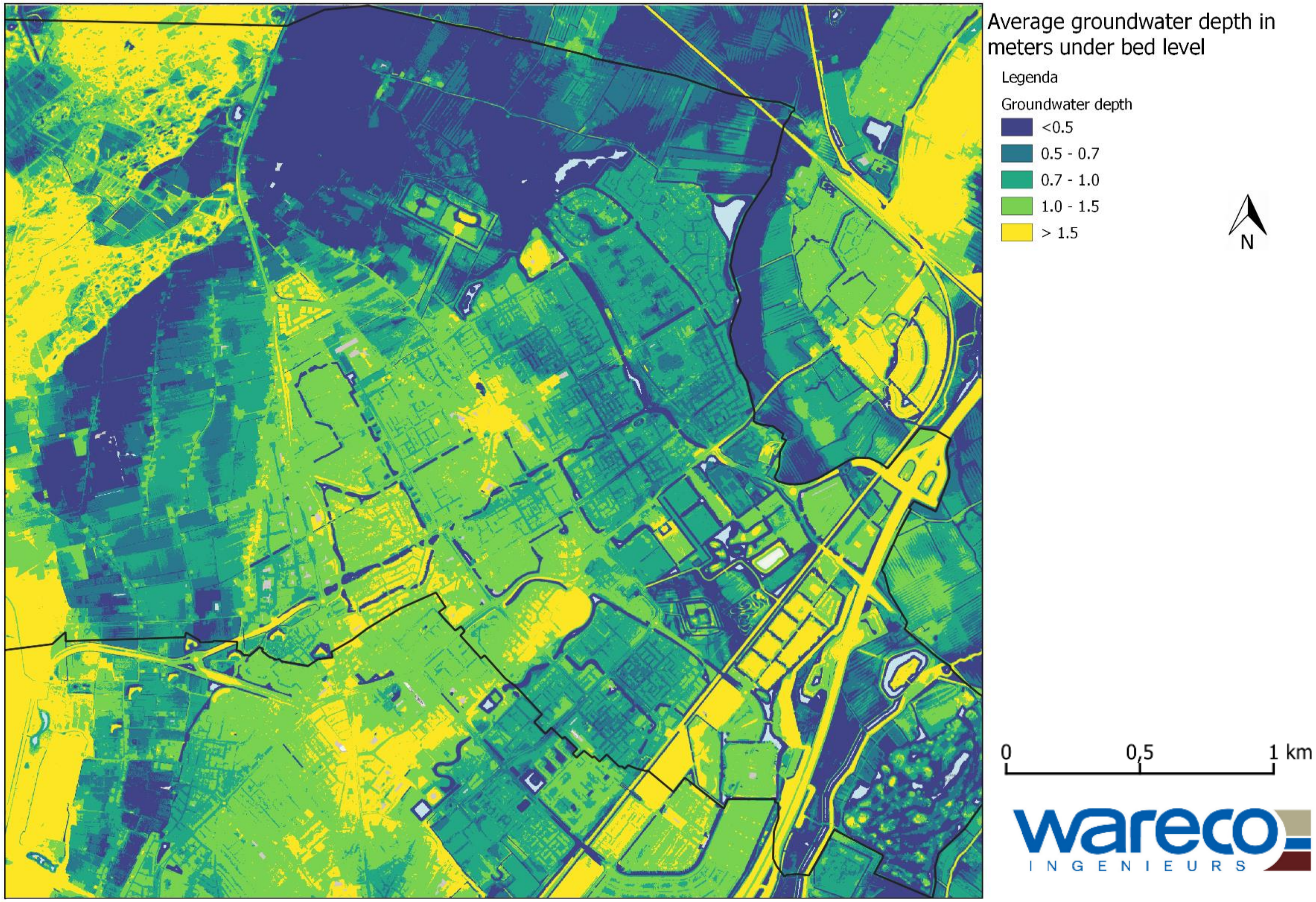
G 1: Flow velocity vectors and the derivated catchment of the research location De Zevenhoeven.

