Delft University of Technology

Master Thesis

Assessing the impact of using Nature-based Solutions to mitigate stormwater flooding in new construction areas in the Netherlands

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1 Summary

Stormwater flooding will be an increasing problem for urban environments. Both the severity and the amount of cases of stormwater flooding will increase. These stormwater flooding can lead to severe consequences such as large economic damages, traffic jams and electricity loss.
In the meantime the Netherlands is facing a housing shortage. In order to solve this the new Ministry of Housing and Spatial Planning is taking more control. The Ministry has estimated that a yearly construction of 100,000 houses per year is needed in order to mitigate the housing shortage.
A traditional sewage system can be used to reduce the problem of stormwater flooding for new construction areas. However the costs of mitigating flooding with the traditional sewage system are increasing. Therefore it will be wise to take increased stormwater flooding into account while developing these new construction areas.

Nature-Based Solutions can be used as a solution to stormwater flooding. Nature-Based Solutions are solutions which tackle societal challenges by working with nature such as green-roofs, rain gardens and permeable pavements. Nature-Based Solutions can work well in combination with with currently existing gray infrastructure to mitigate stormwater run-off.

Very few academic papers have investigated the effect of the implementation of stormwater flooding on new construction areas in the Netherlands. Therefore the following research question was used in this paper:

What is the impact of the implementation of Nature-Based Solutions on stormwater flooding in new construction areas in the Netherlands under uncertainty of extreme rainfall due to climate change?

A literature review has found that the national government of the Netherlands is increasingly focusing on the problem of stormwater flooding in it's vision for spatial planning. Furthermore the national government is is also increasingly playing an active role in spatial planning issues. Therefore the issue of stormwater flooding will receive more attention in new construction projects.
Another thing that was found in the literature research is that national

government of the Netherlands prefers a combination of functions over a single use of a function in spatial planning issues. Therefore this paper will focus on green-roofs as a NBS specifically as it combines the usages of a residential building an stormwater flood mitigation.
However there is an academic gap on the effectiveness of NBS' on stormwater flooding in new construction projects in the Netherlands. Furthermore it has been found that the effectiveness of Nature-Based Solutions depend on the characteristics of the NBS itself and the environment in which the NBS is implemented. Therefore there is another academic gap on which implementation conditions will result in green-roofs being an effective solution to stormwater flooding.

The research question will be answered by applying the Arc-Mahlstrom model to generate results. This model is well documented and a 1D-model is a good fit for this research. Furthermore the district of Het Zand, Utrecht, has been chosen as a case study. Het Zand was finished in 2014 and features an interesting lay-out with areas where there is a compact lay-out with houses which are built close to each other and areas which are less compact and have more and larger gardens. Stormwater floods of 35mm, 70mm and 140mm of rain in 2 hours have been used on Het Zand which resemble a stormwater event once every 10, 100 and 1000 years respectively.

The results show that the implementation of green-roofs have only a slight reduction of 1 or 2% on the average water height of stormwater floods in the overall area. This is both the case for implementing green-roofs on 50% or on 100% of the houses. However the results show that implementing green-roofs can reduce the height of the severe floods by 20cm in the case of 70mm of rain. Therefore the green-roofs can offer a solution to tackle the most severe floods in an area. Furthermore the results also show that the effect of NBS' on stormwater flooding depend on the neighborhood in which they are implemented. Neighborhoods of which the area consists of relatively a high amount of houses will have more reduction in the average flood height. This is the case for neighborhoods of which the area consists of 20 to 30% of houses. For instance in the 70mm scenario the average water height can be reduced by 6.784% when implementing 50% green-roofs.

Policy-makers can use this information for planning new construction areas. Policy-makers will need to know that the implementation of Nature-

Based Solutions will not drastically reduce stormwater flooding problems on an overall level of the area. However Nature-Based Solutions can be used to mitigate the most severe problems of stormwater-flooding. This is especially the case for neighborhoods with a compact lay-out with houses built close to each other.

2 Abstract

The Netherlands will be facing more cases of extreme rainfall in the future. Meanwhile the Netherlands is also facing a large housing problem which requires a yearly construction of 100,000 houses per year to solve. Nature-Based Solutions can be used as one of the solutions to flooding due to extreme rainfall events in urban areas. The goal of this research is to asses the impact of the implementation of Nature-Based Solutions on stormwater flooding in new construction areas in the Netherlands under uncertainty of extreme rainfall due to climate change. This was investigated by running the flood model, the Arc-Malstrom model, for the case-study of Het Zand, Utrecht. Furthermore scenarios of 35, 70 and 140 millimeters of rain were used including the implementation of 50% and 100% green-roofs in the area. It has been found that green-roofs provide only a small improvement of 1 or 2% in flood problems overall in the area, but that the most severe floods have a reduced water height of 20cm. However the implementation of green-roofs can improve the flood problems in some areas significantly. Green-roofs will have the most improvement in flood problems in areas where 20 to 30% of the area consists of houses and thus houses are built more close to each other.

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3 Introduction

3.1 Motivation

The Netherlands will be facing increased precipitation in the winter and more cases of extreme rainfall in the summer caused by climate change KNMI (2023a). Specifically the amount of cases with extreme rainfall during an hour will increase more than the amount of cases with extreme rainfall during the day. Furthermore the KNMI (2023b) has found that cases of extreme rainfall which happen once every year will have the same increased probability as cases of extreme rainfall which happen once every 10 or 20 years. Similarly a report by the IPCC (2021) states that Europe will face increased precipitation. However the paper by the IPCC doesn't describe the situation in the Netherlands in more detail.

Although increased precipitation due to climate change is one of the reasons for increased urban flooding, cities will also have more cases of stormwater flooding because of denser populations, increasing amounts of impermeable surfaces and sewage infrastructure aging (Gaitan, van de Giessen, & ten Veldhuis, 2016). These stormwater floods can have severe consequences. Stormwater floods can for example lead to large economic damages, traffic jams and electricity loss (Brockhoff, Koop, & Snel, 2019). Furthermore even small cases of stormwater flooding could to large economic and societal consequences as today's society is very dependent on infrastructure such as communication networks, transportation systems and water systems (Booth et al., 2010).

All this takes place while the Netherlands currently faces a large housing problem (P. Boelhouwer, 2020). Current housing shortages are mostly the result of deregulation and an increase of free market policy instead of government interventions. Furthermore pro-cyclical governmental financial policies during the economic crisis of 2008-2013 have worsened the problem (P. J. Boelhouwer & Heijden, 2022). To mitigate the housing shortage, the new Ministry of Housing and Spatial Planning is taking more control. Solving the shortage would need a yearly construction of over 100,000 houses per year (De Jonge, 2024). It will be wise to take increased stormwater flooding into account while developing these new houses because the costs of mitigating flooding with the traditional sewage system are increasing (Chen et al., 2017).

Nature-Based Solutions can be used as one of the solutions to flooding due to extreme rainfall events. Chausson et al. (2021) defines Nature-based solutions as solutions which tackle societal challenges by working with nature. For example Dedekorkut-Howes, Esraz-Ul-Zannat, and Morgan (2024) have found in their literature research that green roofs, rain gardens (bio retention), permeable pavements, rainwater harvesting, infiltration trenches and urban forests can work well to prevent urban flooding due to extreme rainfall events. Furthermore the paper states that Nature-Based Solutions can work well in combination with currently existing gray infrastructure to mitigate stormwater runoff. Similarly Barbagallo et al. (2025) have found that implementing Nature-Based Solutions can work well against stormwater runoff. However, Nature-Based Solutions can be hard to implement in urban areas because of limited space and the cost of retrofitting NBS' in the city (Aerts et al., 2022).

It is noticeable that very few papers have investigated the implementation of NBS' against stormwater flooding in new construction areas . For instance, Aydin, Casali, and Twohig (2022) have looked into the implementation of Nature-Based Solutions such as green roofs in Helsinki, Finland. The paper investigated mostly existing neighborhoods and did not focus on new construction areas. Alivio, Bares, et al. (2024) have looked into the implementation of Nature-Based Solutions such as permeable pavements and green roofs on the campus of KU Leuven, Belgium. However a university campus is not fully comparable to (new) residential areas. Another example is the paper by Costa et al. (2024) which did look into the implementation of NBS' in the Netherlands but investigated the entire city of Eindhoven, thus the paper included both new construction areas and older parts of the city.

3.2 Research objective and process

Based on the studies in section 3.1 a clear gap arises. First of all, it is not known to which extent new construction areas can be adapted to the increase of stormwater. Additionally the effect of implementing Nature-

Based Solutions in the new construction areas to mitigate stormwater is not fully known. All this information leads to the following research question:

What is the impact of the implementation of Nature-Based Solutions on stormwater flooding in new construction areas in the Netherlands under uncertainty of extreme rainfall due to climate change?

Several sub-questions have been used to answer this main research question. All sub-questions will be shown and explained below. Some of this explanation contains information that will be described in more detail in later sections such as the methodology.

Sub-question 1: *What are the key insights to be able to construct a model which can help understand the Nature-Based Solutions impact on the new development areas?*

This sub-question will help to discover information that is relevant for the research. For instance, Het Zand has been selected as a case-study because it resembles the lay-out of new construction projects. Furthermore research has been performed on the different types of Nature-Based Solutions and their characteristics. Furthermore, a few papers have been read to gather knowledge on the amount of infiltration of green surfaces such as grass or trees.

Sub-question 2: *How can a model be conceptualized to asses the impact of NBS on stormwater flooding?*

This sub-question has been used to think about the model itself. The Arc-Malstrom flood model has been selected to process the Digital Elevation Model into flood data. Furthermore ArcGIS PRO is chosen to visualize results and to perform most spatial operations. Furthermore it is important that the model can generate accurate results given the data quality. Therefore the required quality of input data such as the Digital Elevation Map was determined.

Sub-question 3: *How can a model be operationalized to learn the effects of NBS in new construction areas in the Netherlands?*

During this sub-question all information derived from the first sub-question has been implemented into the conceptualized model from the second sub-question. Therefore several spatial operations have been performed in ArcGIS Pro to make sure the Digital Elevation Model could be used in the Arc-Malstrom model. Furthermore Nature-Base Solutions, in this case green-roofs, have been implemented to asses their impact.

Sub-question 4: *Which lessons can be learned from the model that can help understand the impact of NBS on resilience in the new construction areas?*

The results that have been generated during the third sub-question have been analyzed during this phase. This was done on both an overall view of the area and by looking at the visual results of specific areas. Furthermore the data that has been generated in this research was validated with data from earlier research.

3.3 EPA Relevance

This research is a typical EPA research problem. During this research a deep understanding of previous research was needed. Therefore a thorough literature review has been performed. Additionally an in-depth research for an international grand challenge has been performed. Issues with urban flooding are increasingly common in the world. EPA focuses a lot on international grand challenges such as this one. Additionally, there is a significant amount of countries facing housing shortages currently. Last but not least, this research will has required a significant amount of modeling. Modeling while regarding issues such as low data quality and decision making under uncertainty are typical for EPA. Furthermore, the research requires a multi-disciplinary approach: an extensive literature review has been performed, a model has been made and the physical component was analyzed.

4 Literature research

4.1 Overview

A literature review has been performed to discover the landscape of existing research. The information from this literature research has been used to gather information in order to be able to answer the main research question. Furthermore the methodology is based on the information that can be found in the literature research. This literature review will focus on the following 4 topics:

- The recent history of policies in the Netherlands on new spatial planning. Therefore the vision of the government of the Netherlands will be analyzed over time.
- The publications on research which is already performed on the implementation of Nature-Based Solutions in the Netherlands.
- The characteristics of Nature-Base Solutions. For instance, the different types of Nature-Based Solutions, their effectiveness, if they can be combined etc.
- The different types of flood models and their characteristics.

At the end of this section the information in the literature research will be summarized and the choices that will be made for this research will be motivated.

4.2 History of spatial planning policies

The national government of the Netherlands has published several documents over the years which the describe the vision on spatial planning. These documents show the priorities and processes which are used in spatial planning and in collaboration with local government bodies (Ministerie van Onderwijs, n.d.).

The document which is currently used is the NOVI (Nationale Omgevingsvisie). Central to the NOVI is that the document recognizes that spatial planning should take challenges such as climate change, environmental issues and construction of residential areas into account. These challenges will change the Netherlands and the goal of the NOVI is to adapt to these challenges. Usage of the physical environment should be adapted to the characteristics of the ground-water system (BZK, 2020).

Another important characteristic of the NOVI is that the national government will take more control and work more closely with other bodies of the government. This is in contrast to the deregulation which has already been discussed in the motivation. The national government is planning to give directions to considerations which are specific to local government bodies. These considerations should prioritize a combination of functions over a single use of a function. This means that solar panels on houses are preferred over houses without solar panels (BZK, 2020).

Furthermore the NOVI makes clear that it is important to take different considerations into account. Choices should be made between nature, landscape and water. Furthermore the environment we live in should be clean and healthy but also good for our economy. The Netherlands has a long tradition of adaptation to the environment (BZK, 2020).

Related to this research the NOVI states that climate adaptation is very important. The goal is to adapted to climate change and have a robust water system in 2050. Natural systems will be used to enhance both blue and green infrastructure (BZK, 2020). This is interesting as Blue-Green Infrastructure is an older name of Nature-Based Solutions. Furthermore the NOVI states that mitigation and adaptation measures in both the social and physical domain are needed (BZK, 2020).

Only one sentence in the NOVI states that it is important to adapt urban areas to increased stormwater flooding. This is interesting because the NOVI contains a significant amount of information about climate adaptation. Flooding by rivers and sea are discussed in more detail. Therefore it seems that adaptation for increased stormwater flooding in urban areas is not important in the current vision of spatial planning (BZK, 2020).

Before the NOVI the SVIR (Structuurvisie Infrastructuur en Ruimte) was used. The SVIR focuses on economic competitiveness, accessibility in terms of (personal) transport, livability and safety. It is clear that the SVIR has significantly more focus on economic improvement and mobility than the NOVI. Although there is some attention to climate change and adaptation, most of the focus of the SVIR goes to economic improvement (IenM, 2012). This can be seen as logical as the SVIR has been made official during the economic crises. However that would also mean that construction projects during this period would have less focus on climate adaptation.

Furthermore the SVIR states that it leaves control to local government bodies and reduces complicated rules. The national government abolishes national policy on spatial planning and reduces national direction for nature. Additionally the SVIR formulates 13 interests. The local government bodies should operate according to these interests. Local government bodies have freedom of policy outside of these interests. Of these 13 interests only one is aimed at climate adaptation and flooding. Only flooding from the sea and rivers are taken into account in the SVIR.

The NOVI will be replaced by the Nota Ruimte in 2026. Nota Ruimte still has only a concept version as it is not finished yet (Informatiepunt-Leefomgeving, n.d.). The choices and analyses of the Nota Ruimte are based on 3 layers: the ground-water system, infrastructure networks and usage of the area above ground. The Nota Ruimte makes considerations between these 3 layers. For instance space is scarce in the Netherlands and therefore choices have to be made.

It is also clear that the circumstances in which the Nota Ruimte has been written is very different to the NOVI. It is quite clear in the Nota Ruimte that there are new large uncertainties. For instance the uncertainty on climate change is larger than previously thought and extreme weather conditions have an increased occurrence. Furthermore some previous certainties have turned out differently. For instance the housing shortage and the population growth are larger than anticipated (BZK, 2024).

It is very interesting that there is a significant focus on stormwater flooding. It is written that we will face an increased amount of cases of extreme rainfall caused by higher temperatures. There is still also a significant focus on flooding from rivers and the sea. However it seems that this focus is evenly balanced with the focus on stormwater flooding. The landscape, towns and villages have to be adapted to extreme rainfall. It is also interesting that the Nota Ruimte states that climate adaptation against stormwater flooding has to start in new housing construction projects (BZK, 2024).

The Nota Ruimte states that the national government has an active role in spatial planning issues. This role can change between initiating, stimulating or accommodating. The national government will actively work together with local government bodies (BZK, 2024).

When synthesizing the NOVI, SVIR and Nota Ruimte some clear trends emerge in spatial planning policies. First of all it is clear that stormwater flooding is increasingly seen as problematic. The SVIR does not mention stormwater flooding at all, the NOVI mentions it as a problem only once and the Nota Ruimte has some significan focus on stormwater flooding. This is very interesting because this would also mean that new construction projects will be increasingly adapted to stormwater flooding.

Furthermore the national government of the Netherlands currently has a more active role in spatial planning issues. The SVIR states that it leaves control to local government bodies and that national direction for nature will be reduced. However both the NOVI and Nota Ruimte provide a more active role for the national government. Both state that the national government will work actively together with local government bodies. This means that local spatial planning policies will fall more in line with the national policies and therefore that the national focus on stormwater flooding will translate to more focus on this issue in new construction projects.

4.3 Publications in the Netherlands on NBS'

The paper by Boogaard and Koning (2024) has looked into rain infiltration by swales, a type of Nature-Based Solutions, in the Netherlands. The paper states that local government bodies are often struggling with the design and maintenance of swales. This is the result from a lack of design guidelines which are missing because little is known of the functioning of swales. This information is missing because local government bodies often don't monitor the performance of their swales. Therefore the aim of this paper is to investigate the effectiveness of swales, setting guidelines for designing swales and setting up methodologies for evaluating the performance of swales

(Boogaard & Koning, 2024).

Something interesting that can be read in the paper is that the Netherlands already started working on Nature-Based Solutions before climate change considerations where taken into account in water management. One of the reasons for this is that sewage systems were struggling with peak discharge during stormwater conditions. The sewage system was working too fast which resulted in floods in lower-lying areas (Boogaard & Koning, 2024). This is very interesting because it would suggest that Nature-Based Solutions are already implemented in the Netherlands after 2000.

The paper also states that swales replenish water during droughts and displace water during storwater conditions. Furthermore the paper states that swales are ideal for urban environments with lower building densities (Boogaard & Koning, 2024).

The methodology for investigating the performance of swales was done by a method the paper calls a "Climatecafé approach". This is basically a participatory approach where researchers, students and inhabitants work together. Therefore the method is a learning-by-doing and multi-disciplinary approach. These Climatecafés performed field work by analyzing real-life swales (Boogaard & Koning, 2024).

The results of the paper show that most but not all of the investigated swales perform better than the Dutch national guidelines. These guidelines state that swales should empty 30cm of water in 48 hours. Furthermore the paper has found that the age and storage capacity of swales don't seem to have an impact on the infiltration capacity (speed of infiltration) (Boogaard & Koning, 2024).

However the paper is mainly focused on the technical details of the swales themselves. The paper does not focus on the impact of implementing swales on the infiltration of stormwater on an urban level (Boogaard & Koning, 2024). Therefore the paper does not show the impact of implementing swales as a NBS' on stormwater flooding in an urban area.

A similar report was made on two swales in Enschede and Utrecht, the Netherlands (Boogaard, Fu, Sing, & Yang, 2024). It can be noticed that one of the authors is the same as the previous paper. This paper only focuses on investigating what the constant hydraulic conductivity is. The constant hydraulic conductivity means the speed at which water is absorbed into saturated ground. The paper states that the constant hydraulic conductivity is determined by factors such as the soil and grass type, the presence of grass roots, temperature of the climate etc (Boogaard et al., 2024).

The goal of the research was to develop a hydrological model which can estimate the value of the constant hydraulic conductivity. The model that was made shows poor results for short-term modeling which means a rainfall event with a short time duration. The model shows better results for long-term modelling which resembles a rainfall event with a long time duration. Therefore the model can be used to predict the constant hydraulic conductivity (Boogaard et al., 2024). Furthermore the research shows that the hydraulic conductivity was higher in summer and winter compared the spring and autumn. It is interesting that the paper shows that the hydraulic conductivity is reduced after long-term operation of the swale which is in contrast with the paper by Boogaard and Koning (2024) which did not find a relation between infiltration capacity (similar to hydraulic conductivity) and the age of the swale.

The paper by Boogaard and Koning (2024) is also only focused on the hydraulic conductivity of swales. The paper does not look into the impact of implementing swales as a Nature-Based Solution on stormwater flooding in a new construction area.

Wageningen University & Research has written a report which contains information on Nature-Based Solutions and their impact on society and the environment in the Netherlands. The paper is mostly meant as a vision document on how the Netherlands could be shaped in 2120 when many nature-based solutions are used. The document used many design discussion sessions with researchers as methodology. The vision document was made because climate change will lead to rising sea levels, extreme weather events and higher temperatures (WUR, 2019).

The paper states that cities will produce more water than they consume and that rainwater will be used optimally. Rainwater will be collected as much as possible by houses and green areas (WUR, 2019).

Sadly the document does not provide more detail on how rainwater will be collected specifically. For instance a preference between different types of Nature-Based Solutions is not provided. Therefore this paper does not contain enough detail that is useful for this research. However the paper shows the relevance of this research because it argues for a future where Nature-Based Solutions are used to mitigate stormwater flooding.

The paper by Klostermann, Lehner, Snep, and Weppelman (2023) also studies the implementation of Nature-Based Solutions in the Netherlands. The paper states that Nature-Based Solutions can be used to improve the resilience of a neighborhood for instance by mitigating the effects of heat waves. However lower-income neighborhoods have less green areas than higher-income neighborhoods. Neighborhoods with mostly social housing have a higher population density and therefore less space for green areas.

The goal of the paper is to investigate if NBS' can be used to improve the social housing areas to improve distributional justice. The methodology that was used was the Living Labs methodology. This means that a case study was used on a real-life neighborhood and that residents' input was used in a participatory approach. The results show that NBS' can indeed be used to improve distributional justice in cities. Furthermore the input of the residents of the neighborhood should be included to improve justice (Klostermann et al., 2023). Although the paper mentions climate adaptation, it does not provide any detail on the implementation of Nature-Based Solutions to mitigate stormwater flooding.

Alkemade, Breman, Van Hinsberg, De Knegt, and Roelofsen (2024) have written an interesting paper on the impact of NBS' on multiple environmental challenges in the Netherlands. The paper states that Nature-Based Solutions can offer benefits on multiple different environmental challenges. However there is a lack of knowledge on what the quantitative impact of Nature-Based Solutions is on these environmental challenges. There is also a lack of knowledge on the impact of NBS' on the national scale as most previous research has looked only into local implementation.

The research has looked into six different environmental challenges: transition to a sustainable agriculture, protection and restoration of biodiversity, good quality of water bodies, good quality of the living environment, climate change mitigation and adaptation and the transition to the production of renewable energy. Furthermore the environmental challenges are categorized within a few environments of which the urban environment is one of them (Alkemade et al., 2024).

The conclusion of the paper states that NBS can significantly improve on all six of the environmental challenges. For this paper the result on the challenge of climate change mitigation and adaptation is the most interesting challenge. The paper shows that the implementation of NBS' can reduce the amount of people living in flood-prone areas by 10-20% (Alkemade et al., 2024). However the paper does not specify whether this result is based on flooding by the sea, rivers or stormwater.

The paper by Costa et al. (2024), which was already mentioned in the motivation, also investigates the implementation of NBS' in the Netherlands. The paper states that not only the flood depth is important when assessing flood damages but also variables such as flow velocity and duration of the flood can result in damages. Therefore the aim of the paper is to assess the effectiveness of the implementation of NBS' on flooding including flood variables such as flood depth and velocity.

The paper uses the entire city of Eindhoven as a case-study. Therefore the research investigated both older and newer construction areas. Green roofs, green parking and water storage on the streets were used as Nature-Based Solutions. Furthermore a 1D/2D-coupled model was used as a method.

The results show that the implemented Nature-Based Solutions reduce the flooded area for rainfall events that happen once every 5, 10 and 100 years. The same results are shown for flood depth and flood velocity. The results also show that the impact of Nature-Based Solutions depend on the area in which they are implemented. The impact on the area mainly depends on the surface area of the Nature-Based Solution. If a Nature-Based Solution can be used on a larger area in the neighborhood the impact of the Nature-Based Solutions also be larger.

To summarize this section it is clear that there is a significant amount of research into Nature-Based Solutions in the Netherlands. However only the paper by Costa et al. (2024) has looked into the impact of the implementation

of NBS' on stormwater flooding. Furthermore the paper by Alkemade et al. (2024) has looked into the impact of NBS' on flooding however it is not clear if this means that stormwater flooding has been investigated.
The paper by Costa et al. (2024) does not focus on new construction areas specifically but has looked into the entire city of Eindhoven. Therefore it is not clear what the impact of the implementation of NBS' on stormwater flooding is in new construction areas. However it is interesting that the paper shows that the impact of NBS' in an area depends on the area itself and primarily the size of the area which is suitable for implementing NBS'.

4.4 Nature-Based Solutions

As already presented in the introduction, the literature review by Dedekorkut-Howes et al. (2024) states that green roofs, rain gardens (bio retention), permeable pavements, rainwater harvesting, infiltration trenches and urban forests have the most effectiveness in preventing urban flooding due to extreme rainfall events. Other NBS' that were discussed in their literature research include: swales, detention ponds, constructed wetlands, retention ponds, urban agriculture, riparian buffers, sand filters, green walls, green streets and blue walls. The paper states that most studies are focused on green roofs, rain gardens and swales. However in the case of green roofs not all studies have studied the impact of the implementation of the NBS' on urban stormwater flooding.

While Dedekorkut-Howes et al. (2024) have found in their literature research that traditional gray infrastructure (sewage systems) is able to drain stormwater quite fast, they report significant benefits of Nature-Based Solutions. The aim of this research is to gather information on the context, implementation and effectiveness of different Nature-Based Solutions. A literature study was used as a method in order to gather this information Dedekorkut-Howes et al. (2024).

The researchers have found that the implementation of NBS' can be cost-effective. Furthermore NBS' can have co-benefits such as an improvement in biodiversity. The paper states that more research is needed into the effectiveness of combining both gray infrastructure and NBS' and combining multiple types of NBS' as the these combinations could work well. The paper states that one of the limitations is that more research is needed on the robustness of stormwater mitigation by Nature-Based Solutions particularly for urban areas and extreme weather events. There is not enough evidence on the effectiveness of Nature-Based Solutions (Dedekorkut-Howes et al., 2024). This adds to the relevance of this research .

Similarly the paper by Henze, Keilholz, Pauleit, and Zolch (2017) shows a comparison between the effectiveness of multiple types of Nature-Based Solutions. The reason for this is that stormwater floods are increasing due to an increase of impervious surfaces and climate change. The academic gap that is identified in the paper is that there is a lack of knowledge on the effectiveness of different types of Nature-Based Solutions on stormwater flooding. Therefore the research has investigated the effectiveness of two types of Nature-Based Solutions: trees and green roofs (Henze et al., 2017). The research uses the city of Munich as a case-study mostly because of an increasing population and an increasing pressure on open space. An increasing pressure on open space suggests that there is an increase of impervious surfaces. Furthermore the research uses the MIKE SHE integrated hydrological model. Two scenario's were used: a rainfall event which occurs once every 2 years and a rainfall event which occurs once every 5 years (Henze et al., 2017).

The research has found that areas with a high amount of impervious surfaces will face more severe stormwater flooding. The implementation of Nature-Based Solutions results in a 14.8% reduction of runoff for green-roofs and a 2% reduction of runoff for trees. Both of these results come from the fact that green-roofs and trees increase interception, evapotranspiration and infiltration. The paper states that an advantage of green-roofs is that they use space which is normally not being used (Henze et al., 2017).

An interesting thing the paper has found is that the impact of green-roofs on flooding decreases as precipitation rises. This can be attributed to the fact that the green-roofs will reach their full-capacity during more severe rainfall events. Therefore better results for mitigating stormwater flooding can be achieved by designing green-roofs with a higher capacity (Henze et al., 2017).

Azadgar, Azl, Gancza, Nyka, and Salata (2025) show that there is a academic gap on the optimization of the consideration between the implementation of Nature-Based Solutions and the benefits of stormwater flood reduction. There are multiple objectives which are conflicting such as water retention capacity, cost-efficiency and land-use. Therefore the researchers have developed a framework which combines a genetic algorithm and the InVEST Urban Flood Risk Mitigation model. The genetic algorithm is used to quickly optimize the placement of Nature-Based Solutions based on trade-offs. While GIS-based approaches are useful for quick assessments, they are not useful for making an optimized design. The InVEST model was used to generate flood model data which is used by the genetic algorithm (Azadgar et al., 2025).

The results show their approach is highly effective in placing Nature-Based Solutions in order to improve water retention which reduces flood problems. According to the research low-cost NBS' such as retention ponds and concave green lands work well to improve retention. While higher cost NBS' such as green-roofs and vegetated swales also work effectively (Azadgar et al., 2025). The conclusion can be drawn that multiple NBS' can be combined for stormwater flood reduction. The Nature-Based Solutions should be combined and placed based on the characteristics of the Nature-Based Solutions and the characteristics of the area.

Similarly Alivio, Bezak, Hume, and Perez-Corredor (2024) have found that a combination of NBS' can work well. The goal of the research was to investigate the effects of NBS' on peak discharges due to stormwater. Both the quantity of the peak discharge itself and the possible time delay in peak discharge can be found in the paper. Furthermore surface run-off (in mm) was also looked at. The paper investigated the impact of green roofs, permeable parking and water ponds on stormwater run-off. It has found that water ponds work well to reduce the peak discharge, while green roofs and permeable parking work well to discharge the water.

Another similarity with the paper by Azadgar et al. (2025) and Alivio, Bezak, et al. (2024) is that they have both found that the effectiveness of an implemented Nature-Based Solutions depends on the area it is implemented in. For instance permeable pavements work well in areas with a significant amount of parking area (Alivio, Bezak, et al., 2024).

Furthermore the paper has found that in scenario's with a very high rainfall event the ability of Nature-Based Solutions to mitigate stormwater flooding may be reduced. Once the saturation point is reached, the implemented Nature-Based Solutions will not be able to mitigate stormwater flooding as effectively.

Alivio, Bezak, et al. (2024) have used the HEC-HMS method which needs a calibrated CN-number and a percentage of impervious area in order to work. The method is widely used and takes the initial moisture level of the soil into account. The study area is a park in Ljubljana, Slovenia. The research area consists of 82% trees and only 13.6% of built environment, which is a different kind of area than the new construction area that this research is investigating. Following the logic of the conclusion by Alivio, Bezak, et al. (2024), the implemented NBS' will have a different effectiveness as the chosen area is also different.

The paper by Dias, Ferrario, Mourato, and Rodrigues (2024) investigated the effects of NBS' on urban flooding due to stormwater The paper uses statistical methods on previously performed studies. Therefore the paper also performed a literature study. The papers that were used from the literature study were papers that described the effect of the implementation of NBS' on temperature and stormwater flooding. The results from the effects of NBS' on temperature and stormwater flooding were then analyzed in RStudio by performing a statistical model. An interesting thing that the paper has found is that 74% of the researches they investigated analyzed green-roofs. Therefore the effect of the implementation of green-roofs to mitigate storwmater flooding is the most well known. Green-roofs have probably analyzed most often because they are the most straightforward to implement (Dias et al., 2024).

It has found that bioretention cells have the most run-off reduction. In decreasing order, green roofs and parks result in less run-off reduction. Single trees have a very small run-off reduction. Furthermore it shows that intensive green roofs (similar to small parks on roofs) result in more run-off reduction than extensive green roofs Dias et al. (2024).
An interesting point in the discussion is that most researches from the literature study analyze NBS' which have already been implemented. Therefore it is possible that these NBS' are reported as effective because they have been implemented in an area in which they are effective Dias et al. (2024). The specific Nature-Based Solutions might not be effective in all areas. This also links to the papers by Alivio, Bezak, et al. (2024) and

Azadgar et al. (2025) that the effectiveness of NBS' also depends on the area in which they are implemented.

When synthesizing the literature it can be seen that all papers show different results on which is the most effective Nature-Based Solution to mitigate stormwater flooding. Furthermore it is often stated that it is not completely known what the effect of Nature-Based Solutions on stormwater flooding is. However all papers do report that Nature-Based Solution are effective as a mitigation solution, there is only discussion on the extent of the effectiveness. The paper by Azadgar et al. (2025) and Alivio, Bezak, et al. (2024) state that the effectiveness of an implemented Nature-Based Solution depends on the characteristics of the Nature-Based Solution itself and the characteristics of the area in which it is implemented. Therefore a combination of Nature-Based Solutions could be used. When combining multiple Nature-Based Solutions, each NBS will be implemented in an area where it is most effective.
Furthermore it is interesting that Nature-Based Solution are effective up to a certain amount of rainfall. If the saturation point is reached the effectiveness of the Nature-Based Solution will be lower (Alivio, Bezak, et al., 2024), (Henze et al., 2017).

4.5 Flood Model characterization

Abustan, Balogun, Mudashiru, and Sabtu (2021) have performed an extensive literature research into the different modeling methods of flooding problems. The paper states their methodology and advantages and disadvantages. Below is a summary of the 3 different flood modeling methods they have found:

- Physical models are models that use realistic experimentation of real-life flood events. Physical models recreate a flood event in a physical environment but on a smaller scale than the real-life event. These models are time-intensive and require complex operations. Because of the rising computing power these models are increasingly replaced by physically-based models.

- Physically-based models simulate physical flood processes by using real-world data. These models consist of numerical models that calculate the flood process over time and space. Physically-based models can be 1D-, 2D- or 3D- models. Topographical Digital Elevations Maps are needed as an input for this type of modeling. 1D-models do not account for the flow dynamics of a stream while 2D- and 3D-models do account for this. 2D-models require significantly more computation time than 1D-models. 3D-models incorporate turbulent flows and therefore tend to be more accurate than 2D-models.

- Empirical models don't simulate a flood process. However these models are trained to predict the outcome of a flood-event by predictions based on the input data. It is a more statistical approach. There are two types of empirical models: qualitative and quantitative. Quantitative models require information on the relation between factors that cause floods and flood occurrence. Qualitative models require expert opinions to determine weights.

Of all these methods the physically based modeling method seems the most usable for this research. First of all, physical model are increasingly becoming irrelevant as they are being replaced by physically-based models. Furthermore a quantitative empirical model will have a lack of data as section 4.3 shows that there is currently limited data on Nature-Based Solutions against stormwater flooding in the Netherlands. Because there is very limited data it is also expected that there would not be enough experts whose opinions can be used for a qualitative empirical model.

Ultimately a 1D-model has been chosen. This is for the fact that the paper by Abustan et al. (2021) has shown that 1D-models can be effective for modelling floods. 2D- and 3D- models also take the flow dynamics of streams into account. However this is not needed as the residential areas in the Netherlands are mostly flat and therefore lack a significant stream dynamic. 1D-models will generate sufficient results for this research.

The Arc-Malstrom model has been chosen as a flood model because this 1D-model has been well described by (Balstrom & Crawford, 2018). The aim of this model is to generate data which is on a more coarse and general level than traditional 2D-models. The Arc-Malstrom model reduces the amount of processing power needed by dividing the map into local sinks, their catchments and paths between these local sinks. A local sink can be understood as a local minimum point of height in which water is collected. This is different compared to to traditional 2D-models which consider the whole landscape (Balstrom & Crawford, 2018). A local sink is called a bluespot if it contains water. A few disadvantages of the Arc-Malstrom model are:

- The model does not account for infiltration by green surfaces such as grass or trees. In essence it views the landscape as completely impermeable. However, infiltration can be accounted for after the fact (Balstrom & Crawford, 2018).

- The model is only applicable for situations where the flow of water can be considered 1D. This means that the direction of flow is only from higher points in the landscape to lower points in the landscape. However it can still be used in cases of stormwater where infiltration is low enough to be ignored. Therefore the model is mainly applicable to cases with only infiltration by green surfaces and not by sewage systems (Balstrom & Crawford, 2018).

- All sinks are assumed to be completely empty before the stormwater event. Therefore the model is not suited for situations where some areas are expected to already contain some water from for instance a previous stormwater event (Balstrom & Crawford, 2018).

- The model does not include the concept of time. This means that all rain from a stormwater event falls on the start of the model. Furthermore, the model calculates the final-state in which all has flowed to it's destination. Thus the model results are from a model run in infinite time (Septima, 2020).

In itself the Arc-Malstrom model itself does not take the implementation of Nature-Based Solutions into account. This has been solved in the research by Aydin et al. (2022). In their research Nature-Based Solutions solutions were applied in a GIS-environment after the flood data has been generated by the Arc-Malstrom model. This means that the impact of Nature-Based Solutions on stormwater flooding can be assessed while still using the Arc-Malstrom model.

4.6 Summary

The research into the history of spatial planning policy show that some clear trends can be seen in the Netherlands. Over time stormwater flooding is increasingly seen as a problem. While the SVIR of 2012 has no attention at all for stormwater flooding, the NOVI of 2020 mentions it once and the concept version of the Nota Ruimte has significant attention for stormwater flooding as a problem. This is interesting as construction projects will be increasingly more adapted to the problem of stormwater flooding. Therefore it is also interesting to investigate a new construction project.
Furthermore it is interesting that the national government of the Netherlands has an increasing active role in spatial planning issues. While the SVIR leaves control to local government bodies both the NOVI and NOVA Ruimte state the government has an active role. This will mean that local construction projects will be increasingly made according to national policies. Therefore the increasing national focus on stormwater flooding will also have an increasing role in new local new construction projects.

Furthermore there is a significant amount of previous publications on the implementation of Nature-Based Solutions in the Netherlands. However there is very little research into the implementation of Nature-Based Solutions on stormwater flooding. There is only one paper which has looked into the entire city of Eindhoven.

Therefore it can be concluded that there is an increasing attention on stormwater flooding in new construction projects, but there is not enough research into the effects of possible implementations of Nature-Based Solutions in the Netherlands. Therefore the first academic gap can be summarized as follows:

It is unknown if Nature-Based Solutions are an effective solution against stormwater flooding in new construction projects in the Netherlands.

The literature research into Nature-Based Solutions has some clear findings. Most of the papers that have been read start with the fact that it is unclear what the impact of Nature-Based Solutions is on stormwater flooding. The results of all papers show that Nature-Based Solutions can be an effective mitigation measure against stormwater flooding. However, the papers seem to disagree on which is the most effective Nature-Based Solution and the degree of the effectiveness of Nature-Based Solutions on stormwater flooding.

Therefore the papers by Azadgar et al. (2025) and Alivio, Bezak, et al. (2024) are very interesting. These papers state that the effectiveness of an implemented Nature-Based Solutions depends on the characteristics of the Nature-Based Solution itself and the environment in which the Nature-Based Solution is implemented. According to Alivio, Bezak, et al. (2024) Nature-Based Solutions will have to be combined and placed in areas where they are the most effective. The fact that the effectiveness of Nature-Based Solutions depend on their implementation and characteristics explains why papers on Nature-Based Solutions don't agree on which is the most effective Nature-Based Solution and the effectiveness itself.

The fact that the impact of Nature-Based Solutions depends on their implementation and characterstics is interesting when looking at the NOVI. The NOVI states that considerations should prioritize a combination of functions over a single use of a function. Because the national government currently prioritizes a functions it will be interesting to look at Nature-Based Solutions which can be combined with other functions.

Of these Nature-Based Solutions green-roofs are the most interesting NBS for this research. This is for the fact that this research is looking at new residential construction areas. Residential areas have a significant amount of rooftop area which can be used for green-roofs. Another alternative for green-roofs would be permeable pavements. Still green-roofs have been chosen for this research as they have been called most often as the Nature-Based Solution with the largest impact on stormwater flooding. Based on this information the following academic gap has been defined:

Which implementation conditions will result in green-roofs being an effective solution to stormwater flooding?

The research into the different types of flood models shows that there are many types of flood models that can be used. The research shows that a 1D-model is most applicable for this research. Furthermore the Arc-Malstrom model has been chosen because it is well documented by Balstrom and Crawford (2018) and Septima (2020). Additionally the

Arc-Malstrom model has already been applied in the research by Aydin et al. (2022) which has observed the impact of the implementation of NBS' on stormwater flooding in Finland.

The literature research has shown that all advantages and disadvantages of the different modelling methods have been already documented. Furthermore it is not the goal of this research to generate a new flood model. Therefore the research into the different flood models does not lead to a new academic gap.

5 Methodology

5.1 Case-study

5.1.1 Case-study selection

The case study has been selected by a few criteria. These criteria can be read below:

- Criteria 1: The construction project should be as recent as possible. Construction projects which are being planned since 2020 take the NOVI into account and therefore should therefore be planned with stormwater flooding into account.
- Criteria 2: The construction project should contain more than 50 homes. The reason for this is that larger projects will have a large area in which green-roofs are implemented. Therefore the implementation conditions for effective green-roofs can be investigated.
- Criteria 3: The construction project should have enough area which can be flooded. For example a single apartment building will not have stormwater flooding on the streets or in parks.
- Criteria 4: A Digital Elevation Map should be available for the construction project. This will be needed for the Arc-Mahlstrom model.
- Criteria 5: Calibration data should be available. Calibration data will be needed to validate the implemented Arc-Mahlstrom model.

The following figure shows the score of each construction project that has been found:

	Criteria 1	Criteria 2	Criteria 3	Criteria 4	Criteria 5
Boogaard, Rijswijk	+	++	+	-	−
Het Zand, Utrecht	+/-	++	++	++	+
Kabeldistrict Delft	++	++	+	−	−
De Kuil, Rotterdam	++	++	+	−	+/-

Based on these scores Het Zand in Utrecht has been selected as a case-study. Although it is not a new construction project and thus scores low on criteria 1, it scores high on the rest of the criteria. Especially the scores on criteria 4 and 5 are important as a Digital Elevation Map and the availibility of calibration data make sure that the Arc-Mahlstrom can be made and validated successfully.

Initially it was the goal the have an unfinished construction project as a case-study. A construction project that would still be in the planning phase would be ideal. Projects currently in the planning phase would be made according to the vision of the NOVI and would probably take the Nota Ruimte already into account. However the projects of Boogaard, Kabeldistrict and De Kuil did not have any public available data on stormwater flooding. Therefore it would not be possible to investigate the validity of the model. Furthermore the lay-outs of construction projects in the planning phase were not in the Digital Elevation Model format so they would not work in the Arc-Mahlstrom model.

5.1.2 Motivation case-study: Het Zand, Utrecht

The district of Het Zand in the city of Utrecht was chosen as case study for this research. This project was finished in 2014. Therefore it will be made according to the vision of the SVIR instead of the current NOVI. This means that there probably wasn't any focus on stormwater flooding during the construction. However the date of 2014 works well with the calibration data which is explained in section 7.2. Furthermore the neighborhood features many houses which works well when applying green-roofs. The dutch government prefers combined usages such as houses and green-roofs as discussed in section 4.6. Additionally Het Zand has an interesting lay-out. The north has a compact lay-out where buildings are closer together. The south on the other hand has a less compact lay-out with more green and ditches. In the results section it will be discussed whether this difference lay-out will have an influence on the impact of NBS'.

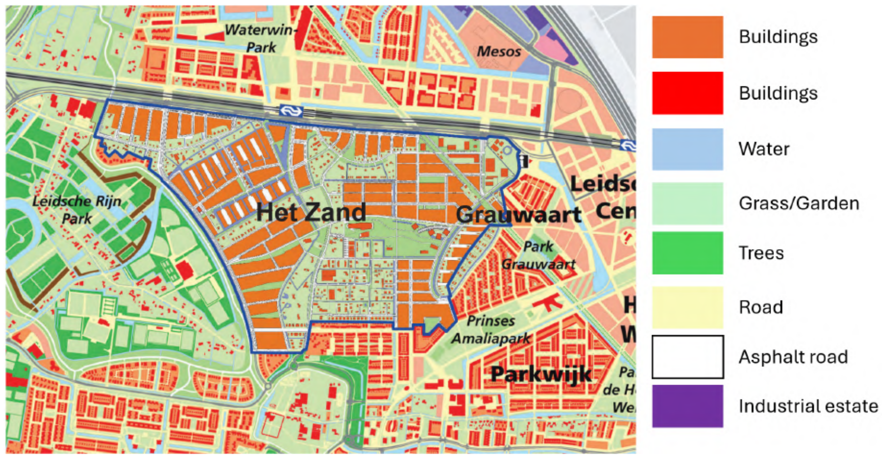


Figure 1: Lay-out Het Zand (Ebberink, 2011)

5.2 Data collection and processing

GIS software has been used for all spatial operations and visualizations that will be described below. The papers by Aung, Irvine, Petschek, and Suwaranit (2024) and Aydin et al. (2022) have shown that GIS software can have a great use in modeling Nature-Based Solutions. ArcGIS Pro has been used because it supports many operations.

5.2.1 Digital Elevation Model

The Arc-Malstrom method requires a Digital Elevation Model (DEM). Therefore the Actueel Hoogtebestand Nederland map has been downloaded from PDOK (2023). This map includes 10 points of elevation data for every square meter. Specifically the Digital Surface Model has been chosen because it also includes elevation data for houses and other parts of the built environment. The area that has been selected can be seen in figure 2. The area of Het Zand itself can be seen in the same figure in blue. The borders of Het Zand were derived from data of the municipality of Utrecht (Utrecht, n.d.).

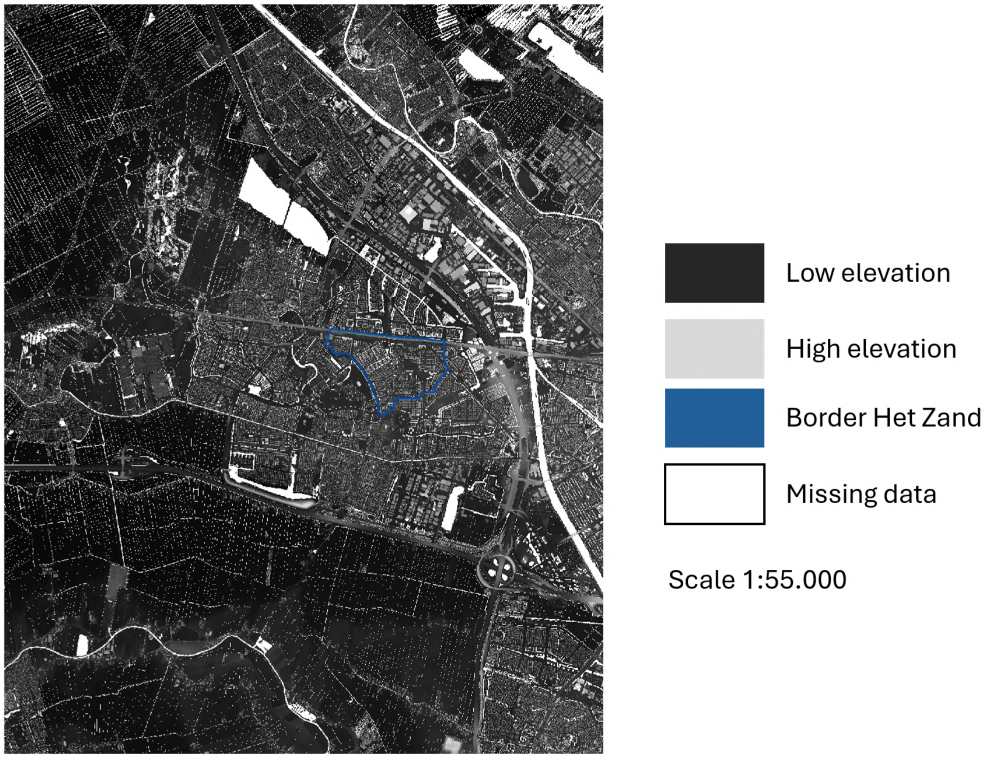


Figure 2: Digital Surface Model (PDOK, 2023)

Because the Arc-Malstrom model is based on the concept of local sinks a larger map than Het Zand itself has been selected. If only Het Zand would be selected the Arc-Mahlstrom model could miss a local sink. That would result in a different flow of water which would influence the results.