G 2: Flow velocity vectors and the derived catchmet of research location Laan van Assemburg



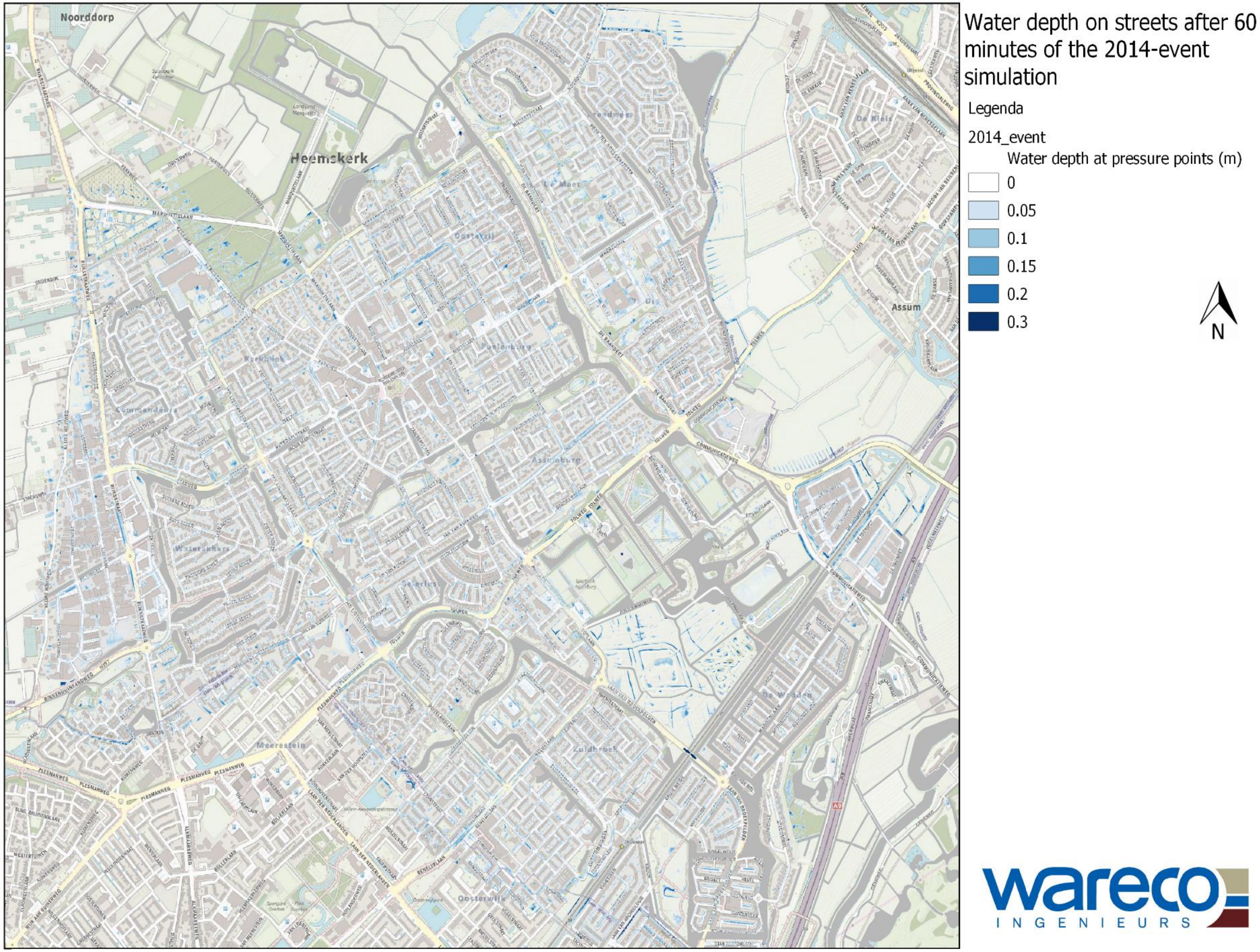
G 3: Flow velocity vectors and the derived catchment of research location De Veste.

Appendix H – Average groundwater depth



H 1:Average groundwater depth in meters under bed level.

Appendix I – Overview maps (60 minutes)



I 1:Water depth (m) after 60 minutes of the 2014 event.

Water depth on streets after 60 minutes of the GL-scenario simulation

Legenda

2014_event

Water depth at pressure points (m)

- 0
- 0.05
- 0.1
- 0.15
- 0.2
- 0.3

N

I 2:Water depth (m) after 60 minutes of the GL climate simulation.