A few white spots can be seen in the figure. These white spots are missing data (NoData). Because these spots are missing data the Arc-Malstrom model will not be able to process the stormwater event correctly. Therefore section 5.2.2 will correct these spots with missing data.

5.2.2 Correction for Digital Elevation Model

It can be noticed that there are two types of missing data in the Digital Elevation Model:

- There are large areas with missing data which can easily be seen. These represent rivers, lakes or other larger water bodies.

- Smaller, hard to see areas with missing data are also present. These areas are mostly small water bodies such as small ditches.

For correction of the Digital Elevation Model two assumptions were made. First of all, the assumption was made that larger water bodies have a height 1 meter lower than the area around it. This represents the significant flood protection which is often present for rivers or lakes. Second, the assumption was made that smaller water bodies have a height 0.5 meter lower than the area around it. This represents some flood protection but not as significant for the larger water bodies.

The workflow that has been applied in ArcGIS Pro can be seen in figure 3. Black lines represent steps where processing took place. Blue lines only transfer data.

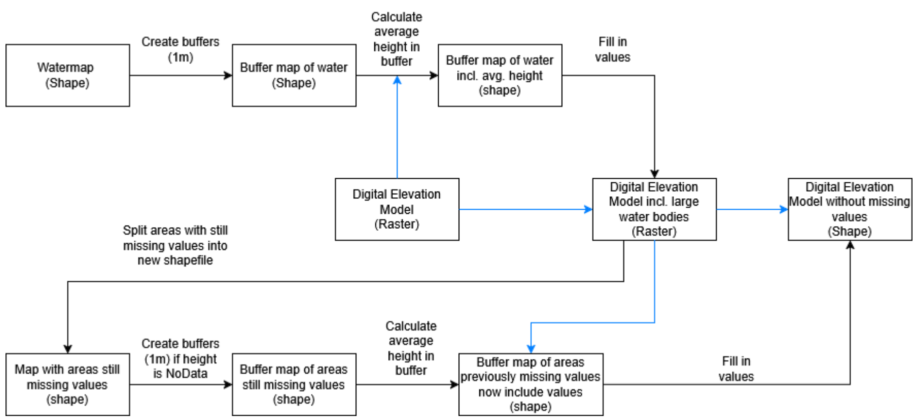


Figure 3: Workflow for correcting DEM (own work)

It is important to note that this is only a schematic that visualizes the project that has been performed. In reality more steps were taken, for instance to change shape files to raster files and to clip files to the correct size. The watermap has been downloaded from Atlas-Leefomgeving (2025). This map contains all rivers and most lakes in the Netherlands.

This method of correcting for the missing values in the Digital Elevation Model works mostly correct and generates the intended results. There are still some limitations. One example of these limitations can be seen in figure 4. It is important to note that a white color represents a higher height than a dark color. The completely white colors in the figure are areas with missing data which are corrected later in the process. The large gray uniform shape in the middle is a small lake which can be found in the watermap. Therefore it should have a height 1 meter below the average height of the area around it. However the gray color indicates that this lake is higher than the area around it. This is probably because the Digital Elevation Model includes trees around the lake which are outliers that influence the average height disproportionally. Small limitations as this one are expected to have a marginal effect in the results of the Arc-Malstrom model.

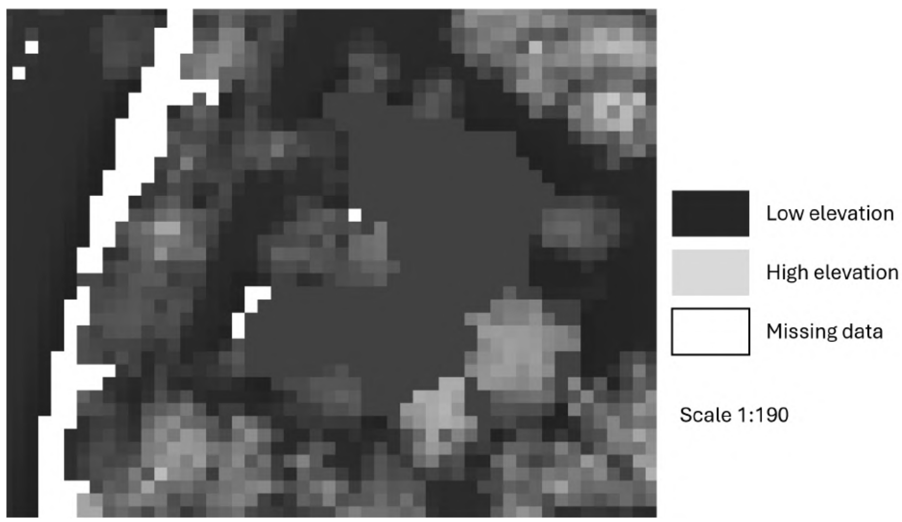


Figure 4: Limitation of correcting for missing values (PDOK, 2023)

5.2.3 Satellite data

In order to be able to account for infiltration in section 5.4 satellite data has been downloaded. An image of the satellite that that has been used can be seen in figure 5. This image contains a bit more area than the city of Utrecht. Het Zand itself is again in blue. The satellite image has been retrieved from Satellietdataportaal (2025) and contains data in RGB-values. The accuracy of the data is 0.3m.

Figure 5: Satellite image that has been used (Satellietdataportaal, 2025)

5.3 Settings Arc-Malstrom model

The Arc-Malstrom model has been performed after the Digital Elevation Model was corrected. A choice was made to apply a filter to automatically remove all bluespots lower than 0.05 meter. As said by (Balstrom & Crawford, 2018) the filter could be higher and therefore more small bluespots would be removed. However that would result in less insight for municipalities on the location of small pools which could still lead to disadvantages for bikers. A scenario with 70mm of rain leads to 1363023 bluespots or 585098 bluespots if the filter has been applied. This amount of bluespots can be found in the area which can be seen in figure 2.

Furthermore 3 scenarios were used. 35 mm of rain which corresponds to an extreme stormwater event once every 10 years, 70mm of rain which corresponds to an extreme stormwater event once every 100 years and 140mm of rain which corresponds to an extreme stormwater event once every 1000 years. These stormwater events have been chosen because they are the same as used by a research that has already been performed for the entire Netherlands (Klimaateffectatlas, 2018), (LIWO, 2018). Therefore the results of this research can be validated by the results of previous research.

5.4 Accounting for infiltration by green surfaces

As already said in section 4.5 the Arc-Malstrom model does not take infiltration by green surfaces (ie. grass or trees) into account. This section will explain how the infiltration was accounted for after the model has generated the results. The method that will be described has been based on the paper by Aydin et al. (2022).

The classification wizard in ArcGIS Pro has been used to identify the different permeable and impermeable surfaces. The classification wizard uses unsupervised learning to identify and categorize classes of surfaces which share the same characteristics. Multiple settings for the classification wizard were used and the best classification was selected by hand. The following table shows the settings that were used.

Test no.	1	2	3	4	5	6	7	8
Spectral detail	13.5	17.5	17.5	20	20	20	15	17.5
Spatial detail	15	15	12	12	10	15	17	20
Minimum segment size	20	15	15	15	15	15	15	15
Max classes	6	8	10	12	10	8	8	8
Max number of iterations	20	20	20	20	20	20	20	20
Maximum number of cluster merges	5	5	5	5	5	5	5	5
Maximum merge distance	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Minimum samples per cluster	5	5	10	12	12	10	10	10
Skipfactor	1	1	2	2	2	2	2	2

Test number 2 generated the best classification result. The satellite image on which the classification results were evaluated can be seen in figure 14 in the appendix. This image contains several details which are interesting. It contains multiple types of trees. Furthermore it contains both permeable surfaces such as trees and grass and impermeable surfaces such as roads, houses and parking lots. Although the area contains a section outside of Het Zand, it is expected that this is to most useful area for evaluation because it contains all these different kinds of surfaces.

The classification was very good in making a distinction between permeable and impermeable surfaces. Furthermore the distinction between grass and trees was not great but decent enough to work with. The classification was quite bad in making a distinction between multiple types of trees. Therefore it was not possible to account for the infiltration values of multiple types of trees. The following values of infiltration were used:

Surface	Permeability	Infiltration value
Grass	Permeable	0.0026 $m^3/hour$
Trees	Permeable	0,0104 $m^3/hour$
Roads	Impermeable	0 $m^3/hour$
Houses	Impermeable	0 $m^3/hour$
Parking lots	Impermeable	0 $m^3/hour$

The infiltration of grass is based on the assumption that the area has light-clay soil. The reason for this is that the park nearby Het Zand has light-clay soil according to Atlas-Leefomgeving (2024). According to the paper by Carsel and Parrish (1988) the hydraulic conductivity of clay loam is average 0.26cm/hour. The hydraulic conductivity was used because accounting for factors such as soil saturation, variable rainfall intensity and heterogeneity in hydraulic conductivity would not fit reasonably in the time schedule for a Master Thesis. Furthermore the papers by Aydin et al. (2022) and Balstrom and Crawford (2018) have shown that only taking the hydraulic conductivity into account provides sufficient results. The hydraulic conductivity of trees is 354% higher than for clay loam (Sepaskhah, 2016).

Shadows are considered to be impermeable. Most of the shadows appear to be shadows from buildings on a road. There are small shadows by trees. Because most shadows are impermeable it has been decided to consider them impermeable.

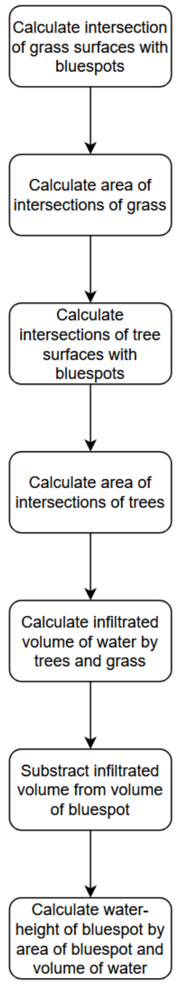


Figure 6: Workflow for accounting for infiltration by green surfaces (own work)

Figure 6 shows the workflow that was used to account for the infiltration. First of all the intersection between the surfaces of grass and bluespots was calculated. This means that ArcGIS Pro was used to calculate which patches of grass were also on bluespots. After that the area of these intersections were calculated. It is important to note that a single bluespot can intersect with multiple different surfaces of grass. Therefore the area of these intersections was summed regarding the bluespots. After that the same steps were taken for trees. The infiltrated volume of water by trees and grass was calculated for every bluespot by the area of the intersecting surfaces of trees and grass and the infiltration values. Then the volume of water after infiltration was calculated from subtracting the infiltrated volume of water by the volume of water from the bluespot. Finally the water height was calculated by the volume of water of the bluespot after infiltration and the area of the bluespot.

5.5 Implementation green-roofs and scenarios

In order to assess the impact of Nature-Based Solutions, in this case green-roofs, on stormwater flooding green-roofs have to be implemented. This section will show how the green roofs were implemented and how their impact was measured.

5.5.1 Implementation green-roofs

Green-roofs were added in a similar but different way as the green surfaces in section 5.4. Figure 7 shows the workflow that was used. First of all green roofs were assigned to houses. This was done by assigning the variable "green_roof" to houses. A "green_roof" value 1 means that the house has a green-roof, a value of 0 means that the house does not have a green-roof.

After that all houses were assigned to bluespots. This is to make sure that a house actually uses it's green-roof to reduce the amount of water of a nearby green-roof. An example of the visualization in ArcGISPro that was used for this can be seen in figure 16 of appendix 9.3. Both the files for the maps of watersheds and bluespots were used for this process. The watersheds map shows in which areas rain flows to which bluespot. The bluespot map was used to visualize the size of the different bluespots. The following rules were used to assign houses to bluespots:

- Houses were assigned as much as possible to bluespots of which they were in the same watershed. This means that the green-roofs of the houses actually reduced the amount of stormwater volume in a bluespot of which they were in the same flow direction.

- Houses were assigned as much as possible to bluespots with a decent amount of volume of rain water. This means that bluespots with a very small size and low water height were excluded.

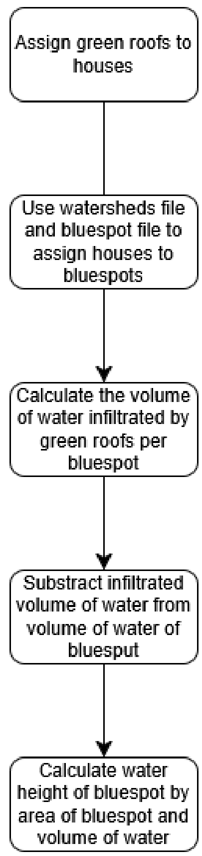


Figure 7: Workflow for implementing green-roofs (own work)

The second rule was chosen because, as said in subsection 5.3, a scenario of 70mm leads to a very large number of bluespots. Therefore it has been decided that it would not be possible to assign every house to the bluespot on which the green-roof of the house had actual impact. Otherwise it would require significantly more time and probably would not change the results much.

The bluespot file map was the one for the 35mm scenario of rain. The reason for this is that doing the same work as well for the 70mm and 140mm scenario would require significantly more work. Therefore it is assumed that the size of the watersheds and bluespot would scale evenly with increase of rain in the scenarios.

After the houses were assigned to bluespots, the volume of water infiltrated by green roofs were calculated per bluespot. An infiltration value of 0.06m^3/hour was chosen based on the paper by Peng, Smith, and Stovin (2020). This infiltration value is significantly higher than for grass or trees when accounting for green surfaces. However that is also reasonable because green-roofs are constructed in such a way that the plants can grow in such a way that their roots are structured.

The last two steps did happen in the exact same way as when accounting for green surfaces. First the infiltrated volume of water by green roofs was subtracted from the volume of water of each bluespot. After that the new water height of each bluespot was calculated by the area of the bluespot and the volume of water after infiltration of the green-roofs.

5.6 Scenarios

The following table shows all scenarios that were used. Scenario 1 through 6 are used to show if there is a difference when accounting for green-surfaces. Scenario 4 through 9 are used to measure the impact of implementing NBS' on stormwater flooding in the area of Het Zand. Therefore scenario 4 through 12 will be used to answer the main research question.

Scenario 7 through 12 implement 50% and 100% green-roofs respectively. These percentages are deliberately high to be able to determine the full potential of green-roof adoption. In the real-world the adoption rate of green-roofs may be significantly lower because the adoption is influenced by ie. municipality support and whether the construction of houses support green-roofs.

Scenario no.	% Houses with green-roof	mm Rain	Accounting for green-surfaces?
1	0%	35mm	✗
2	0%	70mm	✗
3	0%	140mm	✗
4	0%	35mm	✓
5	0%	70mm	✓
6	0%	140mm	✓
7	50%	35mm	✓
8	50%	70mm	✓
9	50%	140mm	✓
10	100%	35mm	✓
11	100%	70mm	✓
12	100%	140mm	✓

6 Results

This section will show all the results that have been generated. For the visual results the color scheme in the table below has been used. The values of this color scheme correspond with the research by (Klimaateffectatlas, 2018) and (LIWO, 2018). Only the colors have been switched from blue to red as this provides a clearer difference with ie. rivers.

Water height	**Color**
$Waterheight < 0.1m$	
$0.1m < Waterheight < 0.15m$	
$0.15m < Waterheight < 0.2m$	
$0.2m < Waterheight < 0.3m$	
$Waterheight > 0.3m$	

Furthermore the area of Het Zand has been marked by a blue line around Het Zand. Bluespots outside of this area have been removed.

The visual results when comparing the scenario's with and without green-surfaces show some clear patterns. First of all there is only a small amount of flooding on the 35mm scenario compared to the 70mm and especially 140mm scenario. This is logical as more rain should lead to more flooding.

Furthermore it can be seen on the images of Het Zand that there is barely any difference between the scenario's with or without accounting for green-surfaces. For instance figure 8 shows only small differences in the 70mm scenario's. There are nearly no bluespots which are disappearing due to having a water height of 0 and there don't seem to be any bluespots which are reduced in height. This is the same for the area in the south of Het Zand which has houses built farther apart and more green areas as already said in section 5.1.2. More detailed results can be read in appendices 9.4 and 9.5.

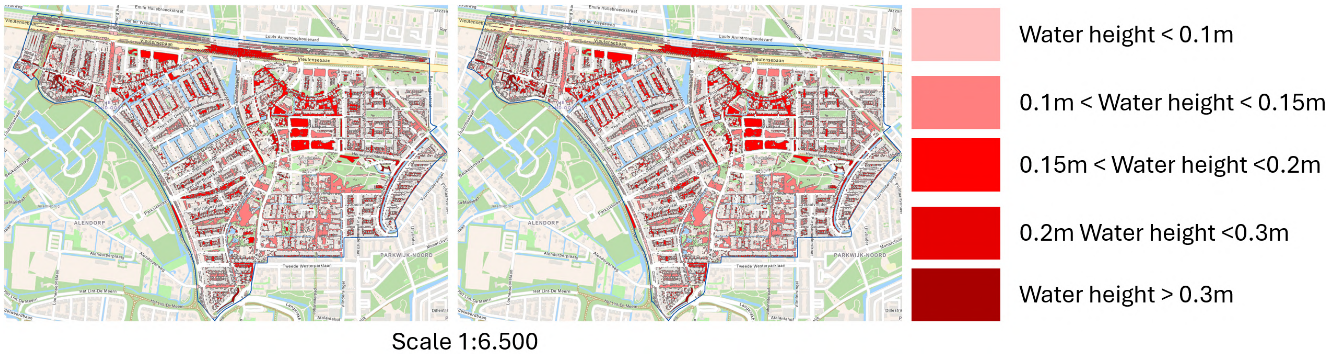


Figure 8: Left scenario 2: 70mm without accounting for green-surfaces, Right scenario 5: 70mm with accounting for green-surfaces (own work)

The visual results for implementing green-roofs show only minor differences. The 50% green-roof scenario's only shows some differences for the largest bluespots. This is especially the case for the 70mm scenario which can be seen in figure 9. Furthermore it can be noticed in to 50% green-roof scenario that the area in the north shows some more significant reductions in bluespot height compared to the south. This is interesting as the north of Het Zand has a more compact lay-out where houses are built more close to each other and the south has a less compact lay-out with more green-areas.

The 100% green-roof scenarios shows a similar reduction in bluespot height compared to the 50% green-roof scenario. Again the the differences are most visible for the largest bluespots as can be seen in figure 10. There does not seem to be a large difference between areas with houses built close to each other or built less close to each other. More visual results for the scenarios with green-roofs can be seen in appendix 9.6.

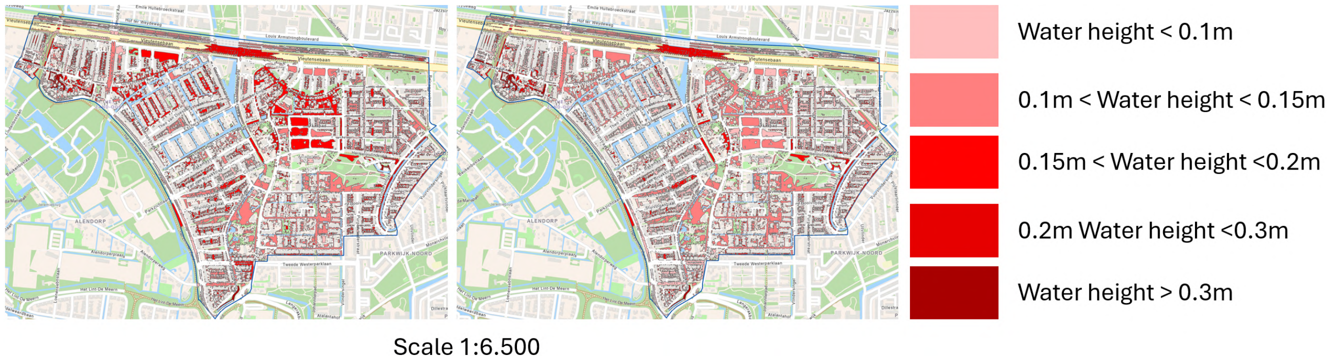


Figure 9: Left scenario 5: 70mm with accounting for green-surfaces, Right scenario 8: 70mm with 50% green-roofs (own work)

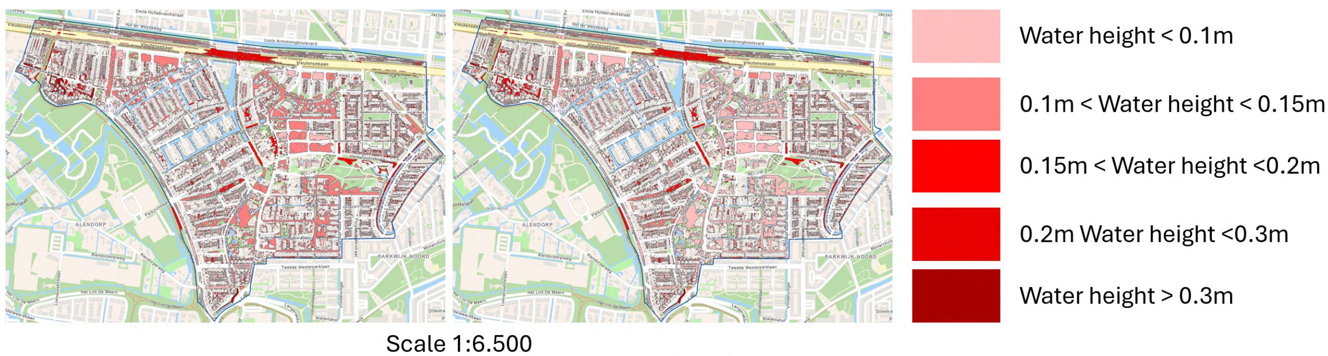


Figure 10: Left scenario 8: 70mm with 50% green-roofs, Right scenario 11: 70mm with 100% green-roofs (own work)

The same story can be drawn from the general summary statistics. These statistics show the results in a non-visual way. The table below shows the results for the scenarios which are accounting for infiltration by green surfaces. Note that the statistic for the number of bluespots counts the number of bluespots with a water height higher than 0cm.

no.	Rain	$\bar{x}$ Water height	σ Water height	no. Bluespots
4	35mm	0,126m	0.0995m	8283
5	70mm	0.194m	0.1541m	8315
6	140mm	0.265m	0.2342m	8321

It can be seen that the amount of bluespots increased from 8283 bluespots in the 35mm scenario to 8321 bluespots in the 140mm scenario, only a 0.45% increase. However the average water height of bluespots increases from 0.126m in the 35mm scenario to 0.265m in the 140mm scenario, a much larger 110% increase. Furthermore it can be seen that the standard deviation increases from 0.0995m in the 35mm scenario to 0.2342m in the 140mm scenario. This information is logical as it is expected that more rainfall will lead to more floodings and that each flooding will become more severe.

The table below shows the statistics for the scenarios which implement green-roofs. It can be seen that the average water height is 1 or 2% lower in the 50% green-roof scenarios versus the scenarios without green-roofs. Furthermore there is a similarly small difference of 1 or 2% between the 50% green-roof scenarios and the 100% green-roof scenarios.
Furthermore the amount of bluespots decreased from 8283 in the 35mm scenario to 8124 in the 35mm scenario with 50% green-roofs. This is only a 2% decrease. The 140mm scenario with 50% green-roofs reduces the amount of bluespots only by 1.5%, from 8321 to 8157.
A similar story can be drawn of the amount of bluespots from the 100% green-roof scenarios. The 35mm scenario shows a reduction of only 0.27% in the amount of bluespots between the 100% and the 50% green-roof scenario's, from 8124 to 8102. Additionally the 140mm scenario shows only a 0.43% reduction in the amount of bluespots, from 8192 to 8157.

The standard deviation shows only minor changes when implementing green-roofs. For instance the 35mm scenario has a standard deviation of

0.0995m without green-roofs, 0.1006m for 50% green-roofs and 0.1007m for 0.1007. Furthermore the 70mm scenario has a standard deviation of 0.1541m without green-roofs, 0.1558m for 50% green-roofs and 0.1560m for 100% green-roofs. However it can be seen that for the 35mm, 70mm and 140mm scenario's the standard deviation increases slightly when implementing 50% green-roofs and has an even more slight increase when implementing 100% green-roofs.

This information shows that the implementation of green-roofs results in only a very small decrease in the average water-height, only a 1 or 2% reduction. This means that the implementation of green-roofs has only very limited effect on the severity of floodings. Furthermore there is a less than 1% reduction in the amount of bluespots which means that the implementation of green-roofs also has limited effect on the amount of floodings.

no.	Rain	% green-roofs	$\bar{x}$ Water height	% improved	σ Water height	no. Bluespots
7	35mm	50%	0.125m	1%	0.1006m	8124
10	35mm	100%	0.124m	2%	0.1007m	8102
8	70mm	50%	0.191m	2%	0.1558m	8166
11	70mm	100%	0.190m	2%	0.1560m	8143
9	140mm	50%	0.261m	2%	0.2360m	8192
12	140mm	100%	0.260m	2%	0.2364m	8157

More information was also gathered on the mitigation of the largest bluespots by implementing green-roofs. Therefore the average height of the bluespots with the 10% largest height in the scenario without green-roof implementation were investigated. The 35mm scenario barely reduces the height of the largest bluespots, 0.350m without green-roofs, 0.349m with 50% green-roofs and 0.349m with 50% green-roofs.
However the 70mm and 140mm scenarios both reduce the height of the largest bluespots significantly. In the 70mm scenario without green-roofs from 0.535m to 0.330m with 50% green-roofs, a 38% decrease. In the 140mm scenario from 0.782m without green-roofs to 0.468m with 50% green-roofs, a 40% decrease. However there is nearly no reduction in the height of the largest bluespots between the 50% and 100% green-roof implementation scenario's. In both the 35mm and 70mm scenario's the water height remains

exactly the same between 50% and 100% green-roof implementation, 0.349m and 0.330m respectively. The 140mm scenario only shows a difference from 0.468m to 0.466m in between the 50% and 100% green-roof scenario's. The tables below show the results for the 35mm and 70mm scenario's.

This means that the implementation of green-roofs can have a large impact of above 35% decrease on the most severe floodings. However this is only the case for the 70mm and 140mm scenario's. The implementation of green-roofs has nearly no impact on the most severe floodings in situations with less intense rainfall such as the 35mm scenario.
Further information can be read in appendix 9.9.

35mm Rain

Scenario no.	Green-roofs	Avg. height 90th percentile
4	0%	0.350m
7	50%	0.349m
10	100%	0.349m

70mm Rain

Scenario no.	Green-roofs	Avg. height 90th percentile
5	0%	0.535m
8	50%	0.330m
11	100%	0.330m

Furthermore statistics were gathered for green-roof implementation in the different neighborhoods or 'scherven' of Het Zand. These statistics were gathered in order to be able to discover the implementation conditions which will affect the effectiveness of green-roofs in mitigating stormwater flooding. There appears to be a link between the reduction in water height of the bluespots and the percentage of area in the neighborhood which consists of houses. This can be seen most clearly in the table below for the 70mm scenario's.
For instance in the 50% green-roof scenario for 70mm the average water-height in Stationsomgeving is only reduced by 0.656% with 16.2% of the area consisting of houses. De Veiling has a 1.523% reduction with 21% of the area consisting of houses and Leidsche Maan has only a reduction of 3.179% reduction in average water height with 21.2% of the area consisting of houses.

Something else can be observed is that the 100% green-roof scenario's perform better than the 50% green-roof scenario's but the increase in effectiveness is smaller than between 0% green-roofs and 50% green-roofs. For instance Rijnsche Hout has a reduction of 3.092% of water height in the 50% green-roof scenario and a reduction of 3.865% in the 100% green-roof scenario. Further results of this analysis can be discovered in appendix 9.7. The different neighborhoods or 'scherven' were selected according to the construction plan of the municipality of Utrecht. A picture of the boundaries of these different neighborhoods can be seen in appendix 9.8

These results show that the environment in which the NBS are implemented affects the effectiveness of the NBS itself. This corresponds with findings from Alivio, Bezak, et al. (2024) and Azadgar et al. (2025) as discussed in the literature review. While the implementation of green-roofs only has a 1 or 2% reduction on the average water height of bluespots, the reduction could go up to 7.259% in the case of Tussen de Parken with 30.3% of the area consisting of houses.

Neighborhood	$\bar{x}$ Water height	% lower 50% gr	% lower 100% gr	% area houses
Park Groot Za...	0.220m	-0.528%	-0.770%	11.1%
Stationsomgeving	0.165m	-0.656%	-0.846%	16.2%
Bongerd	0,205m	-1.156%	-1.320%	19.4%
Johanniterveld	0.236m	-0.929%	-1.048%	19.4%
Rijnsche Hout	0.191m	-3.092%	-3.865%	20.3%
Rijnsche Maan	0.203m	-3.183%	-3.787%	20.3%
De Veiling	0.168m	-1.523%	-1.714%	22.0%
Waterwijk	0.199m	-1.732%	-2.079%	21.0%
Leidsche Maan	0.146m	-3.179%	-3.577%	21.2%
Tussen de Parken	0.161m	-6.784%	-7.259%	30.3%

7 Discussion

7.1 Interpretation results

The results of the statistics for Het Zand show that there is only a very slight reduction of 1 or 2% in the average height of bluespots when implementing green-roofs. This is the case for 35mm, 70mm and 140mm scenario's of rainfall. This means that the implementation of green-roofs has only a very small impact on the stormwater flooding in the area overall. Furthermore there is similarly small difference of 1 or 2% between the 50% bluespot and 100% bluespot scenarios. Additionally the number of bluespots also has only a very slight reduction for both the 50% and 100% scenarios. The reduction of average water height when implementing 50% green-roofs is around 1 or 2%. The reduction of average water height from 50% green-roof implementation to 100% green-roof implementation is even less than 1%. This means that the implementation of green-roofs also has a very small impact on the amount of stormwater floodings in the area overall.

The visual maps show similar results when implementing green-roofs. On an overall picture there are only small differences in the amount and height of bluespots. However, this story changes when looking at specific areas when implementing 50% or 100% green-roofs. The 50% green-roof scenarios show that especially the bluespots with the largest water-height are reduced in height. Furthermore it can be seen that the areas with houses built close to each other are most affected.

A similar result can be seen when looking at the results for the bluespots with the 10% largest height. It can be seen for both the 70mm and 140mm that there is a large reduction in the average height of these bluespots. The average height of the 90th percentile is reduced from 0.535m and 0.782m to 0.330m and 0.468m when implementing 50% green-roofs for the 70mm and 140mm scenario's respectively. However the 35mm scenario's show only a reduction from 0.350m to 0.349 when implementing 50% green-roofs.
The implementation of 100% green-roofs however shows almost no difference. The average water height of the 90th-percentile is 0.349, 0.330 and 0.466 for the 35mm, 70mm and 140mm scenario's respectively.
This means that although green-roof implementation doesn't result in a significant reduction in the amount or size of stormwater floods, the most

severe floods are still reduced by a large amount. However this is only the case when implementing 50% green-roofs.

When looking at the statistics for the different neighborhoods it can be seen that neighborhoods with a relatively large area which consists of houses have more reduction in the average water height. While there is only a 1 or 2% reduction in average water height in Het Zand. The neighborhood with the largest percentage of the area consisting of houses, Tussen de Parken, has a 6.784% reduction in water height when implementing green-roofs in the 70mm scenario with 30.3% of the area consisting of houses. This means that neighborhoods which are built more compact with houses closer to each other will have a higher reduction in stormwater flood height compared to neighborhoods with houses built more far apart. This is interesting as the same can be seen when looking at the visual results. Additionally the papers by Azadgar et al. (2025), Dias et al. (2024) and Alivio, Bezak, et al. (2024) also have found that the effectiveness of the implementation of NBS' depends on the area in which they are implemented. However there is a smaller reduction in average water-height when implementing 100% green-roofs compared to not implementing green-roofs. For Tussen de Parken this difference is 7.259%.

This will have significant implications for the Netherlands. First of all, the Netherlands has a lot of areas where houses are built close to each other. Therefore green-roofs might be more suitable for application in the Netherlands. Furthermore, green-roofs can be used in areas with stormwater problems directly. Although green-roofs don't have a large impact on the average or total amount of stormwater problems in an area, it is very interesting that they can be used to have an impact on areas with the most stormwater problems.

7.2 Validation

As already said in section 5.3 the 35mm, 70mm and 140mm amounts of rainfall were chosen because the model can be compared with earlier research. This research has been performed to investigate the impact of climate change on future stormwater problems in the Netherlands (Klimaateffectatlas, 2018), (LIWO, 2018). This research did not include the implementation of green-roofs or any other types of Nature-Based Solutions.

Therefore it can not be used to validate the results of the implementation of green-roofs. However, still the results when accounting for green surfaces can be validated.
Furthermore the research was finished in 2018. Therefore Het Zand in Utrecht was ideal as a case study. As the construction of Het Zand was finished in 2014 it can be seen as a recently finished project compared to the research by LIWO and Klimaateffectatlas which was finished in 2018.
These results should reflect the research that can be found in Klimaateffectatlas and LIWO more closely. Below the results of the 35mm, 70mm and 140mm scenarios when accounting for green surfaces can be seen compared with the results which can be found in LIWO and Klimaateffectatlas of the same rainfall scenarios.

It can be seen in all three of the figures that the results from this research provide an over-estimation compared with the data in Klimaateffectatlas and LIWO. This seems to happen in almost all areas besides the area with the small island and canals in the west. That area seems to suffer little consequences from the increase in stormwater both in the results from this research as well as in the research that can be found in Klimaateffectatlas and LIWO.
It can also be seen that the areas with houses built close to each other such as the areas in the top-left and bottom-left seem to suffer significant flood problems from stormwater in both researches. Furthermore the results in the bottom-right where houses are built farther from each other and have large gards are also interesting. It can be seen that the results of this research provides the largest over-estimations in that area. It can be seen in the research of Klimaateffectatlas and LIWO that these regions face small amounts of flooding. Even the 140mm scenario doesn't show major flooding in that area. On the other hand the results of this research show significantly more flooding in that area.

These over-estimations can probably be explained by the fact that the research in Klimaateffectatlas and LIWO also took the infiltration by the sewage system into account. The assumption of that research is that the sewage system infiltrates 20mm/hour. Furthermore they assumed that the paved areas or optimally connected to the sewage system (Klimaateffectatlas, 2018). On the other hand, the infiltration by the sewage system was not taken into account by this research. This assumption was made because the data on the lay-out of the sewage system was not available for this research.

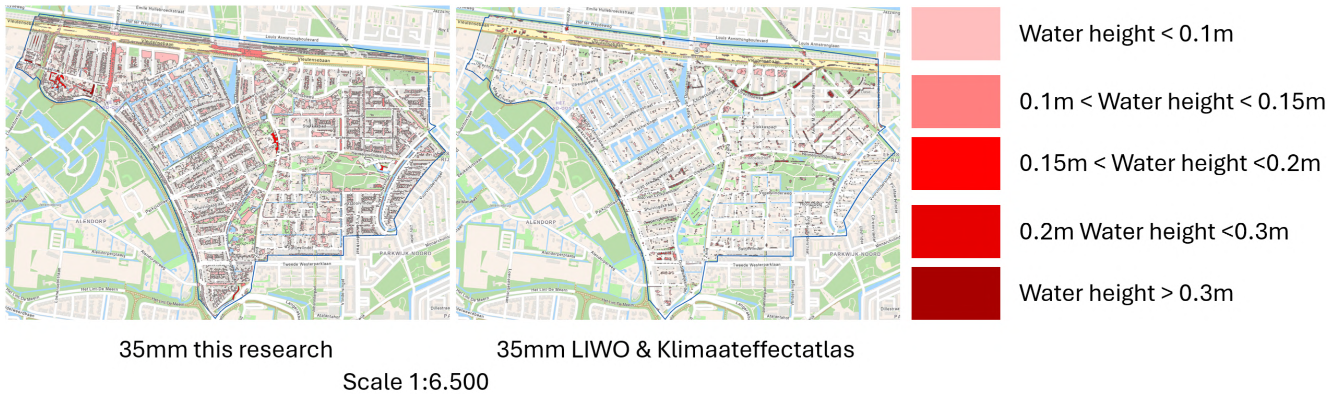


Figure 11: Results of 35mm scenario from this research (own work) compared with data from research in LIWO (2018) and Klimaateffectatlas (2018)

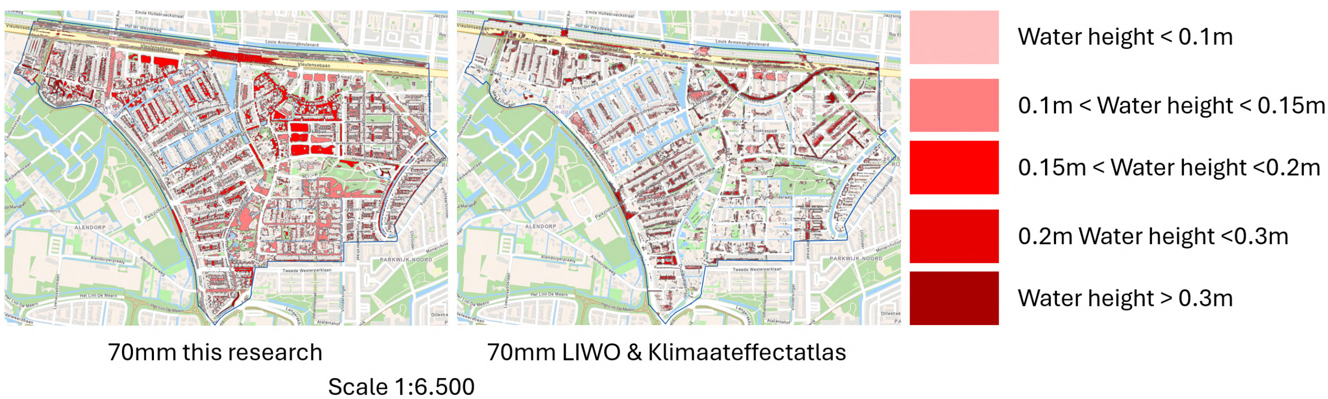


Figure 12: Results of 70mm scenario from this research (own work) compared with data from research in LIWO (2018) and Klimaateffectatlas (2018)

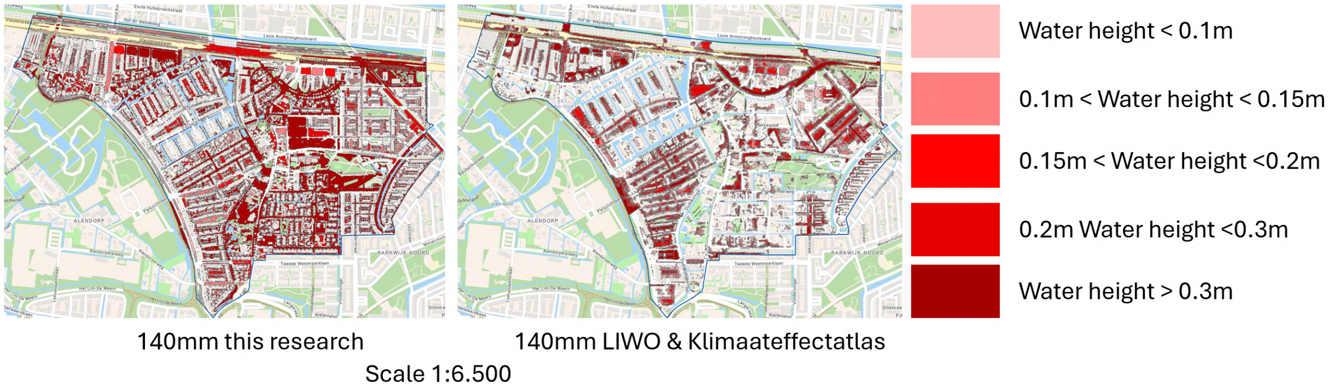


Figure 13: Results of 140mm scenario from this research (own work) compared with data from research in LIWO (2018) and Klimaateffectatlas (2018)

8 Conclusion

Main research question

This research has started with the following research question:

What is the impact of the implementation of Nature-Based Solutions on stormwater flooding in new construction areas in the Netherlands under uncertainty of extreme rainfall due to climate change?

From the literature research green-roofs were chosen to be used in this research to measure this impact. The results show that the implementation of green-roofs in new construction areas provides very little improvement in the total flood problems in the area. Both the average flood-height and the amount of bluespots (or flooded areas) have only very marginal changes of 1 or 2% when implementing 50% green-roofs in the area. Additionally these statistics also change by an insignificant amount of 1 or 2% when implementing 100% green-roofs in the area. These results are similar when implementing 35, 70 and 140 millimeter of stormwater in 2 hours, which mean a stormwater event once every 10, 100 and 1000 years respectively.

However, there are clear differences in the reduction of stormwater flooding by green-roofs when looking at specific areas and neighborhoods. These differences are most clear in areas with a compact lay-out where houses are built more closely to each other. Neighborhoods which have an area which consists for a high amount of houses will have more reduction in the average flood height. In the 70mm the reduction can be up to 6.784% of water height when implementing 50% green-roofs in a neighborhood with a relatively high amount of 30.3% of the area consisting of houses. However the reduction in average water height is smaller when comparing 100% implementation of green-roofs to no implementation of green-roofs, only 7.259% in the same neighborhood in the 70mm scenario. Therefore it is clear that the implementation of green-roofs can have a large impact on stormwater flooding on a local-scale especially when implementing 50% green-roofs in areas which consist of 20 to 30% of houses.

Furthermore the results shows that the implementation of green-roofs have have a larger impact on the stormwater floods which are more severe. Although green-roofs provide very little improvement in the total floods problems in the area, the most severe floods are reduced by a large amount. In the scenario with 70mm of rain the average water height of the 10% most severe floods drops from 0.535m to 0.330m when implementing 50% green-roofs. This result is nearly same when implementing 50% and 100% green-roofs.

Therefore the conclusion can be drawn that the impact of the Nature-Based Solutions on stormwater flooding in new construction areas in the Netherlands is very low when looking at an overall picture. But the impact of Nature-Based Solutions can become significant in areas which consist of 20 to 30% of houses. Furthermore the 10% most severe floods can have a reduction of height of 20 to 30cm in the 70mm and 140mm scenario's. For both statistics there is only a small difference between implementing 50% or 100% green-roofs.

Furthermore it shows that the density of houses is one of the conditions which will lead to a higher effectiveness of green-roofs. If houses are built closer to each other green-roofs will have a more positive impact on stormwater flooding. Additionally these results for green-roofs show that implementing Nature-Based Solutions in new construction areas in the Netherlands is an effective mitigation measure against the most severe floods.

Societal relevance

This information could have a significant use-case for policy-makers. It is clear that policy-makers need to have a look for the stormwater problems in an area when planning for a new construction area because of increased stormwater due to climate change. Policy-makers need to investigate the impact of Nature-Based Solutions in different areas in this planning phase. During this investigation policy-makers will need to keep in mind that Nature-Based Solutions will not change the impact of stormwater flooding overall. But Nature-Based Solutions can alleviate some of the worst problems in areas which are expected to face stormwater problems. Especially in areas where houses are built close to each other (20 to 30% of the area consists of houses) Nature-Based Solutions can be used to mitigate stormwater problems.

These recommendations are interesting because they fit into new development in spatial planning. As already discussed in the literature review the national government of the Netherlands has an increasing focus on stormwater flooding. Furthermore the national government of the Netherlands is taking an an increasingly more active role in spatial planning issues. Therefore the national government could setup laws, guidelines or best-practices etc. for policy-makers on lower levels of government to be able to implement Nature-Based Solutions more effectively.
Furthermore these recommendations also play into an increasing focus on spatial planning issues concerning flood risk mitigation, climate change and rapid urban development (Dabrowski, Meng, & Stead, 2020).

Scientific relevance

The literature review resulted in two academic gaps. First of all it has been found that there is a significant amount of research into the implementation of Nature-Based Solutions in the Netherlands. However there is little research into the implementation of NBS' against stormwater flooding in the Netherlands. Therefore the following academic gap has been formulated:

It is unknown if Nature-Based Solutions are an effective solution against stormwater flooding in new construction projects in the Netherlands.

The conclusion can be drawn that Nature-Based Solutions can work effectively against stormwater flooding in new construction projects in the Netherlands. However this is not always the case. This links to the second academic gap.
The literature review shows that Nature-Based Solutions have been found to be an effective solution against stormwater flooding. However most papers disagree on the effectiveness of Nature-Based Solutions itself. The papers of Alivio, Bezak, et al. (2024) and Azadgar et al. (2025) suggest that the effectiveness of Nature-Based Solutions against stormwater flooding depend on the characteristics of the Nature-Based Solutions itself and the environment in which they are implemented. Because these characteristics are important for the effectiveness of the implementation of the NBS, it is necessary for this research to strategically choose for a Nature-Based

Solutions. Green-roofs have been chosen because these fit into the Dutch policies for spatial planning which state that a combined use in preferred over a single use of. All this information has led to the following academic gap:

Which implementation conditions will result in green-roofs being an effective solution to stormwater flooding?

The results show that green-roofs are significantly more effective against stormwater flooding if implemented in an area which consists of 20 to 30% of houses. Therefore the building density of the area is an important implementation condition for an effective implementation of green-roofs.

Future work

Future work could investigate the implementation of Nature-Based Solutions in new construction areas further. In the literature research it has been found that the combination of different Nature-Based Solutions could be investigated (Dedekorkut-Howes et al., 2024), (Azadgar et al., 2025). For instance some Nature-Based Solutions can be used to transport stormwater to areas where other Nature-Based Solutions can be used to infiltrate as much stormwater as possible. Furthermore the literature research has shown that it would also be interesting to investigate the combination of both gray infrastructure (sewage system) and Nature-Based Solutions (Dedekorkut-Howes et al., 2024).

Additionally new research could look into the effect of saturation when implementing green-roofs against stormwater in the Netherlands. Previous research suggests that Nature-Based Solutions are effective until a certain amount of rainfall (Alivio, Bezak, et al., 2024), Henze et al. (2017). Therefore it would be interesting to investigate until which point green-roofs can be implemented effectively in the Netherlands

Furthermore new research could investigate the same research question in different parts of the Netherlands. The area that has been investigated as a case-study has light-clay soil. It would be interesting to investigate whether the impact of Nature-Based Solutions on stormwater flooding would be the same in other parts of the Netherlands with different types of soil.

Limitations

There were also some limitations during this research. Some of these limitations where the result of assumptions that were made and some of the limitations were the result of data availability for this research.