Water depth on streets after 60 minutes of the WH-scenario simulation

Legenda

2014_event

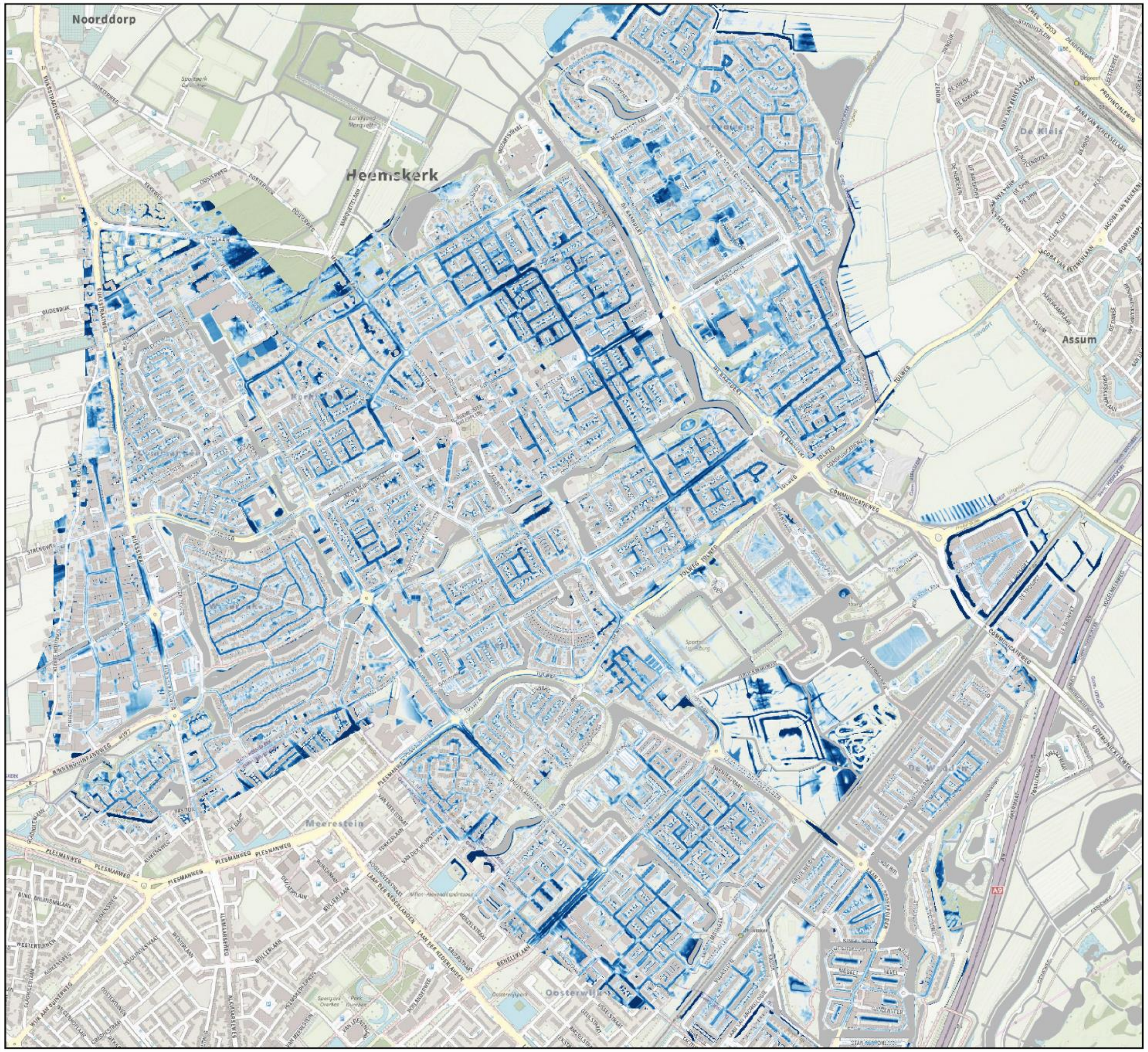
Water depth at pressure points (m)

- 0
- 0.05
- 0.1
- 0.15
- 0.2
- 0.3

N

I 3:Water depth (m) after 60 minutes of the WH climate simulation.