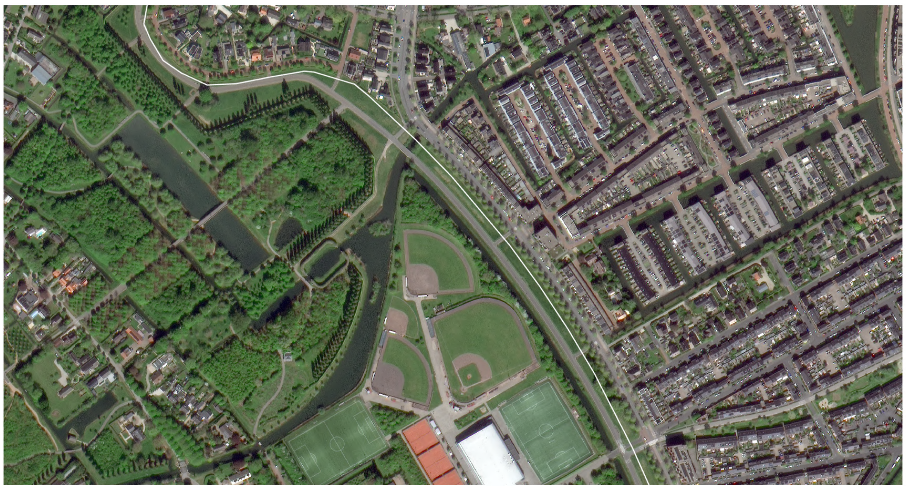
First of all, as discussed earlier the project of Het Zand is not a completely new construction project. Construction of Het Zand was already finished in 2014. Initially the aim for this research was to use a project that was still in the planning phase of construction. However it was not possible to find public data on stormwater flooding on a construction project in the planning phase. It could have been possible to still do research on stormwater flooding on any of these projects. However this would have implications such as not being able to validate the model by previous research. Furthermore, it was also nearly impossible to find a Digital Elevation Map to run the Arc-Malstrom model. Therefore it has been assumed that a recent construction such as Het Zand would provide enough valuable insights to answer the main research question.

Additionally accounting for the infiltration by green-roofs didn't work out as planned. Normally the Digital Elevation Map would be used for this. The infiltration of a green-roof would be determined by the direction of the flow of water determined by the Digital Elevation Map. The infiltration by a green-roof would first be reduced from the volume of water of a bluespot which would be on a lower height than the house itself so that it would be in it's flow direction. If the bluespot would have a volume of zero and therefore by empty the infiltration would be reduced from a bluespot lower than the first bluespot etc. However this was not feasible due to two reasons. First of all there were too many bluespots to do this because it would have to be done by hand in ArcGISPro. Furthermore there are very little real hight differences between houses in Het Zand as in the rest of the Netherlands. Therefore it was not possible to determine for most of these houses what the direction of flow of the water would be.

Last but not least it was not possible to account for the infiltration by the sewage system. This has led to some large differences between data from this research and data from earlier research as can be seen in section 7.2. This is mainly caused by the fact that there could not be found public data on the lay-out of the sewage system in Het Zand. Because the overall trends in the flood data is still similar to the flood data in earlier research it is believed that still a conclusion can be drawn based on the results of this research.

9 Appendix

9.1 Satellite image for classification review



Scale 1:2.600

Figure 14: Satellite image of area which was used for evaluating the classification results. The white line in the middle is the border of Het Zand. Het Zand is on the right side of this border (Satellietdataportaal, 2025).

9.2 Result classification

Figure 15: Classification of the same area as figure 14. The white line in the middle is the border of Het Zand. Het Zand is on the right side of this border (own work).

9.3 Image of assigning green-roofs

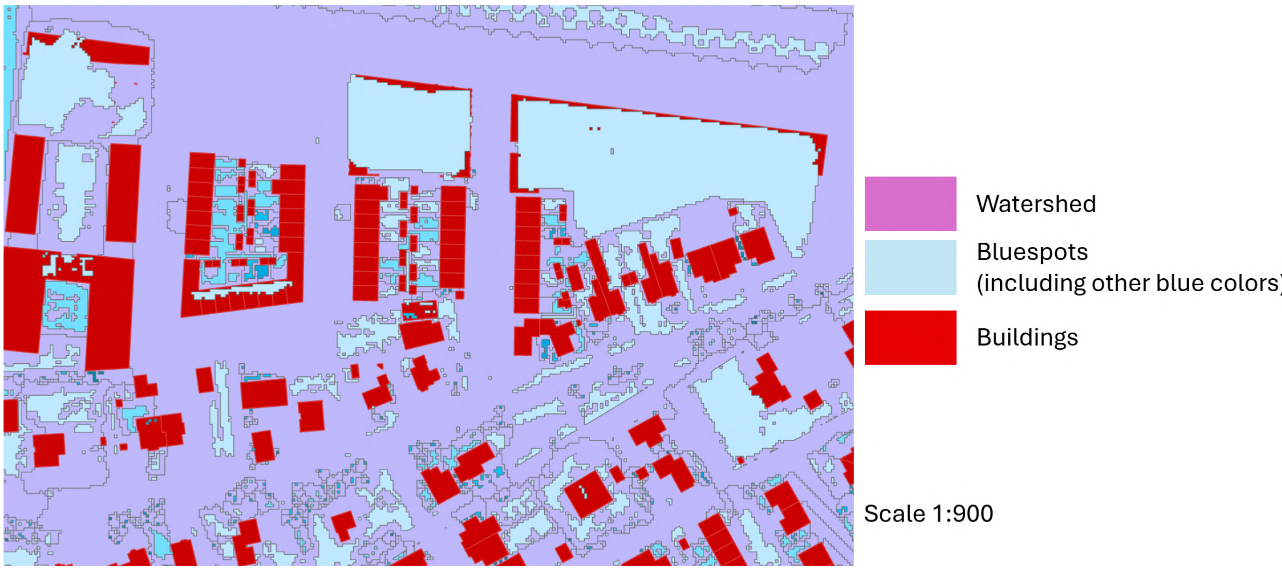


Figure 16: Image which shows how houses were assigned to bluespots. The watersheds file map is shown in purple. It can be seen that some watersheds are very large. The bluespots are visible in blue in the bluespot file map. A darker color for the bluespot means that the water height is higher (own work).

9.4 Visual results without accounting for green-surfaces

This section will shows the results for scenario 1 through 3. In these scenarios the bluespots have not been accounted for infiltration by green surfaces such as grass or trees.

It can be seen that only small amounts of flooding due to stormwater occur in the 35mm scenario in figure 17 while there is major flooding in the 140mm scenario in figure 19. It can be seen that some roads and parking places have more than 30cm of water depths.

Furthermore figure 20, figure 21 and figure 22 show the results for an area in the south of Het Zand. This area is interesting because houses are built relatively far from each other and have large gardens. It can be seen in figure 20 that the 35mm scenario only results in bluespots with a small area and almost all with a water height below 10cm. However in figure 22 it can be seen that almost all roads and gardens have been flooded with a water height above 0.3 cm.

Figure 23, figure 24 and figure 25 show the results for an area in the north. As already said in the explanation of the case-study in section 5.1.2 this area has houses in the top left of the image which are closely built and connected to each other. The gardens here are also quite a bit smaller. The area that can be seen in the bottom right is also interesting. This area consists of small islands with houses built next to each other. Furthermore these islands have large parking places instead of gardens.

In the figures of the north it can be seen that both in the top left and bottom right nearly all roads have been flooded. Furthermore there are less flooded areas around the water bodies in the bottom right as the rain probably flows into the water bodies.

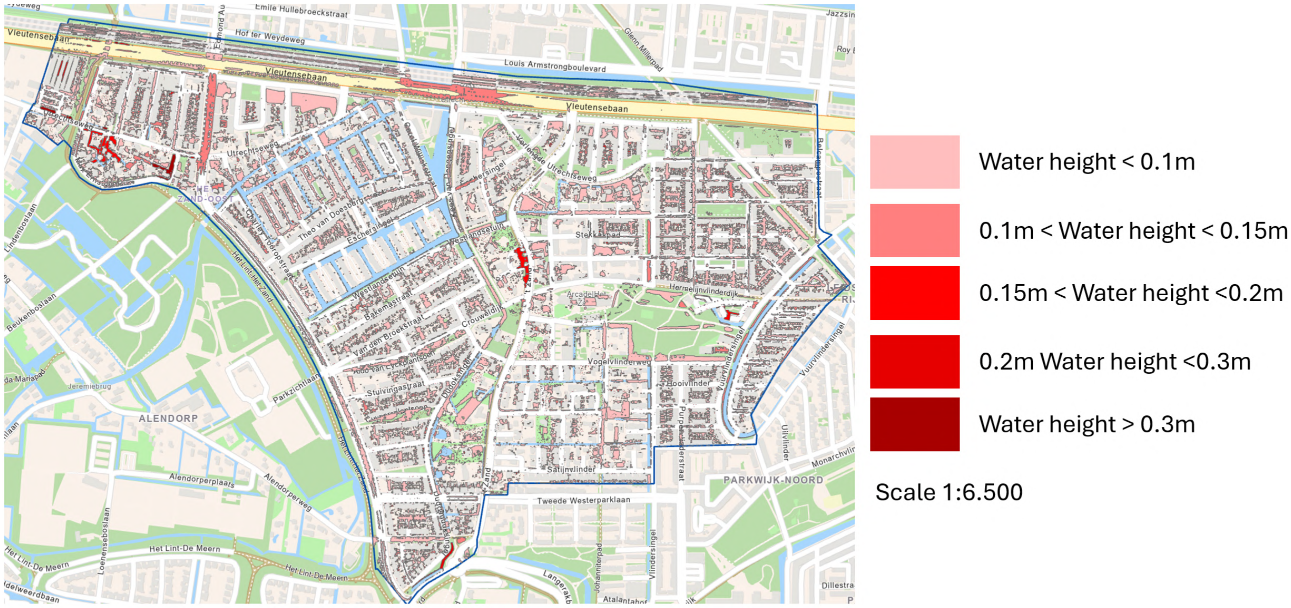


Figure 17: Scenario 1: 35mm rain without accounting for green surfaces (own work).

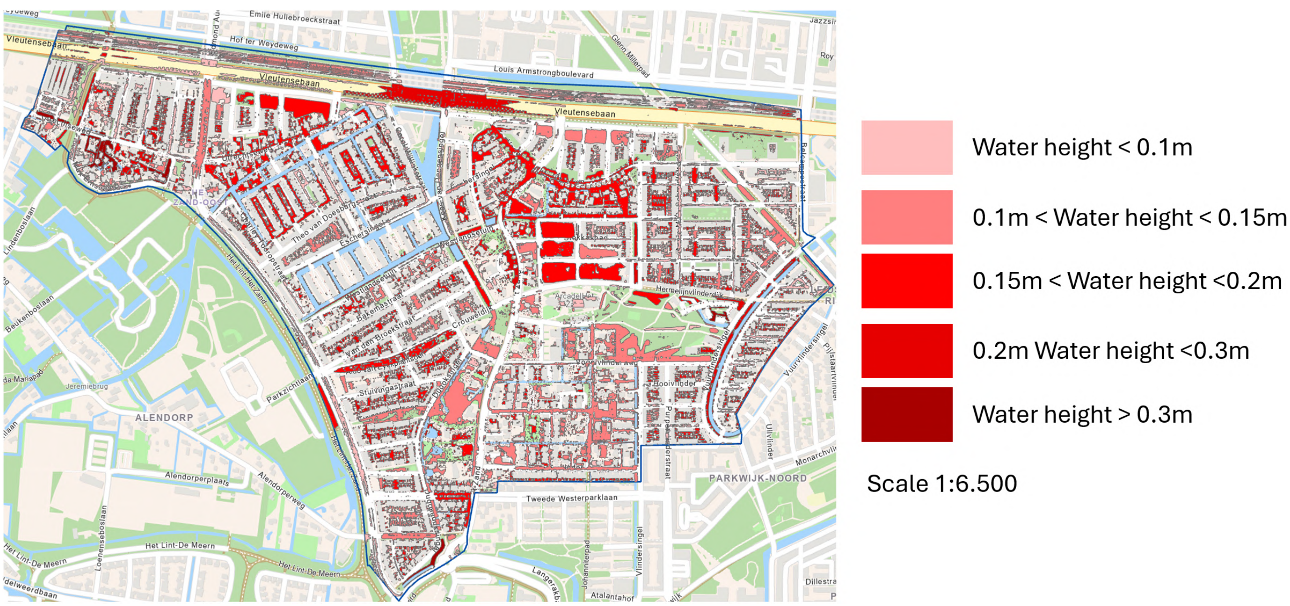


Figure 18: Scenario 2: 70mm rain without accounting for green surfaces (own work).

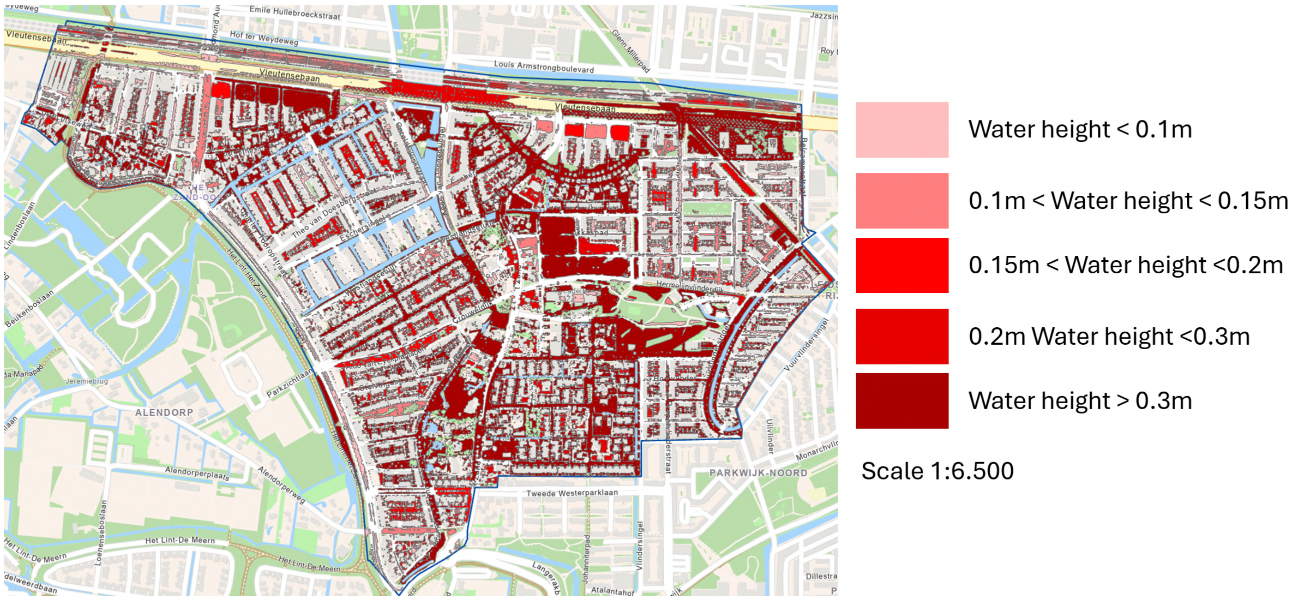


Figure 19: Scenario 3: 140mm rain without accounting for green surfaces (own work).

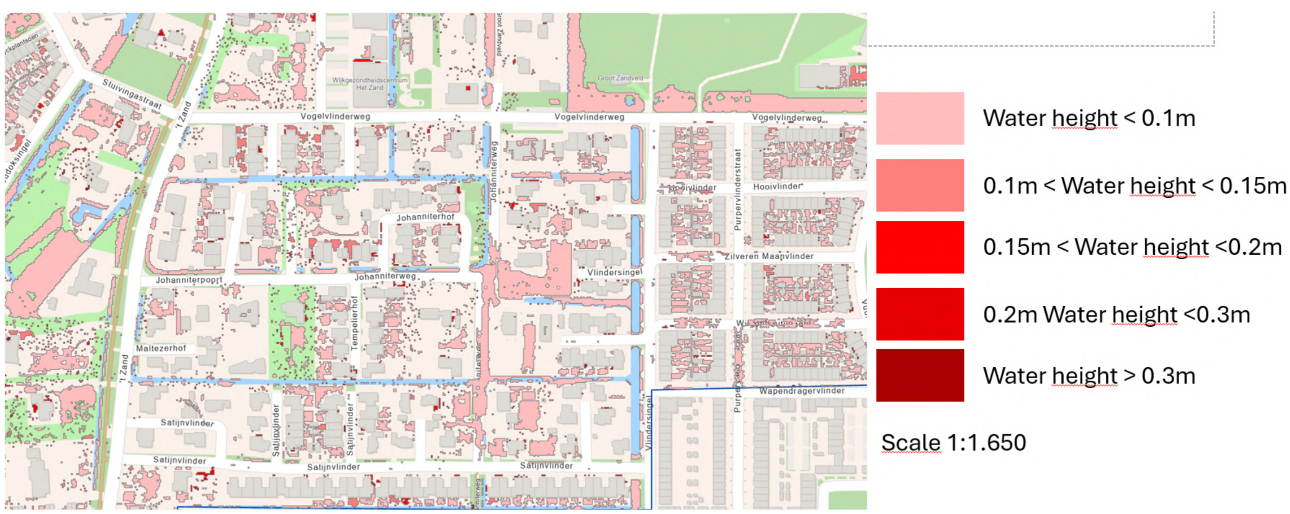


Figure 20: Zoomed in at the south in scenario 1: 35mm rain without accounting for green surfaces (own work).

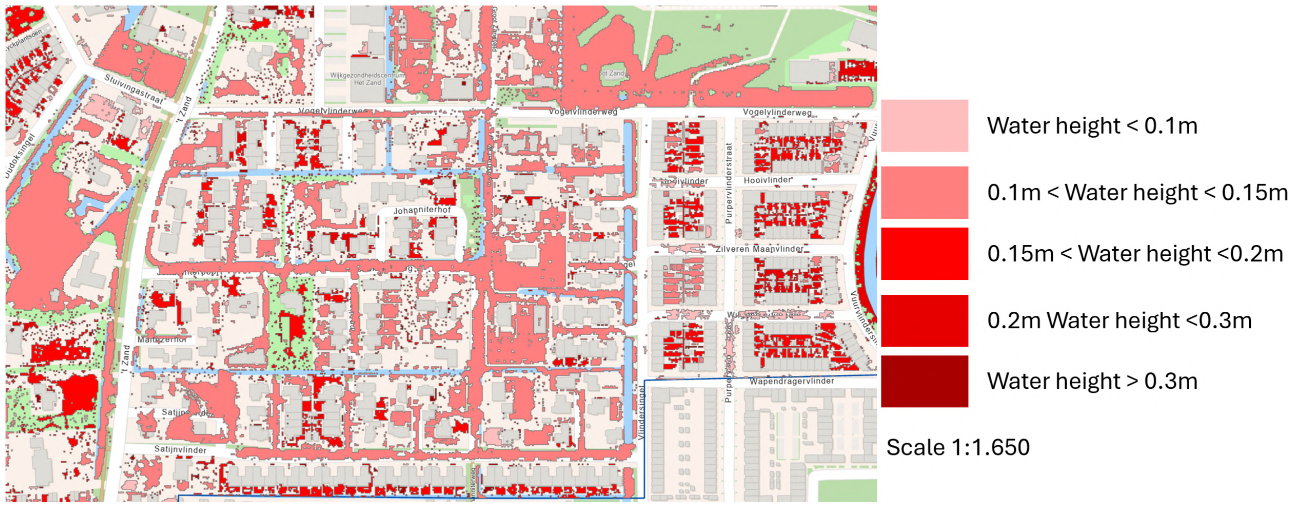


Figure 21: Zoomed in at the south in scenario 2: 70mm rain without accounting for green surfaces (own work).

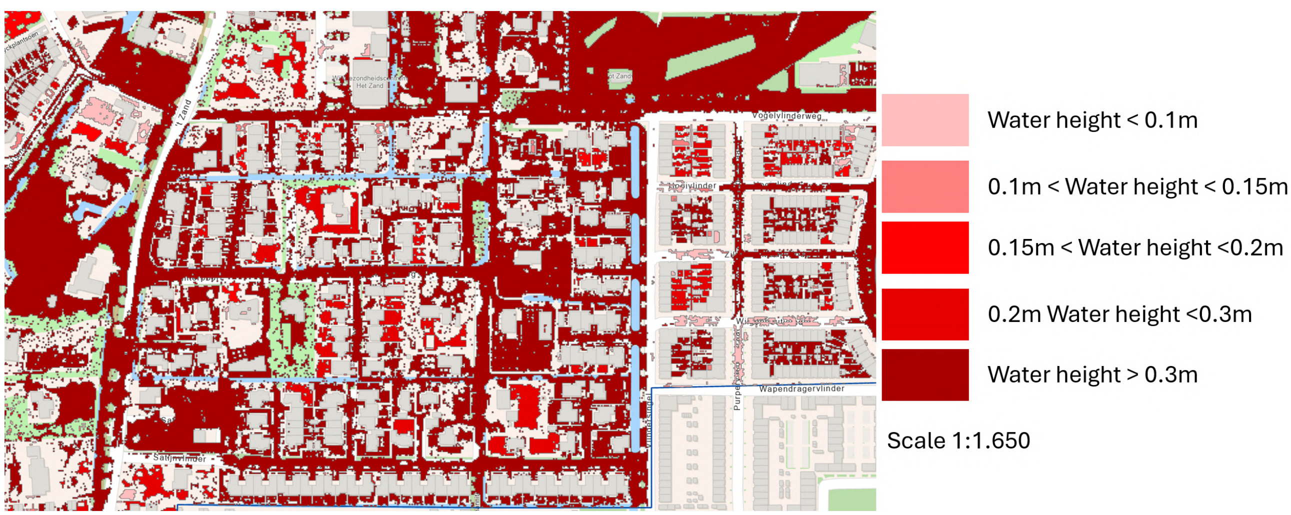


Figure 22: Zoomed in at the south in scenario 1: 140mm rain without accounting for green surfaces (own work).

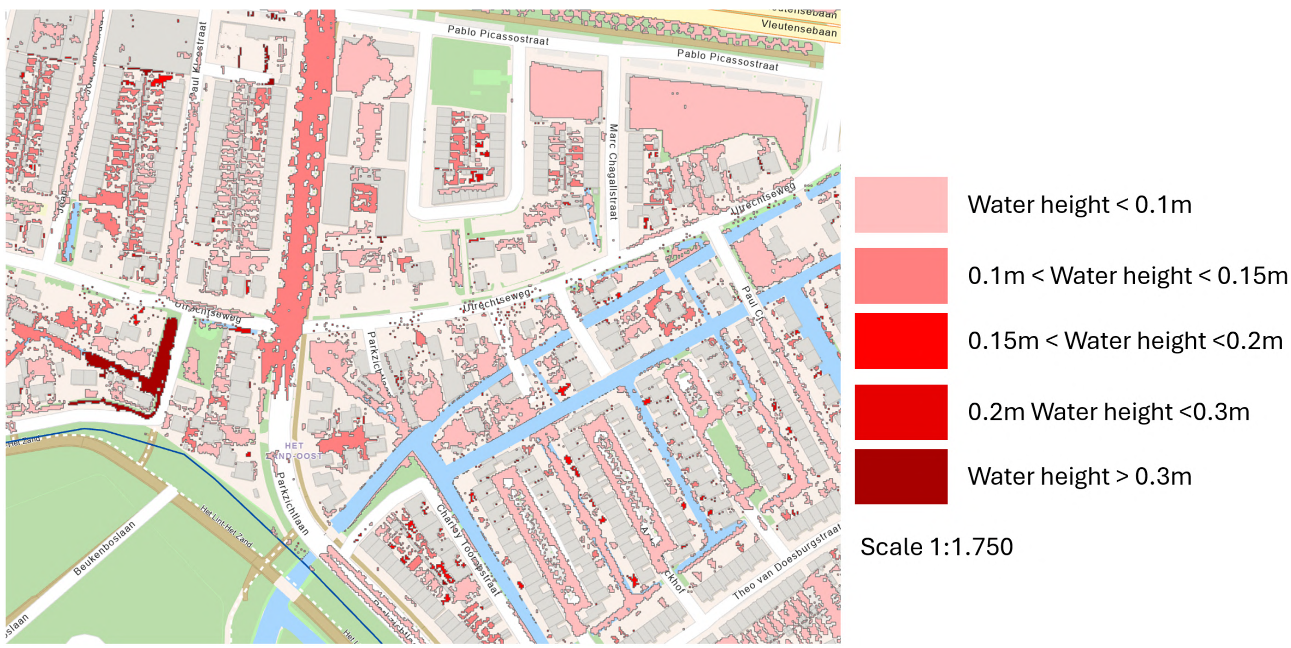


Figure 23: Zoomed in at the north in scenario 1: 35mm rain without accounting for green surfaces (own work).