Appendix J – Overview maps (120 minutes)



Water depth on streets after 120 minutes of the GL-scenario simulation

Legenda

2014_event

Water depth at pressure points (m)

- 0
- 0.05
- 0.1
- 0.15
- 0.2
- 0.3

N

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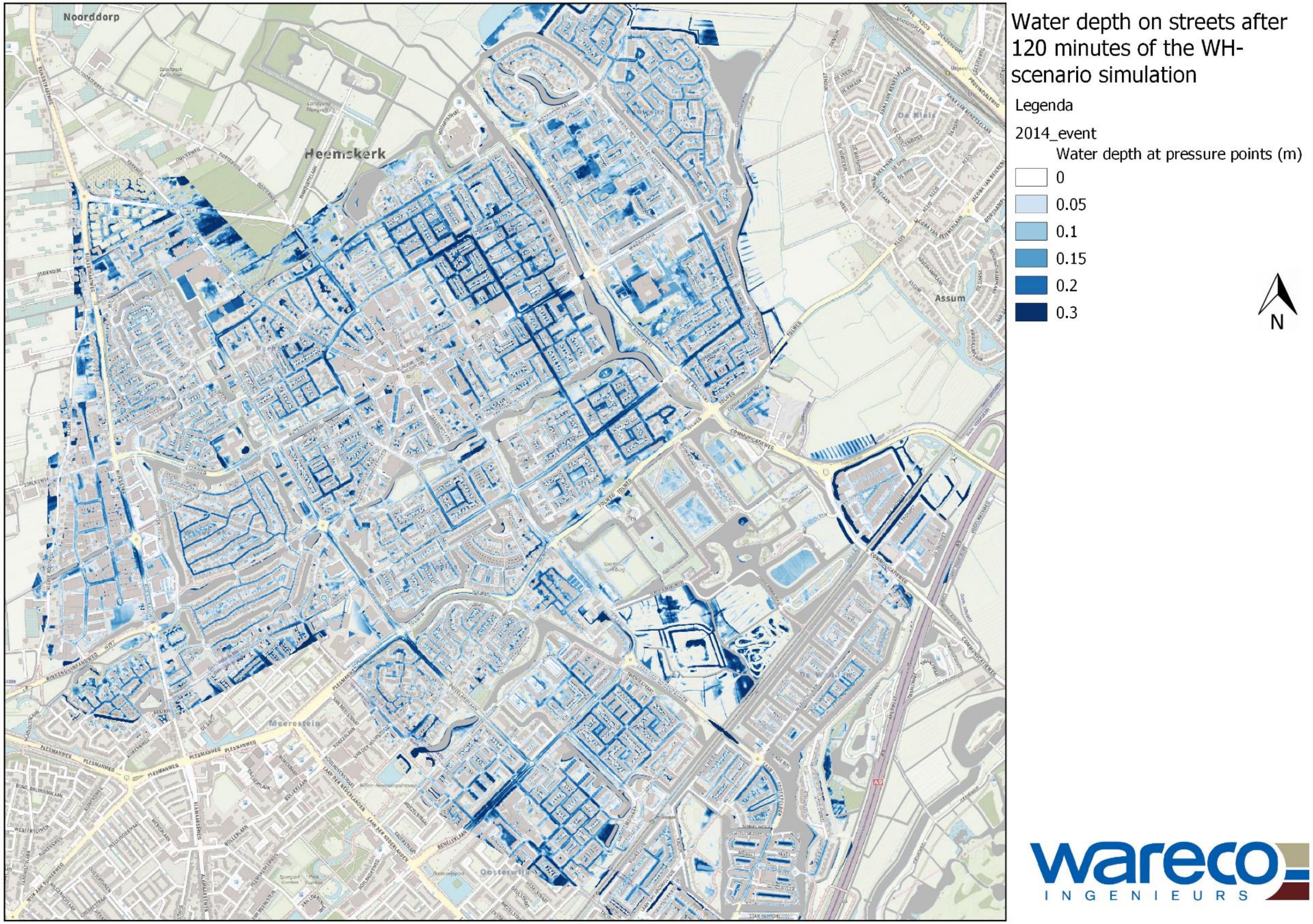
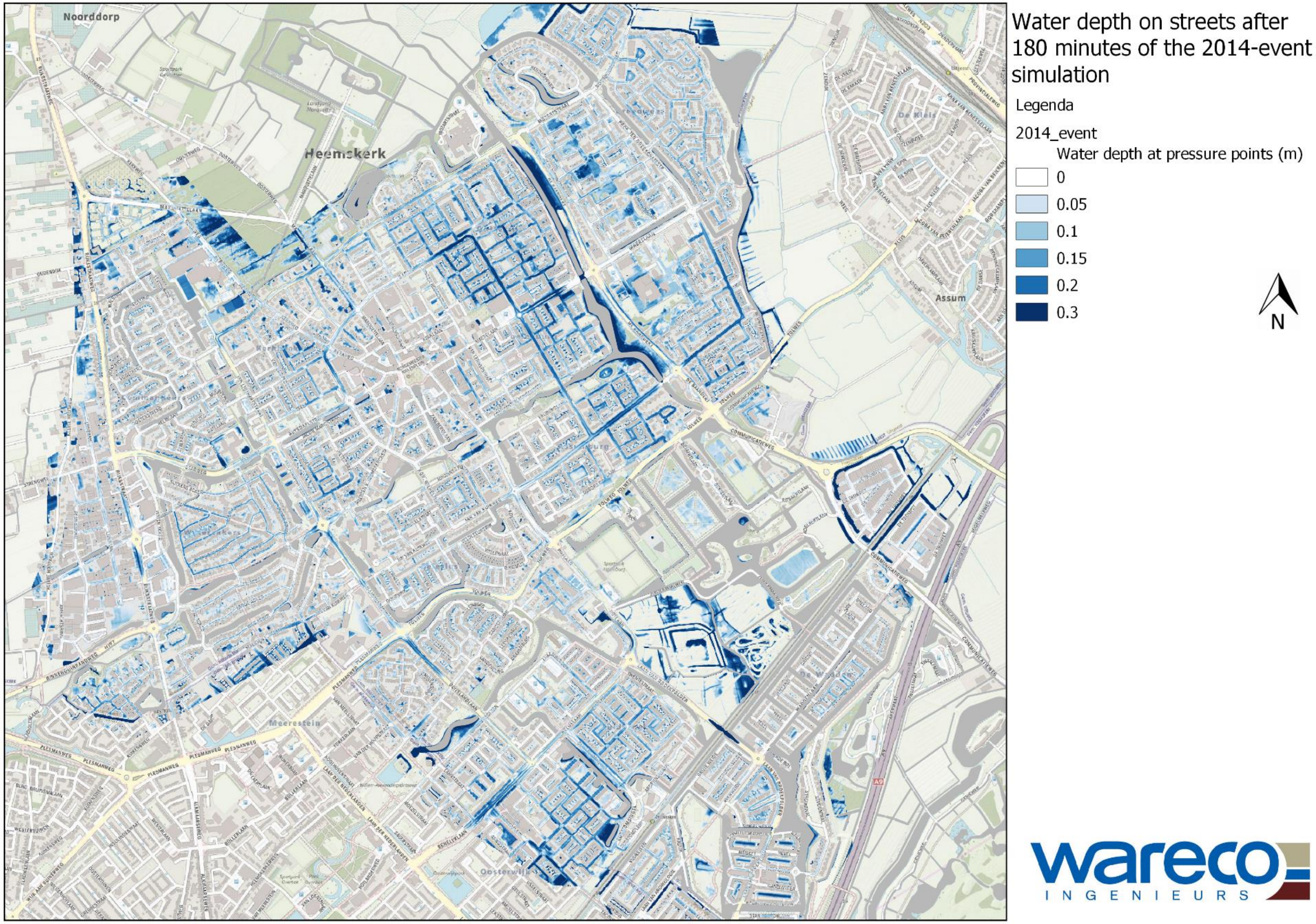
J 1:Water depth (m) after 120 minutes of the GL climate simulation.



J 2:Water depth (m) after 120 minutes of the WH climate simulation.

Appendix K – Overview maps (180 minutes)



K 1:Water depth (m) after 180 minutes of the 2014 event.

Water depth on streets after 180 minutes of the GL-scenario simulation

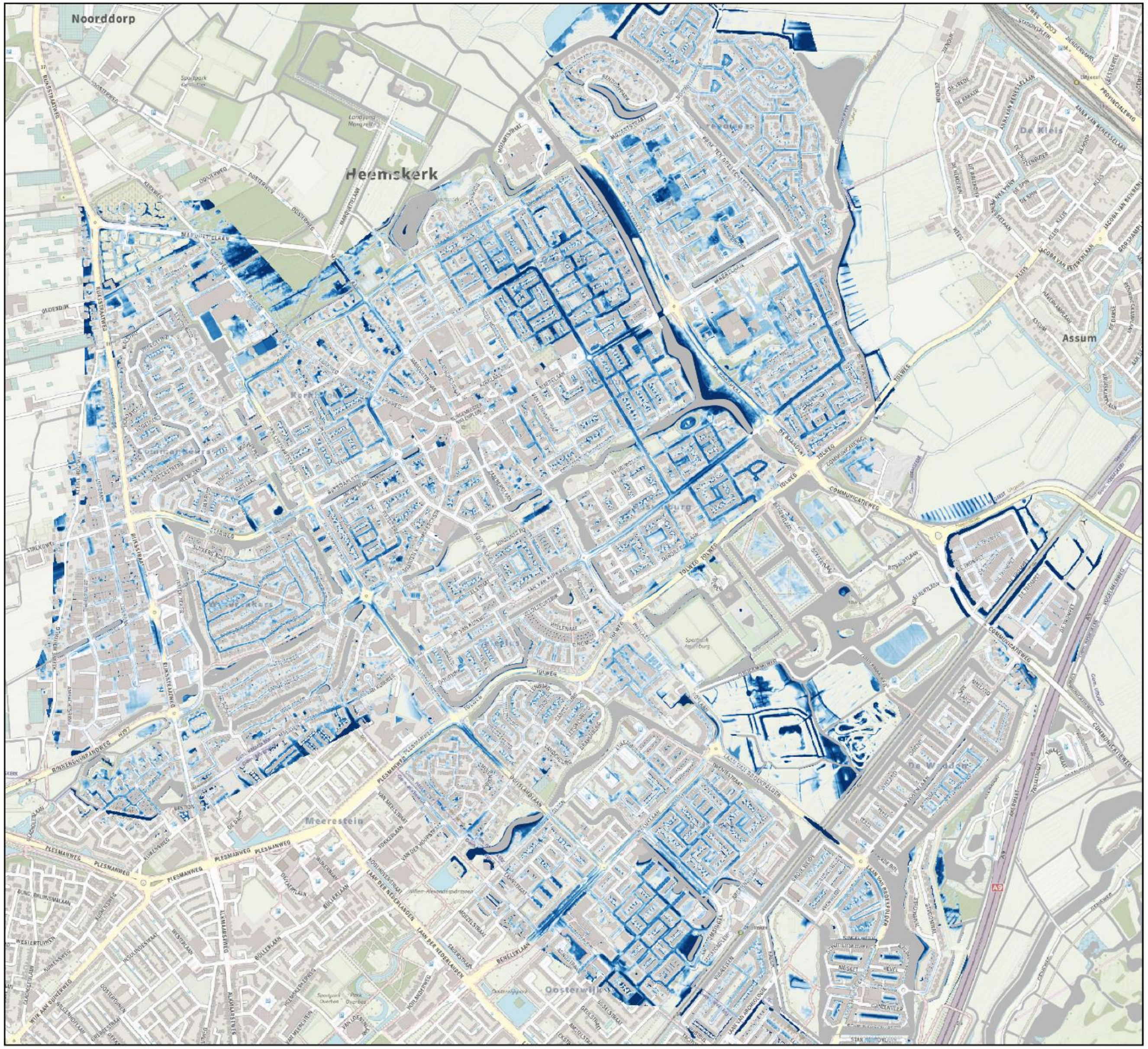
Legenda

2014_event

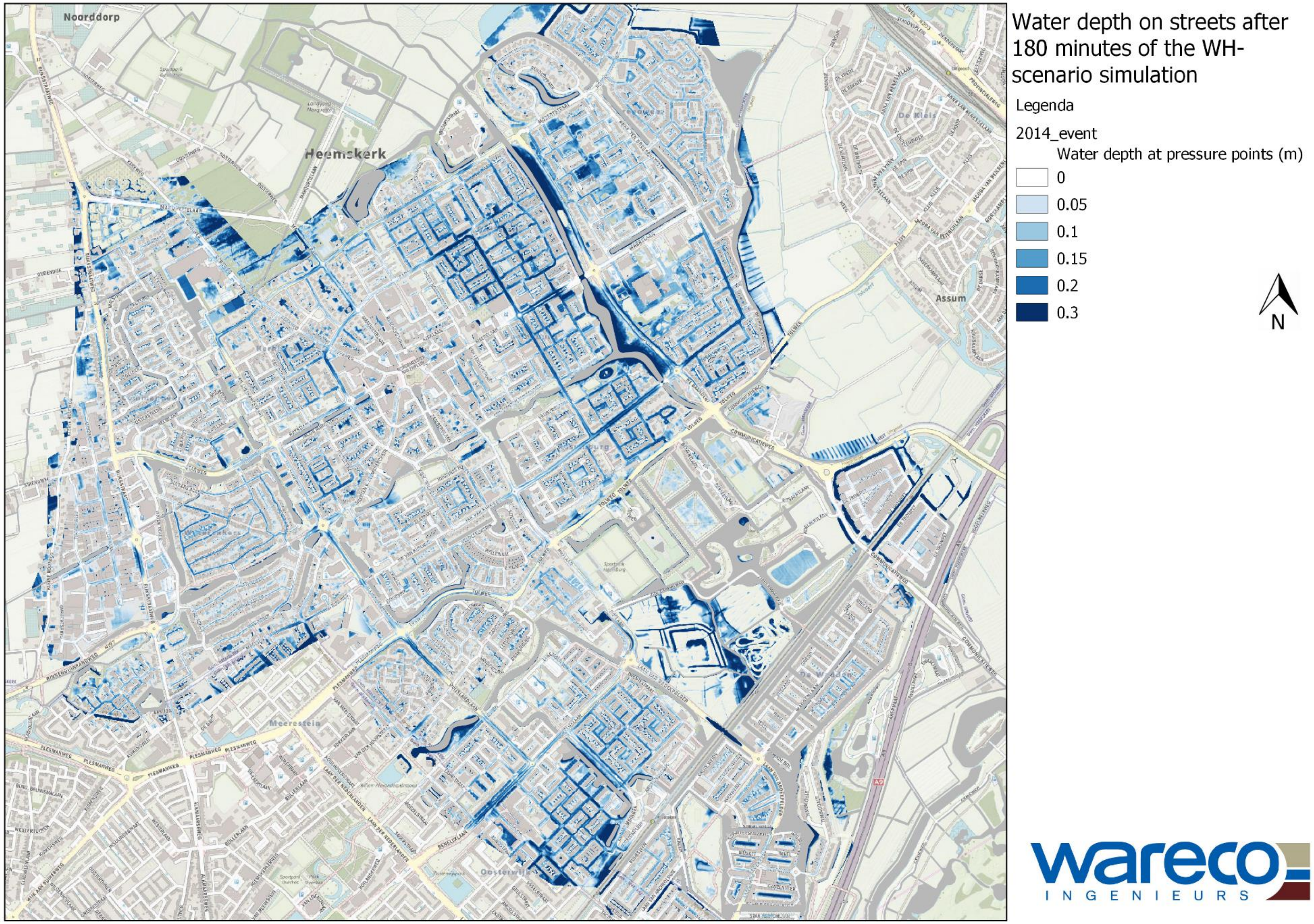
Water depth at pressure points (m)

- 0
- 0.05
- 0.1
- 0.15
- 0.2
- 0.3

N



K 2:Water depth (m) after 180 minutes of the GL climate simulation.



wareco INGENIEURS

K 3:Water depth (m) after 180 minutes of the WH climate simulation.

Appendix L – Adaptation measures

L 1: Selection of adaptation measures and their score for different characteristics. + means the adaptation measure is promising, O means it is between promising and not promising and – means it is not promising.

Adaptation measure	**Objective**	**Scale**				**Urban/Rural**		**Relief**				**Development**				**Groundwater depth**	
		Home	Street	Neighborhood	City	Urban	Rural	No slope (<1%)	Top of slope	Flank of slope	Foot of slope	Existing	Renovation planned	Restructuring	Newly build	Groundwater depth below 1m NAP	Groundwater depth above 1m NAP
Underground storage	Accelerate	-	+	+	o	+	+	+	+	o	+	-	+	+	+	+	+
Deepened roads	Delay	-	+	+	o	o	+	+	+	-	+	-	+	+	+	+	+
Storage in/under roads	Delay	-	+	+	o	+	+	+	+	-	+	-	+	+	+	+	o
Rain barrels	Delay	+	o	o	o	o	o	+	+	+	+	+	+	+	+	+	+
Infiltration transport pipes	Delay	-	+	+	o	+	+	+	+	o	o	-	+	+	+	+	o
Wadis	Delay	-	+	+	o	-	+	+	+	+	o	-	o	+	+	+	o
Permeable paved surface	Delay	-	+	+	o	+	+	+	+	o	+	-	+	+	+	+	o
Parks and green strips	Delay	-	+	+	+	o	+	+	+	+	+	o	+	+	+	+	o