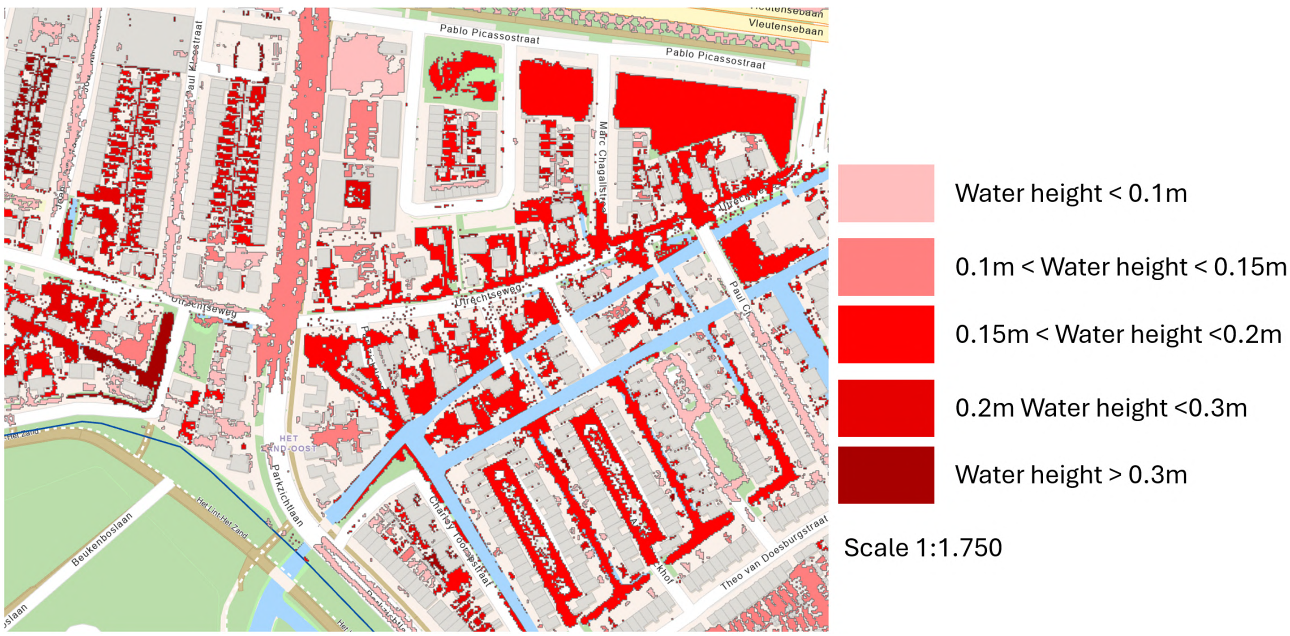


Figure 24: Zoomed in at the north in scenario 2: 70mm rain without accounting for green surfaces (own work).

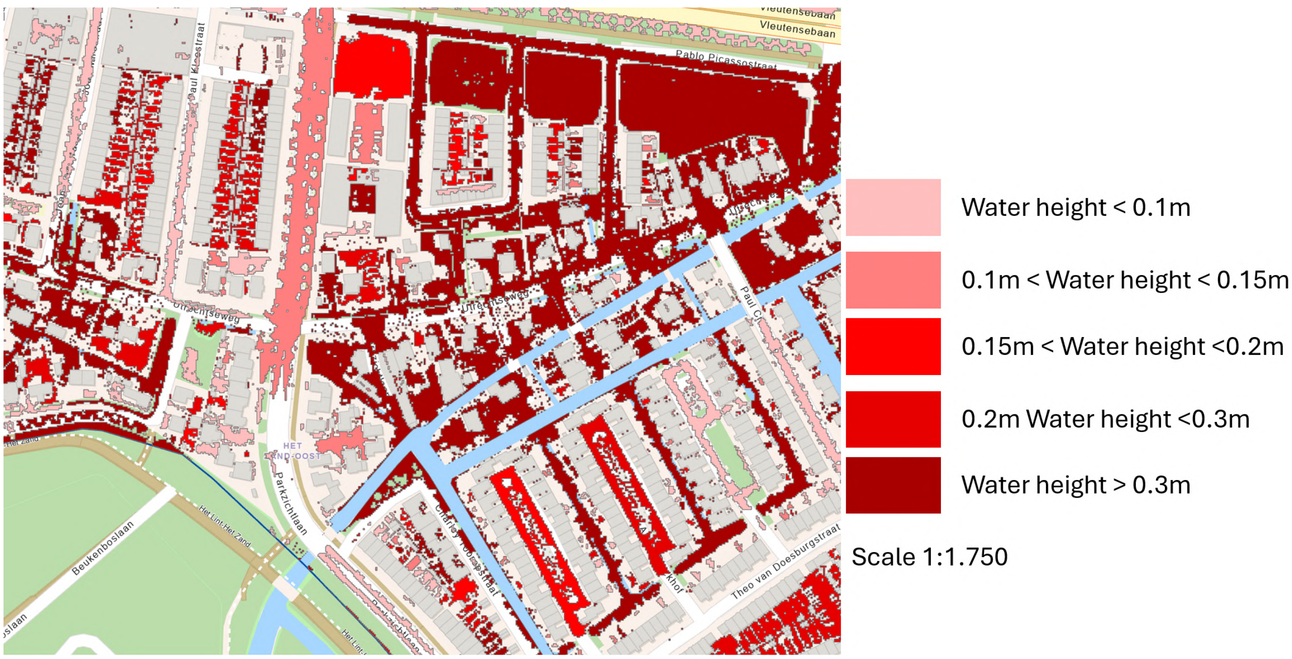


Figure 25: Zoomed in at the north in scenario 1: 140mm rain without accounting for green surfaces (own work).

9.5 Visual results with accounting for green-roofs

This section shows the results for scenario 4 through 6. In these scenarios the bluespots have been accounted for infiltration by green surfaces such as grass or trees. Therefore it is interesting to look at the differences with the results in section 9.4.

When looking at the complete area of Het Zand in figure 26, 27 and 28 it is very hard to spot any differences between the scenarios with and without accounting for green surfaces. Accounting for green surfaces doesn't seem to make any bluespot disappear. Furthermore it doesn't seem that bluespots are getting a significantly lower height.

A similar observation can be made when looking at figure 29, 30 and figure 31. These figures show the results for the same area in the south of Het Zand as before with the 35mm, 70mm and 140mm scenarios. There are only a couple of bluespots which have a reduced water height. This is interesting because this area contains many gardens and therefore there should be infiltration by green surfaces.

In the northern area of Het Zand in figure 32, 33 and 34 there are more differences visible. It can be seen that especially the area on the top left with houses close to each other show some differences. For the 35mm, 70mm and the 140mm scenarios it can be seen that some bluespots have a lower water height when compensating for the infiltration by green surfaces.

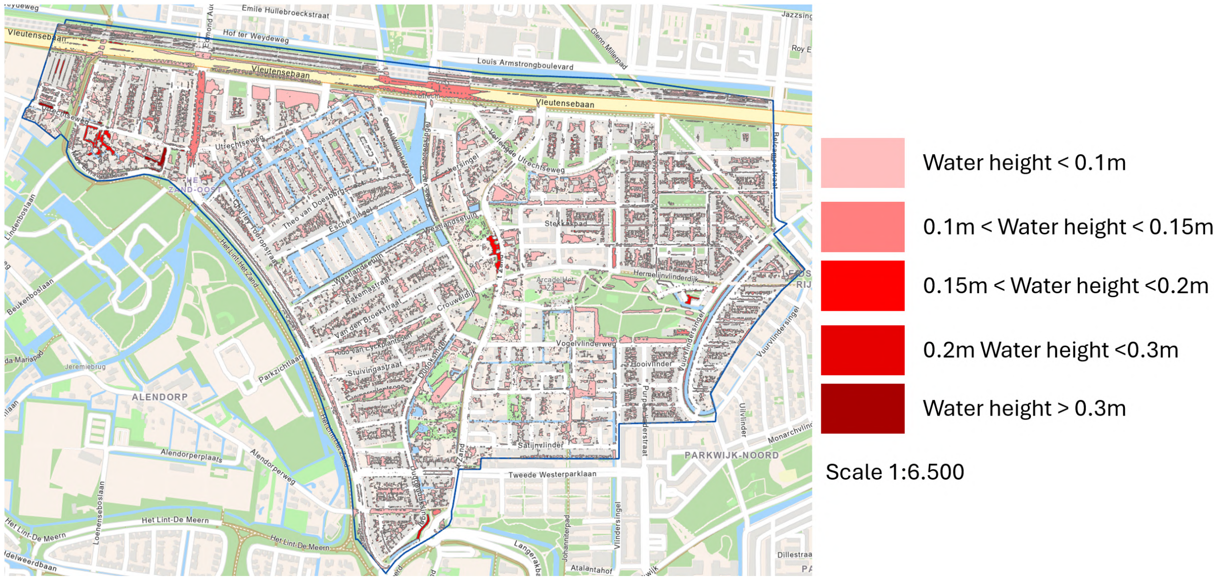


Figure 26: Scenario 4: 35mm rain with accounting for green surfaces (own work).

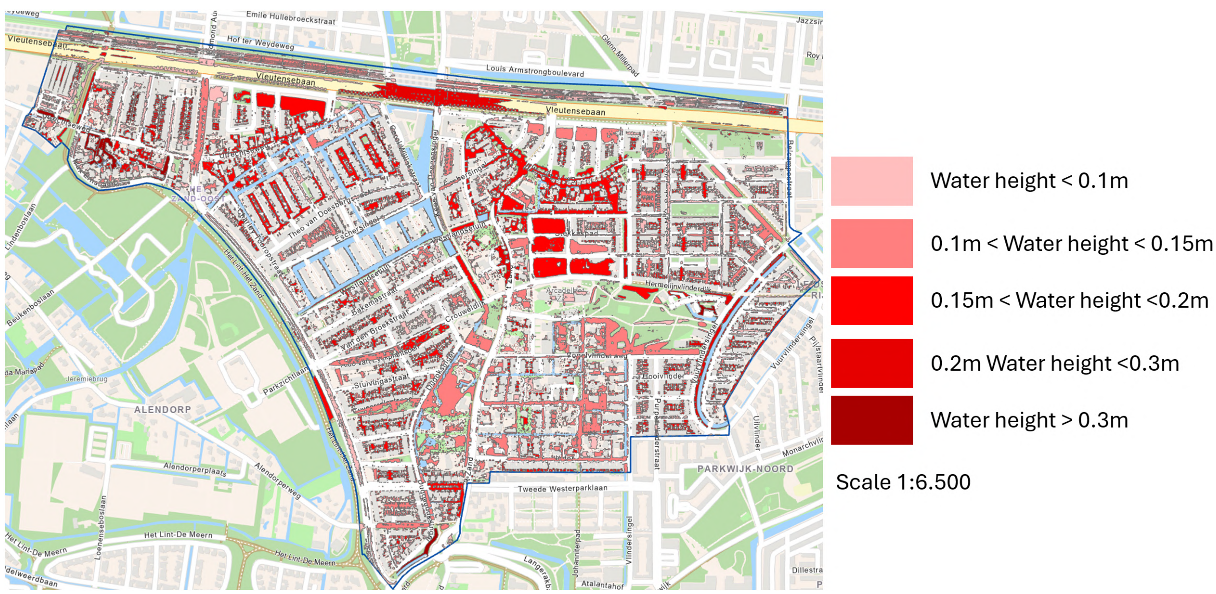


Figure 27: Scenario 5: 70mm rain with accounting for green surfaces (own work).

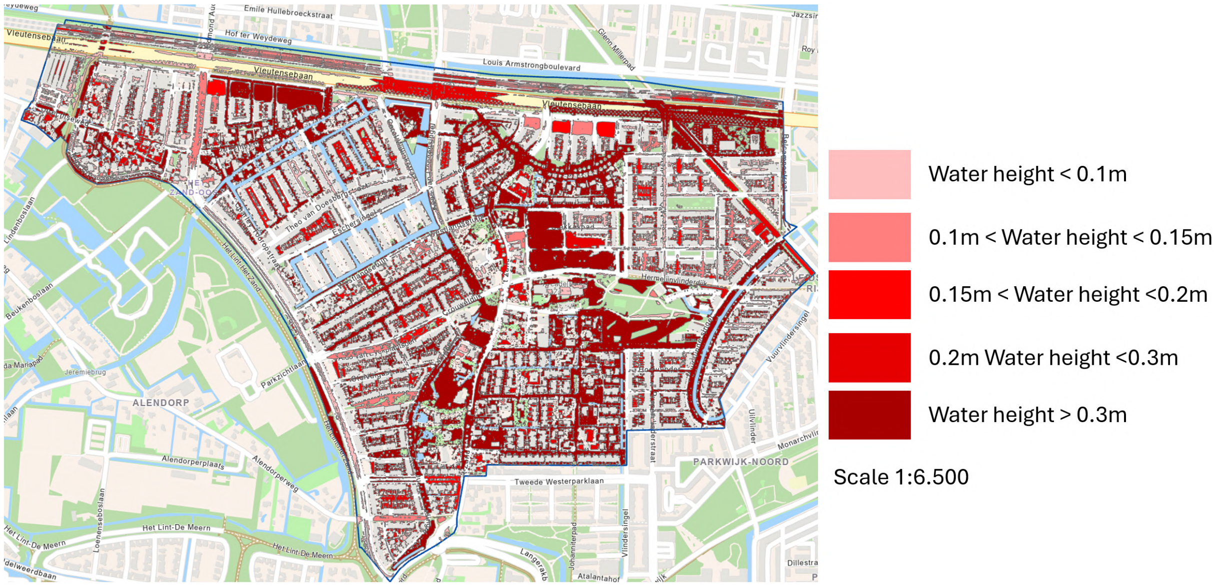


Figure 28: Scenario 6: 140mm rain with accounting for green surfaces (own work).

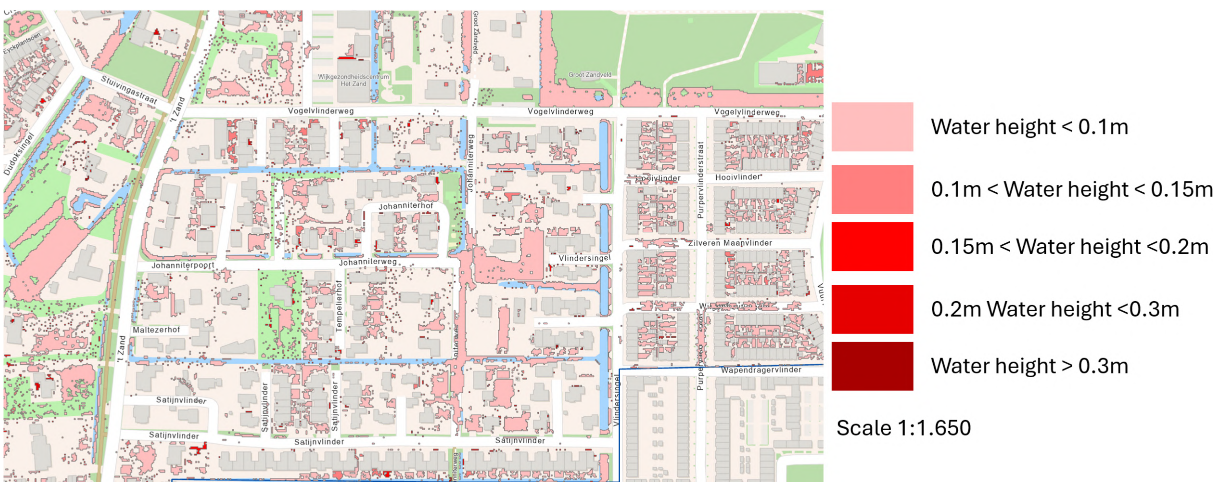


Figure 29: Zoomed in at the south in scenario 4: 35mm rain with accounting for green surfaces (own work).

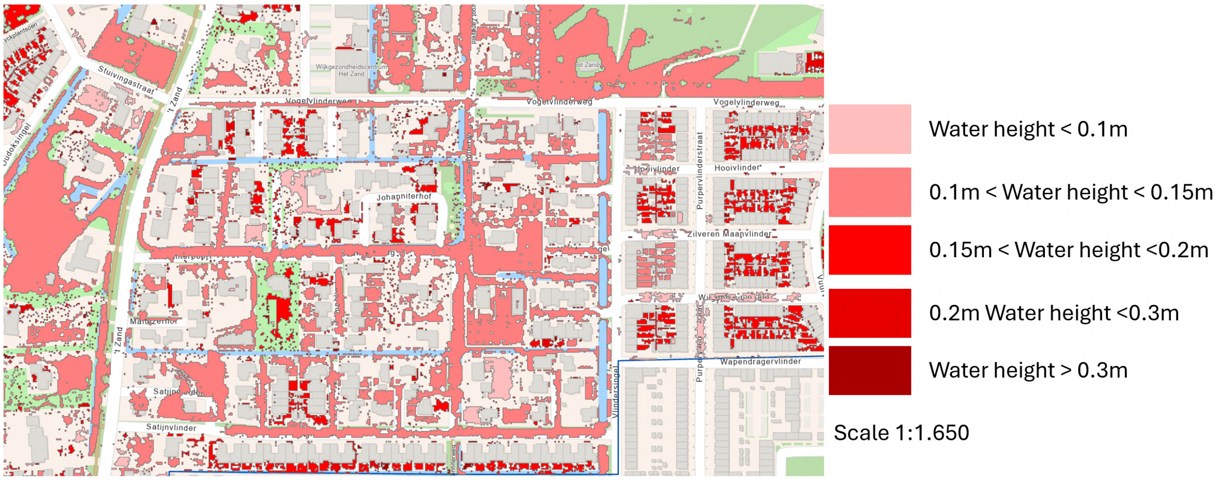


Figure 30: Zoomed in at the south in scenario 5: 70mm rain with accounting for green surfaces (own work).

Figure 31: Zoomed in at the south in scenario 6: 140mm rain with accounting for green surfaces (own work).

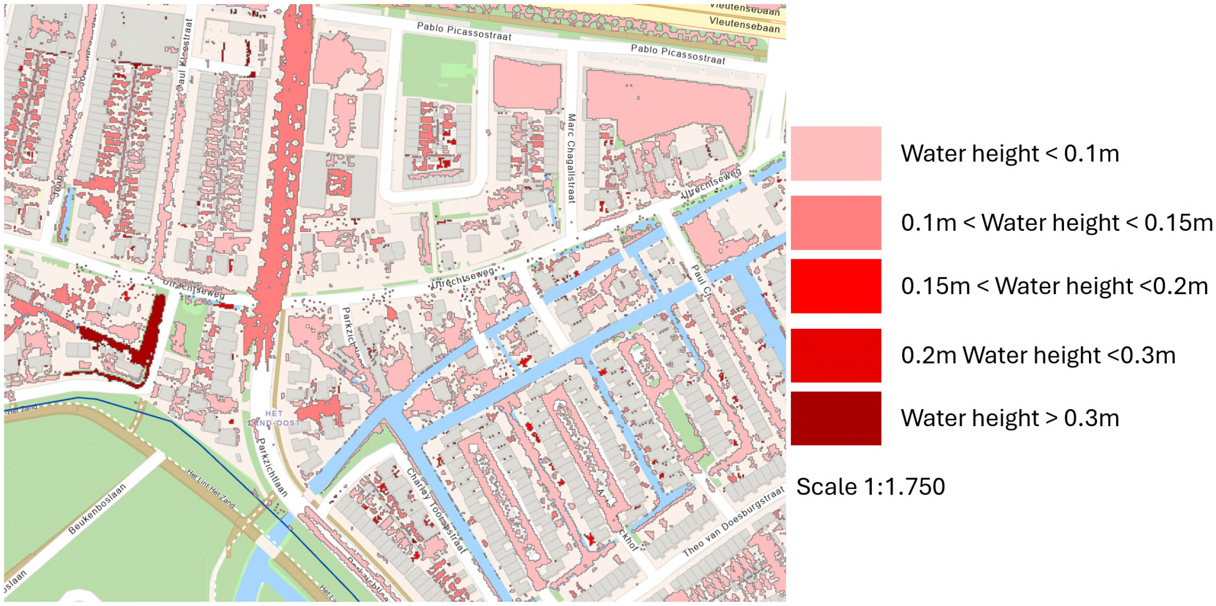


Figure 32: Zoomed in at the north in scenario 4: 35mm rain with accounting for green surfaces (own work).

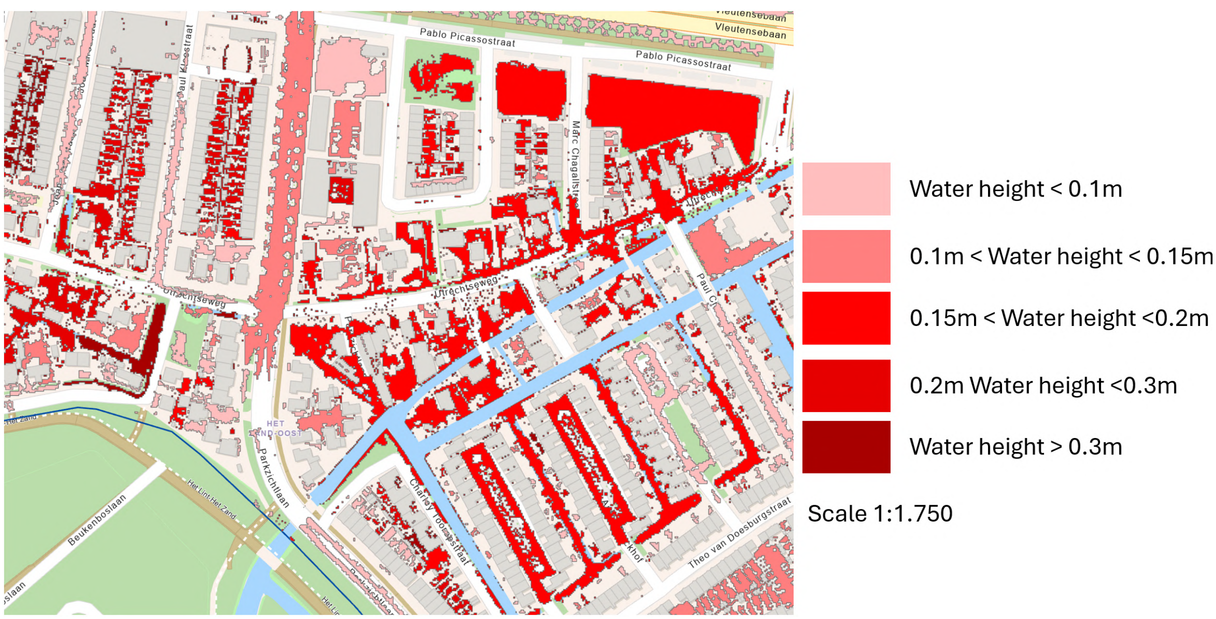


Figure 33: Zoomed in at the north in scenario 5: 70mm rain with accounting for green surfaces (own work).

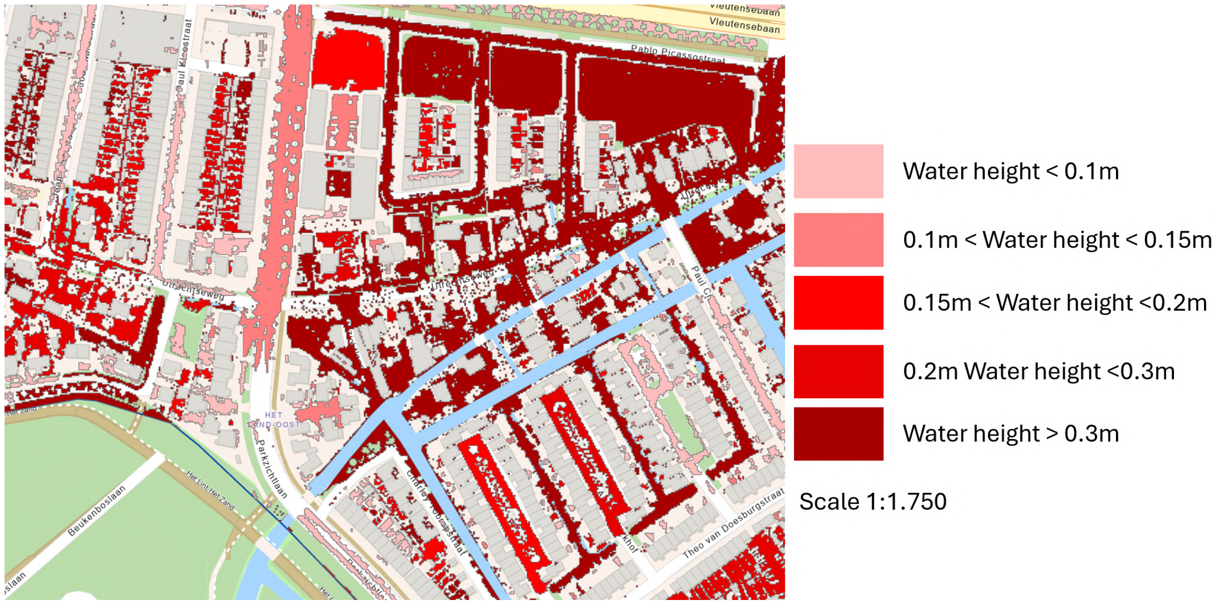


Figure 34: Zoomed in at the north in scenario 6: 140mm rain with accounting for green surfaces (own work).

9.6 Visual results green roofs

This subsection will show the results for the implementation of green roofs in Het Zand. The scenarios of 50% and 100% green roofs are shown in separate sub-sections. The scenarios with both green roof implementations will be mainly compared with the scenario with accounting for green surfaces‘because these are considered more close to real-life than the scenarios without accounting for green surfaces. Furthermore the scenario with 100% green-roofs will be compared with the scenario with 50% green-roofs.

9.6.1 Results 50% green-roofs

In the 35mm scenario only minor differences can be seen between the scenarios with and without the implementation of 50% green roofs. However it can be noticed that especially the bluespots with the largest water-height are reduced in height.

The 70mm scenario shows the same effect much more clearly between figure 35 and figure 27. Most of the bluespots with a large water-height are reduced in height.

The same effect can also be seen in the 140mm scenario. However the differences are minor and only clearly visible in the south-west of Het Zand.

When zoomed into the south of Het Zand, again there are only small small differences visible in the 35mm scenario. This is the area where houses are built relatively far from each other and there are large gardens. The 70mm scenario shows similar minor results in the south. Only some clear differences can be seen on the right of figure 39 where houses are built more closely to each other. The differences in the 140mm scenario are more clearly visible, although still most of the area consists of bluespots.

In the 35mm scenario in the north of Het Zand there are only some differences visible in the top-left where houses are built closely to each other. The 70mm scenario seems to reduce the water height of bluespots nearly everywhere. The 140mm is similar to the 35mm scenario although clearer. Both the areas in the top-left and bottom-right clearly show a reduction in water height when building are built closely to each other.

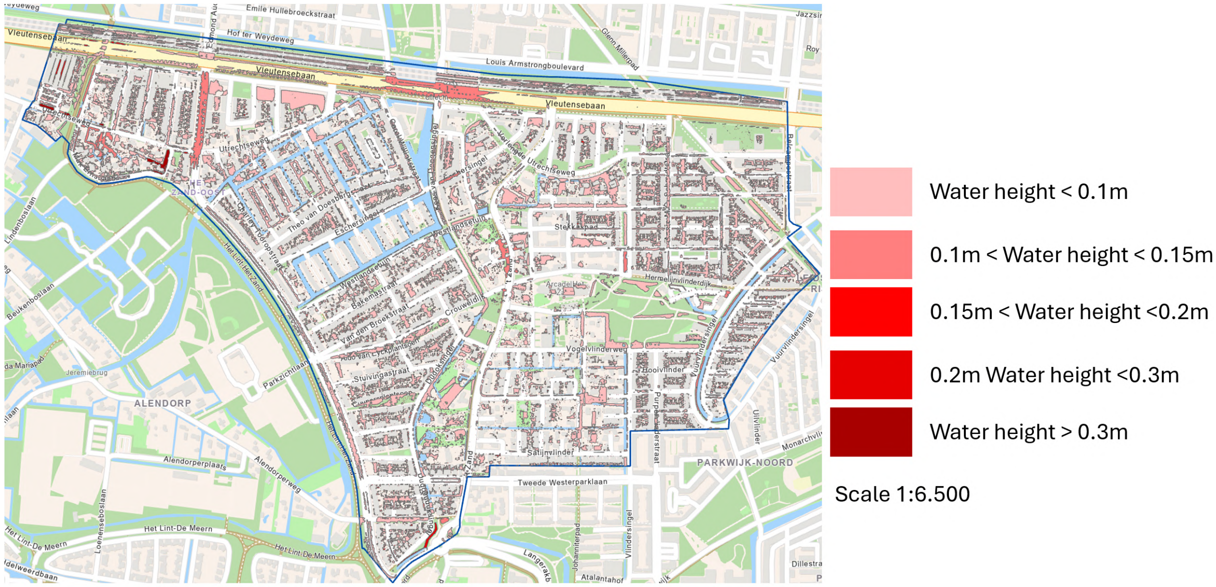


Figure 35: Scenario 7: 35mm rain with 50% green roof implementation (own work).

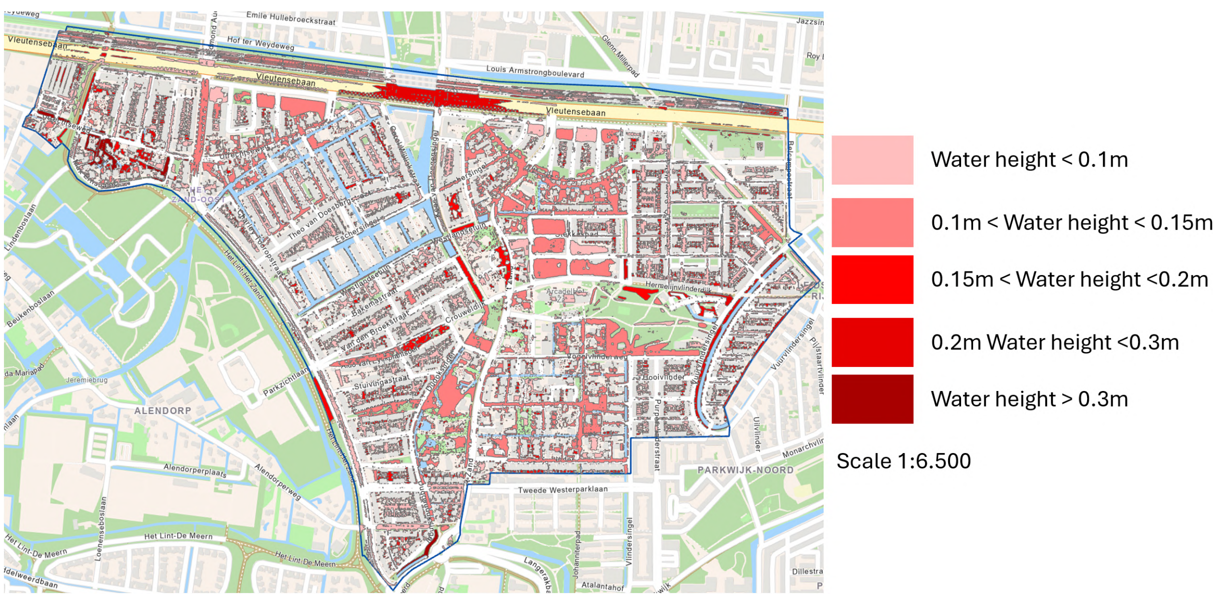


Figure 36: Scenario 8: 70mm rain with 50% green roof implementation (own work).

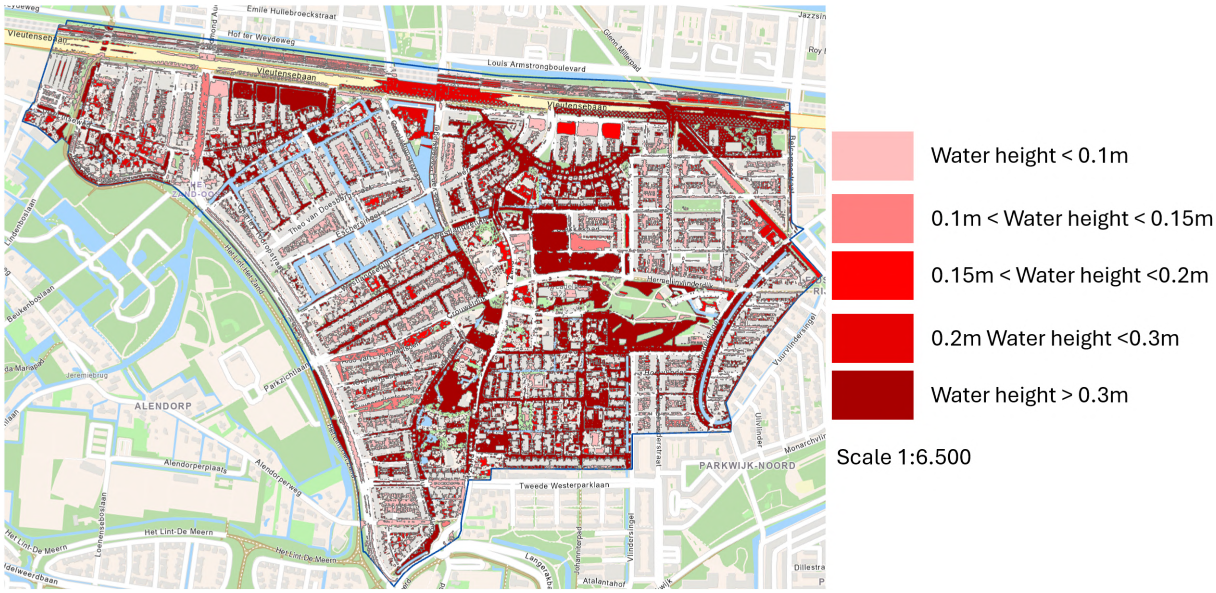


Figure 37: Scenario 9: 140mm rain with 50% green roof implementation (own work).

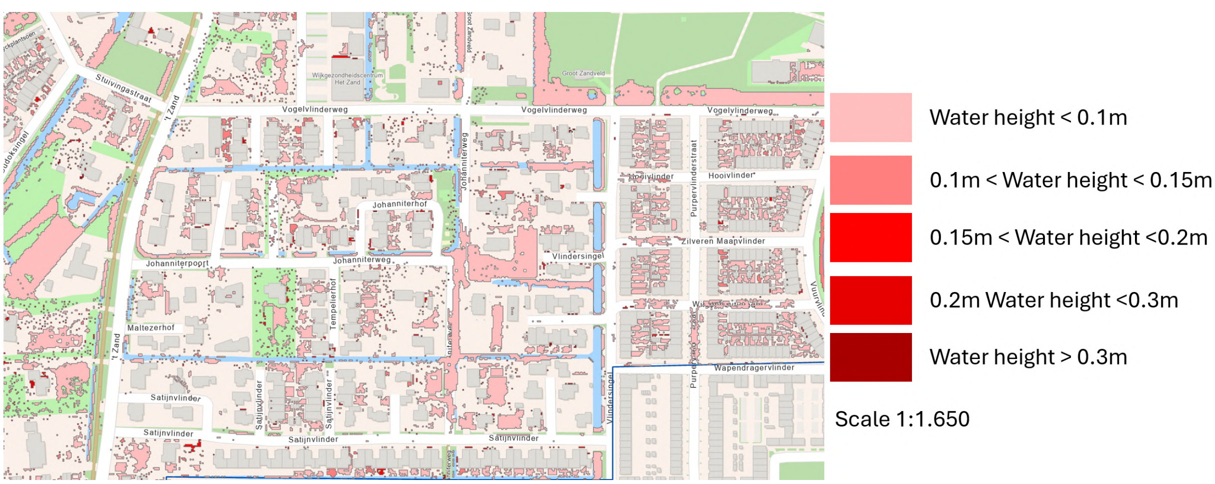


Figure 38: Zoomed in at the south in scenario 7: 35mm rain with 50% green roof implementation (own work).

Figure 39: Zoomed in at the south in scenario 8: 70mm rain with 50% green roof implementation (own work).

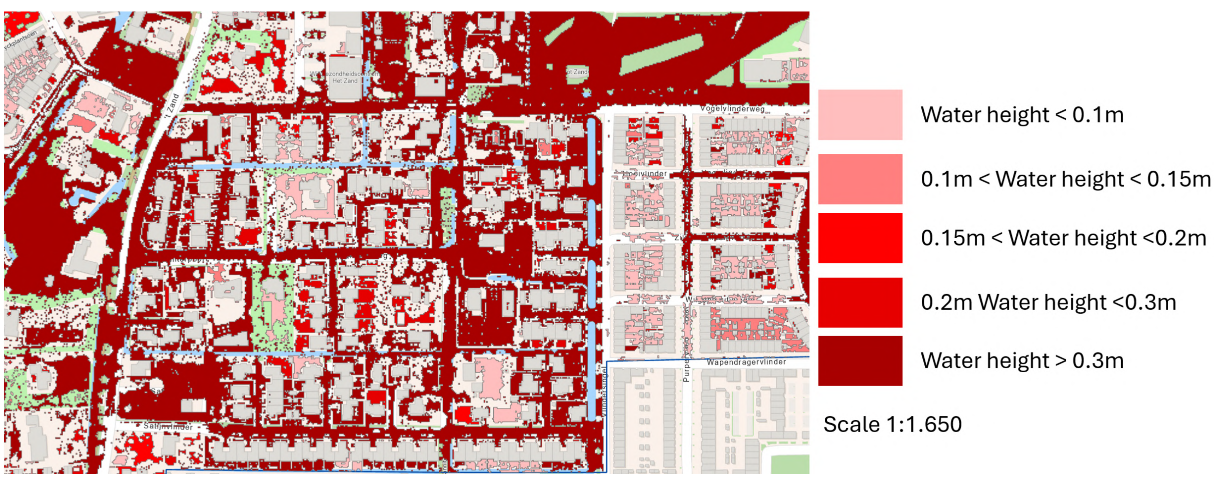


Figure 40: Zoomed in at the south in scenario 9: 140mm rain with 50% green roof implementation (own work).

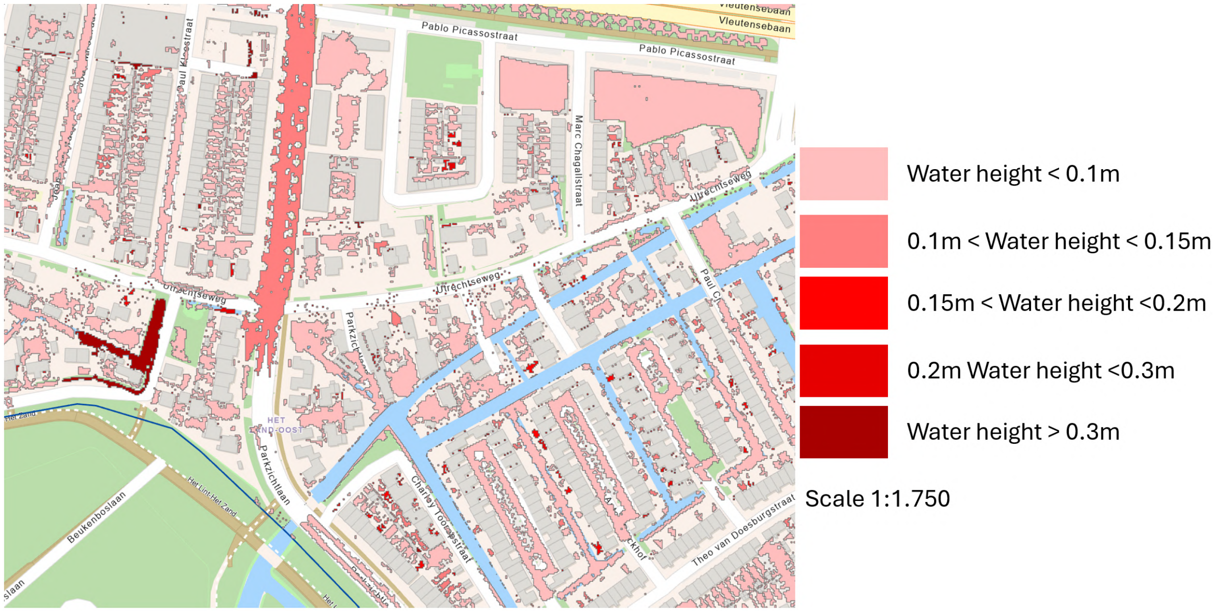


Figure 41: Zoomed in at the north in scenario 7: 35mm rain with 50% green roof implementation (own work).

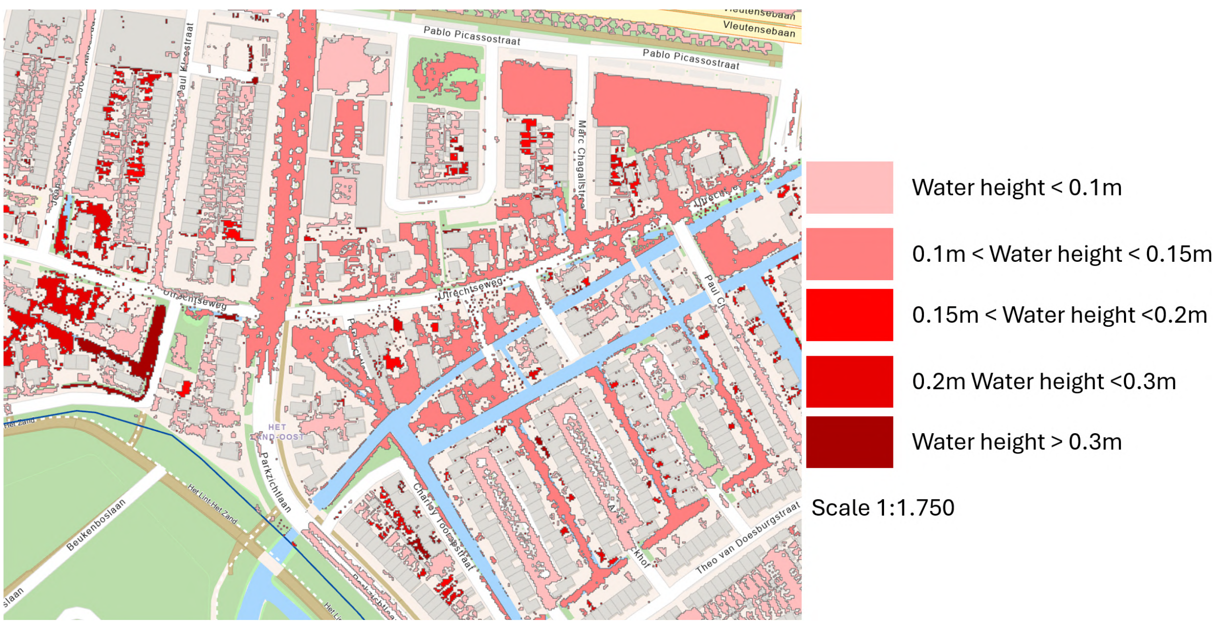


Figure 42: Zoomed in at the north in scenario 8: 70mm rain with 50% green roof implementation (own work).

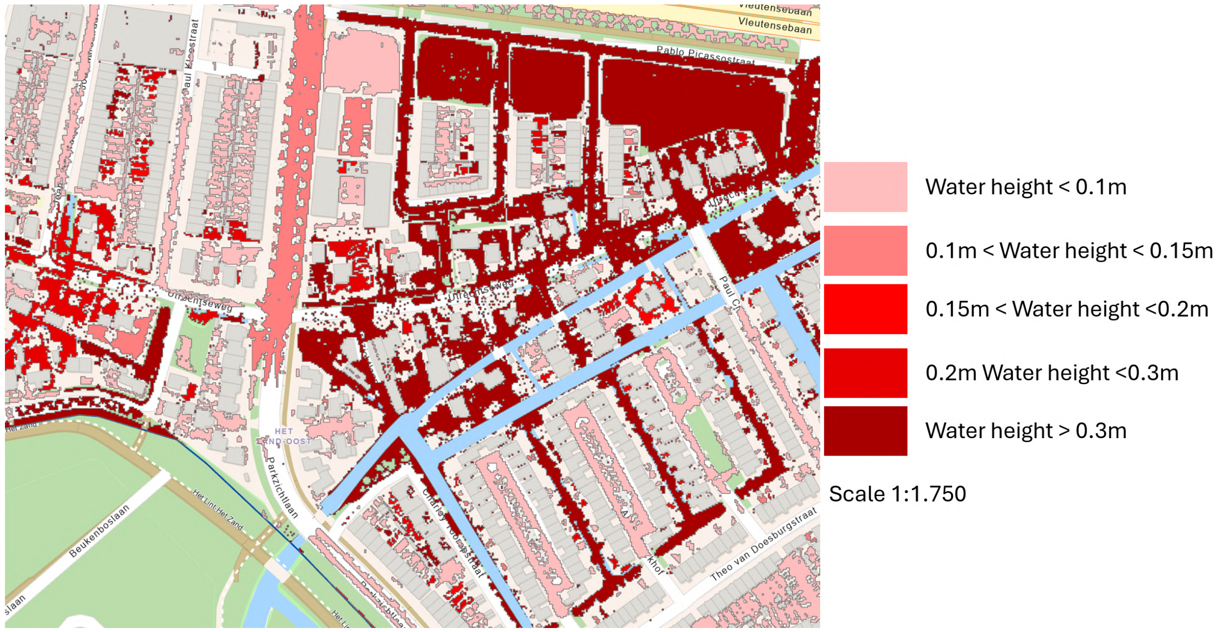


Figure 43: Zoomed in at the north in scenario 9: 140mm rain with 50% green roof implementation (own work).

9.6.2 Results 100% green-roofs

When looking at the complete map of Het Zand only very small differences can be seen between the 35mm scenarios with 100% and 50% implementation of green-roofs. Again the bluespots with the largest water height are impacted the most.

The same effect can be seen when comparing the 70mm scenarios for both 100% and 50% green-roof implementation. This effect can especially be seen in the middle of the map from north to south.

Also the 140mm scenario shows some clear reductions between 100% green-roofs and 50% green-roofs. Most of the bluespots with a large water-height are reduced in height, although still a significant number remains.

When zooming into the south of Het Zand no changes are visible when looking at the 35mm scenario. Significant changes are visible in the

70mm scenario especially on the roads. Furthermore the 140mm scenario also shows significant improvements when implementing 100% green-roofs. Although still most of the area is flooded.

The 35mm scenario barely shows any differences in the north between the 100% green-roof and 50% green-roof scenarios. The 70mm scenario shows some significant improvements, mostly in the areas where houses are not built close to each other. The same can be seen in the 140mm scenario.

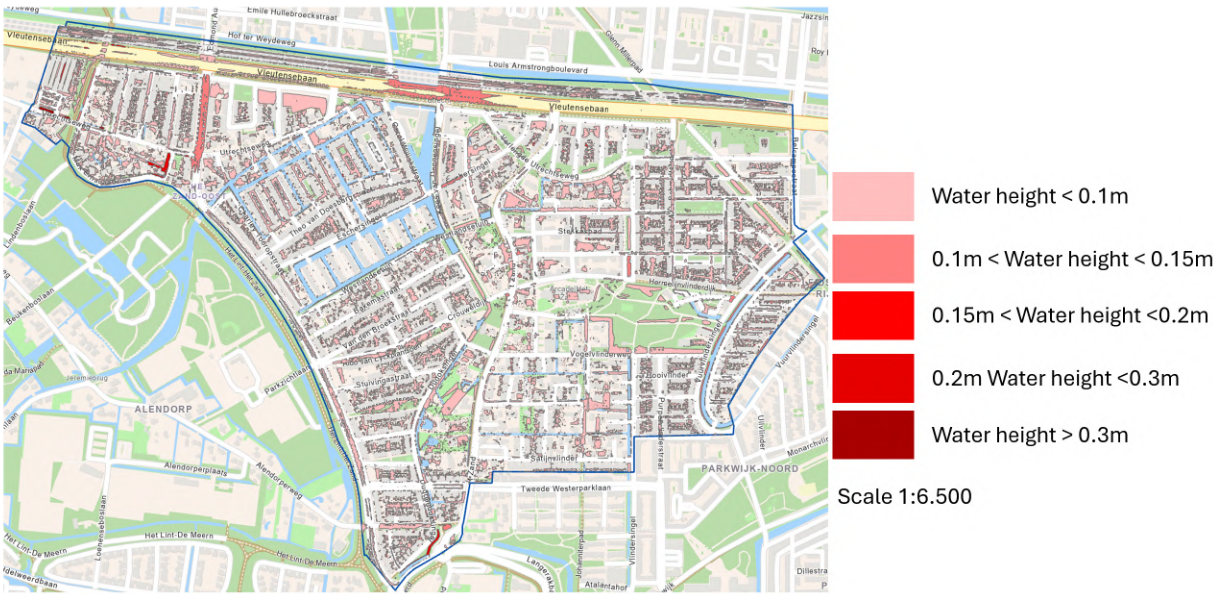


Figure 44: Scenario 10: 35mm rain with 100% green roof implementation (own work).

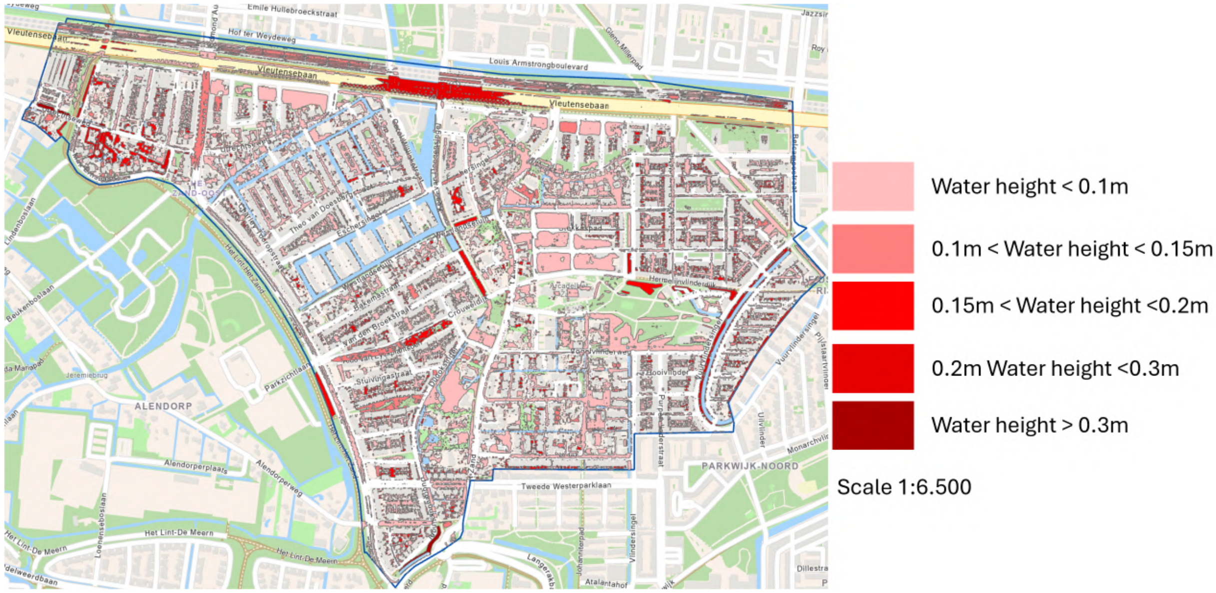


Figure 45: Scenario 11: 70mm rain with 100% green roof implementation (own work).

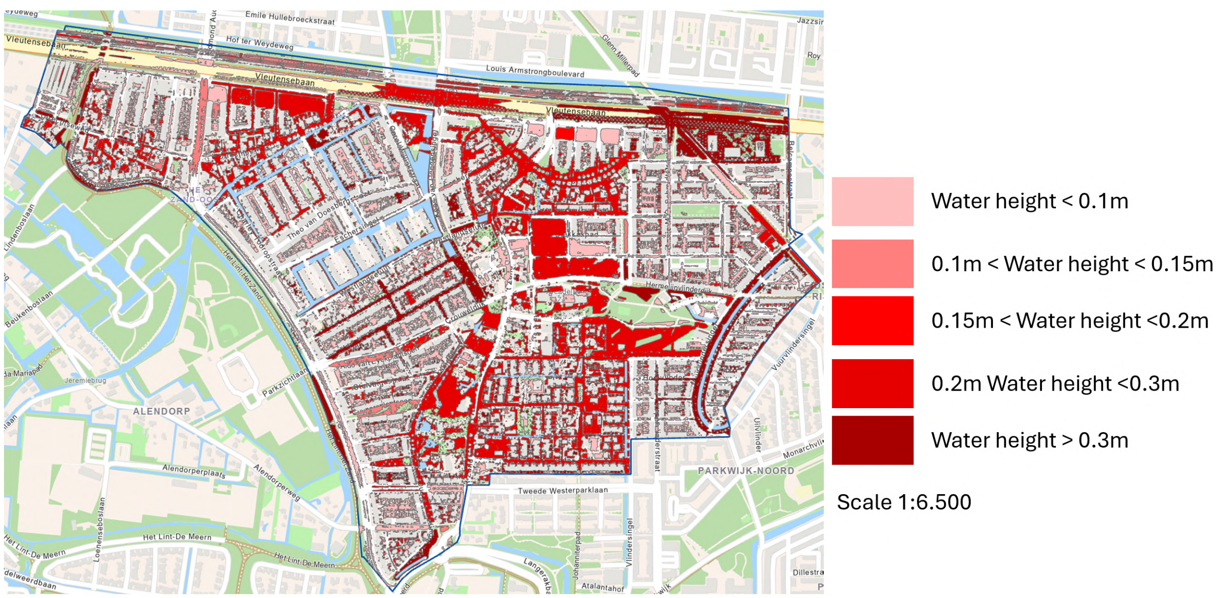


Figure 46: Scenario 12: 140mm rain with 100% green roof implementation (own work).

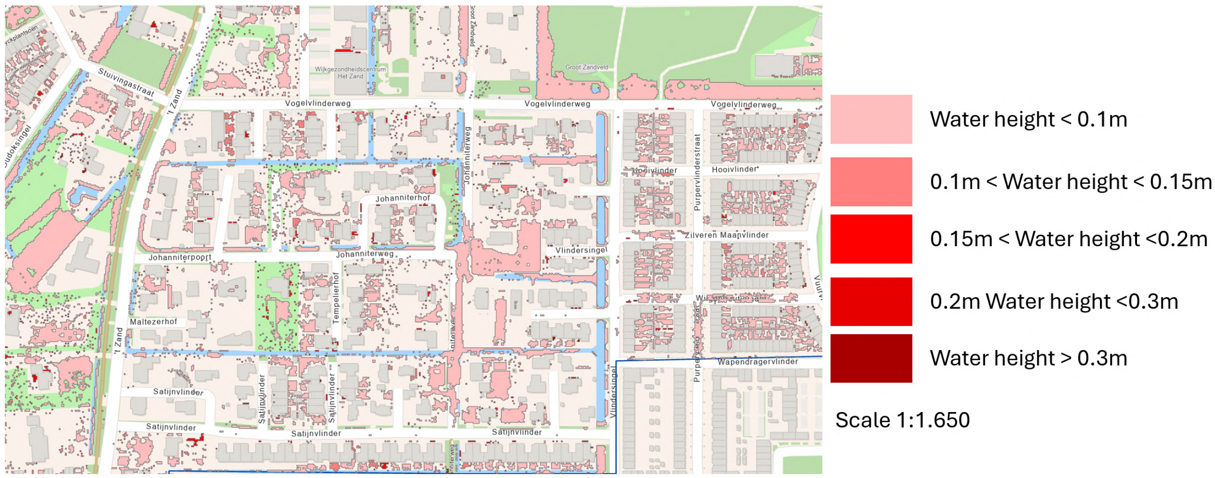


Figure 47: Zoomed in at the south in scenario 10: 35mm rain with 100% green roof implementation (own work).

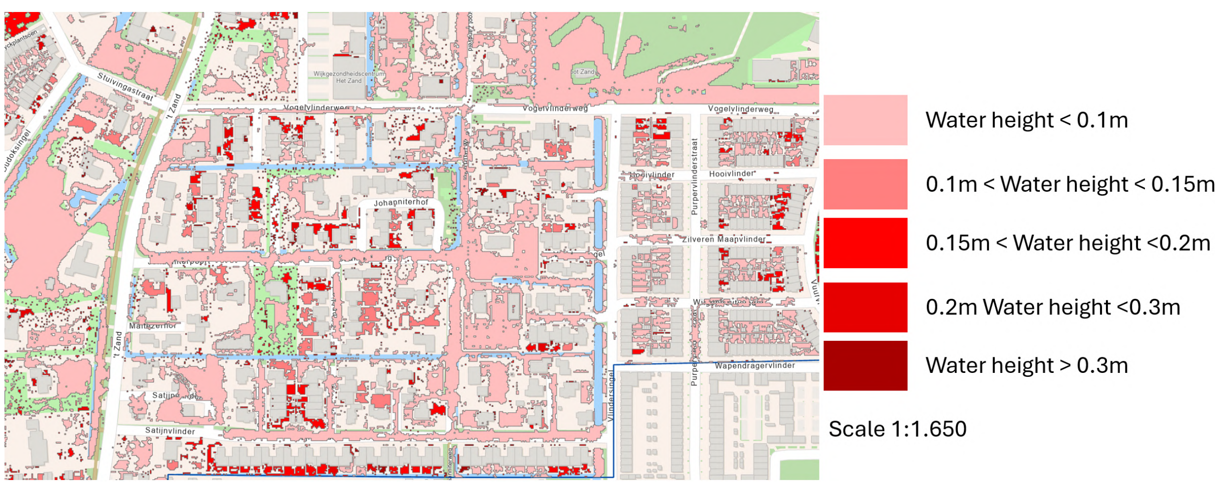


Figure 48: Zoomed in at the south in scenario 11: 70mm rain with 100% green roof implementation (own work).

Figure 49: Zoomed in at the south in scenario 12: 140mm rain with 100% green roof implementation (own work).

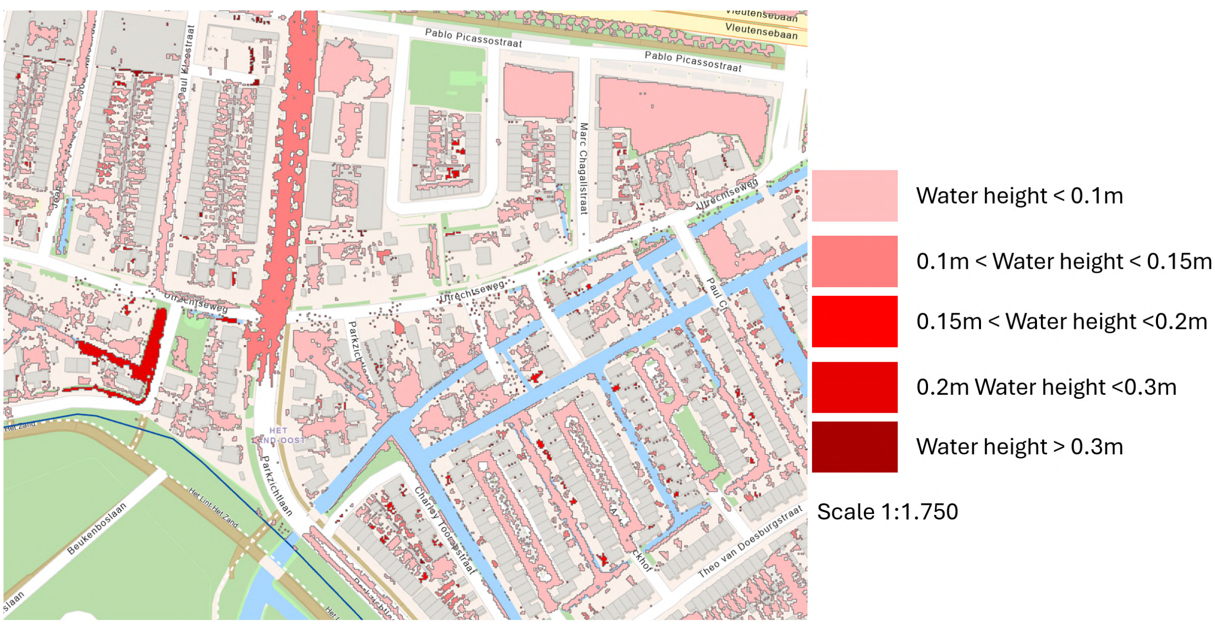


Figure 50: Zoomed in at the north in scenario 10: 35mm rain with 100% green roof implementation (own work).

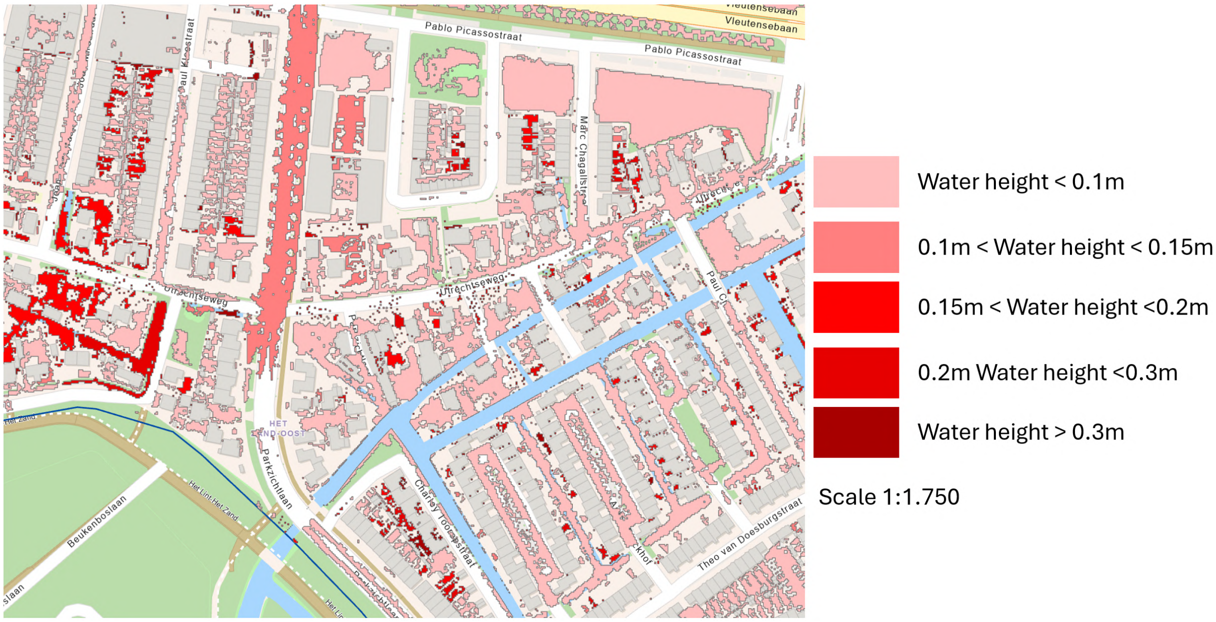


Figure 51: Zoomed in at the north in scenario 11: 70mm rain with 100% green roof implementation (own work).

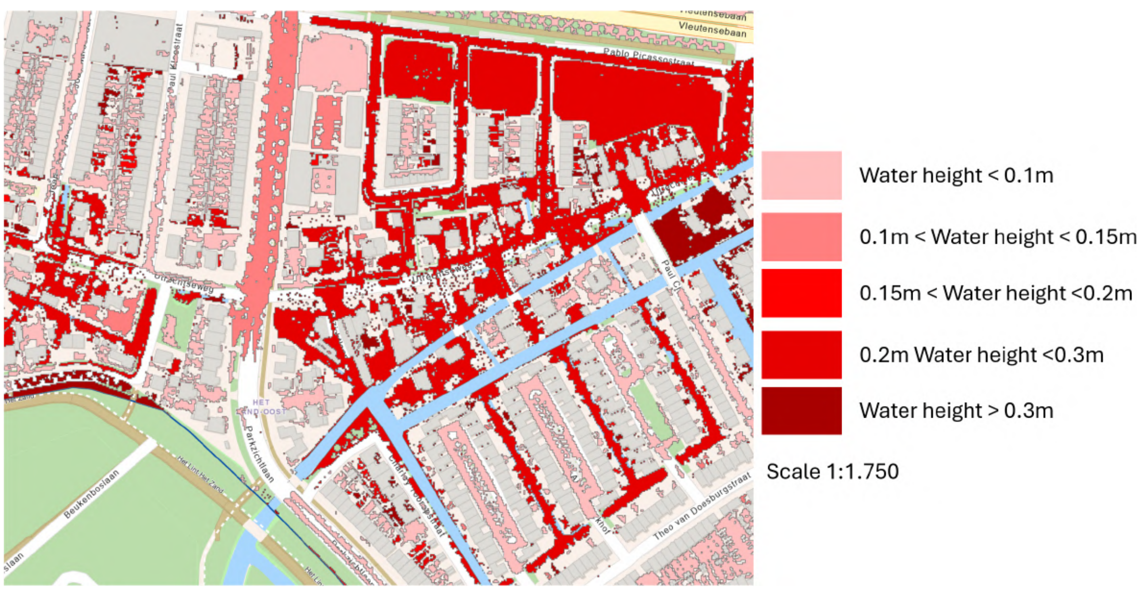


Figure 52: Zoomed in at the north in scenario 12: 140mm rain with 100% green roof implementation (own work).

9.7 Neighborhood statistics

This section shows the summary statistics for the different neighborhoods of Het Zand. These neighborhoods or 'scherven' have been base on the construction plan from the municipality of Utrecht (Utrecht, n.d.). The borders of these neighborhoods can be seen in appendix 9.8.
Similarly to the general summary statistics only scenario 4 through 12 will be discussed.

Only the average water height and standard deviation are taken into account. The reason for this is that some bluespots cover multiple neighborhoods. Therefore these bluespots would be counted multiple times when counting the amount of bluespots with a height higher than 0cm.

Neighborhood	$\bar{x}$ Water height	% lower 50% gr	% lower 100% gr	% area houses
Park Groot Za...	0.134m	-0.0049%	-0.0083%	11.1%
Stationsomgeving	0.114m	-0.0309%	-0.0094%	16.2%
Bongerd	0,133m	-0.0094%	-0.0104%	19.4%
Johanniterveld	0.144m	-0.0057%	-0.0060%	19.4%
Rijnsche Hout	0.132m	-0.0222%	-0.0246%	20.3%
Rijnsche Maan	0.132m	-0.0351%	-0.0408%	20.3%
De Veiling	0.107m	-0.0185%	-0.0192%	22.0%
Waterwijk	0.266m	-0.0176%	-0.0204%	21.0%
Leidsche Maan	0.106m	-0.0319%	-0.0359%	21.2%
Tussen de Parken	0.120m	-0.0309%	-0.0311%	30.3%

70mm

Neighborhood	$\bar{x}$ Water height	% lower 50% gr	% lower 100% gr	% area houses
Park Groot Za...	0.220m	-0.0053%	-0.0088%	11.1%
Stationsomgeving	0.165m	-0.0061%	-0.0086%	16.2%
Bongerd	0,205m	-0.0111%	-0.0120%	19.4%
Johanniterveld	0.236m	-0.0076%	-0.0080%	19.4%
Rijnsche Hout	0.191m	-0.0273%	-0.0303%	20.3%
Rijnsche Maan	0.203m	-0.0377%	-0.0431%	20.3%
De Veiling	0.168m	-0.0190%	-0.0197%	22.0%
Waterwijk	0.199m	-0.0188%	-0.0218%	21.0%
Leidsche Maan	0.146m	-0.0376%	-0.0424%	21.2%
Tussen de Parken	0.161m	-0.0475%	-0.0477%	30.3%

140mm

Neighborhood	$\bar{x}$ Water height	% lower 50% gr	% lower 100% gr	% area houses
Park Groot Za...	0.324m	-0.0053%	-0.0077%	11.1%
Stationsomgeving	0.217m	-0.0066%	-0.0085%	16.2%
Bongerd	0,283m	-0.0116%	-0.0132%	19.4%
Johanniterveld	0.352m	-0.0093%	-0.0105%	19.4%
Rijnsche Hout	0.235m	-0.0309%	-0.0386%	20.3%
Rijnsche Maan	0.284m	-0.0318%	-0.0379%	20.3%
De Veiling	0.225m	-0.0152%	-0.0171%	22.0%
Waterwijk	0.265m	-0.0173%	-0.0208%	21.0%
Leidsche Maan	0.177m	-0.0318%	-0.0358%	21.2%
Tussen de Parken	0.196m	-0.0678%	-0.0726%	30.3%

9.8 Scherven of Het Zand

Scale 1:6.500

Figure 53: Left: Scherven as implemented (own work). Right: Scherven according to the construction plan of the municipality (Ebberink, 2011). Notice that the boundaries of Het Zand slightly differ from the data of the construction plan and the municipality of Utrecht (Utrecht, n.d.) (Ebberink, 2011).

9.9 Results largest water height

35mm Rain

Scenario no.	Green-roofs	Avg. height 90th percentile
4	0%	0.350m
7	50%	0.349m
10	100%	0.349m

70mm Rain

Scenario no.	Green-roofs	Avg. height 90th percentile
5	0%	0.535m
8	50%	0.330m
11	100%	0.330m

140mm Rain

Scenario no.	Green-roofs	Avg. height 90th percentile
6	0%	0.782m
8	50%	0.468m
12	100%	0.466m

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