Witteveen+Bos

UNIVERSITY OF TWENTE.

The determination of a tailored water storage demand for residential parcels with the use of geologic and hydraulic parameters in different contexts

Bachelor's Thesis Final draft

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PREFACE

Before you lies the report that concludes my bachelor study Civil Engineering at the University Twente. The research was commissioned by Witteveen+Bos. Starting in November 2020, I was warmly welcomed at their main office in Deventer. Despite the Covid-19 pandemic, I have been lucky to spend the first few weeks working at the office in Deventer, after which I completed this report working from home. During this period, I've met many colleagues and discussed the matters of water management during a stroll alongside the river IJssel. Both working from the office as well as from home gave me great opportunities to adjust, cope and test my resilience. I feel like I experienced how it was to work for a company, and would like to express my gratitude to all involved parties.

I would like to thank the organization of Witteveen+Bos, the assigned group Urban Water Management, and Climate Adaptation, and then especially Daniël van den Heuvel for the guidance, advice, and support throughout this period. Also, I would like to thank my internal supervisor Maarten Krol for the academic view, always creating room for new discussions and providing an alternative perspective. Also a big thank you to the respondents of the conducted interviews, from which I learned a lot. Finally, I would like to thank the friends and family that have supported me along the way.

Please enjoy reading my thesis,

Jildert de Jong
Enschede, January 2021

SUMMARY
Climate change causes an increase in extreme precipitation and more intense periods of drought. To make the urban areas in the Netherlands water resilient, a broad range of measures have already been implemented. However, these measures have mainly been applied in the public space. Based on the ongoing threat of extreme precipitation on our vulnerable infrastructural systems, in 2009 a concept called the storage demand was introduced in the Dutch Waterwet. It comprises the required amount of rainwater that should be stored, infiltrated, or slowly drained on a private parcel, to prevent water nuisance. Private water storage is already obligatory in some municipalities and instances, advisory and consulting in others. Witteveen+Bos is one of those, which are developing an online web tool that advises private residents on their water storage demand, called "IkBenWaterproof".

The required storage capacity in case of an extreme shower is determined based on dimensional characteristics. The storage demand is uniform for all plots throughout the Netherlands. However, the geologic and hydrologic context carries great variability throughout the Netherlands and has therefore effect on the urgency to take action and the ease with which this can be done. The universal storage demand, although being a relatively new concept, becomes therefore inaccurate and obsolete. Every parcel throughout the Netherlands has different local characteristics and therefore responds differently when exposed to an extreme precipitation event. Therefore, a knowledge gap exists in urban stormwater management, where there is a lack of local dependency incorporated in the storage demand. This study tries to close this knowledge gap, by constructing a model that gives tailored advice on the storage demand, through a local assessment of the geologic and hydrologic context.

The boundaries and opportunities of this study were investigated through a literature study. The local geological and hydrological characteristics throughout the Netherlands vary significantly. Based on the scope of this thesis, a selection of parameters was made and their contribution, relevance, and respective consequences were mapped. The most vital parameters were divided into dimensional, geographic, and contextual parameters. For every parameter, it was indicated whether they were location-specific or policy-dependent. Besides that, research was conducted to investigate the options and limitations of the different types of measures, which were divided into three categories: (1) storage, (2) delayed drainage and (3) infiltration. At last, several artificial precipitation events have been analysed and the most adequate - shower with T=25 years based on W_H-upper scenario - was selected as input for stress-testing the model.

The constructed model was tested through two sensitivity analyses. It appeared that the model was mainly sensitive to the selected precipitation event, as well as to the soil type and groundwater level. This is valuable to consider when implementing the model, especially by municipalities. The model was tested in three real-life contexts, after which the outcome was verified by the private residents of the parcels. Whereas the outcome of the model was approved, the importance of providing 'specific' (quantity of) measures instead of an 'abstract' storage demand was emphasized. The model was compared through cross-validation with a comparable model that is used by the Municipality of Venlo, called the "Beslisboom". The constructed model saw similarities regarding the relevant local parameters and the options. Also, the outcome of both models was in a similar range. However, the constructed model included aspects that could not be found in the "Beslisboom", such as a more tailored approach with more local parameters, a quantification of storage demand instead of categorization, and direct advice on concrete measures instead of solely an indication of the type of measures. Then, the model was reviewed through expert elicitation, with both experts from Witteveen+Bos and the Municipality of Oisterwijk. The feedback formed the validation of the model and provided credibility with their approval of the technical steps of the model.

This research reveals that a tailored storage demand for each parcel is feasible and more reasonable than the universal storage demand some municipalities are currently demanding. This research could therefore have an impact on making the Netherlands water-resilient, especially on a private parcel level, while saving a lot of costs due to the implementation of unnecessarily large storage facilities. However, room for improvement exists, considering automatization, enhancing the accuracy of data, and a more thorough (scientific) substantiation of intermediate technical steps. Though, this research can form a guideline on the path towards a tailored storage demand and can be expanded with a wide range of subsequent studies.

1 INTRODUCTION

1.1 Background

Our climate is changing. Globally, the average temperature has already risen with +1.4°C since 1951 (KNMI, 2015). Based on reports of the Intergovernmental Panel on Climate Change (IPCC) and the assumption that global warming will continue at this rate, this will increase by a further +1.5°C between 2030 and 2052 (IPCC, 2019). One of the effects is a direct increase in the frequency and intensity of precipitation events, due to the higher humidity and unpredictable switches of current. This shift is already occurring. In the Netherlands, annual precipitation rose by 26 percent between 1910 and 2013 (Dai, Wörner, & van Rijswick, 2018). Besides that, the expectation is that extreme precipitation will occur more often, due to the forming of large rainfall clusters, leading to extreme down winds and hail (van Dorland & Lenderink, 2019). Extreme precipitation is an event that does not happen often, and therefore our infrastructure is not well prepared for it. According to reports of the Royal Dutch Meteorologic Institute (KNMI), the number of days with extreme precipitation (> 30 mm/h) rose 5 to 30 percent from 1909 to 2009, where the wide bandwidth is caused by the dependence on local and temporal conditions (KNMI, 2009). The number of days with extreme rainfall is expected to increase by 14 percent per degree of warming (STOWA, 2019). Data from IPCC suggests even an increase of 5 to 27 percent in 2050. Figure 1 shows the expected increase in the intensity of an extreme rainfall event. Another consequence of climate change is the increase in the frequency and duration of severe droughts (Beersma, Buishand, & Buiteveld, 2004). Droughts could disrupt agriculture, cause a disturbed ecology and potentially form a health risk. To give a plausible prediction of the effect of climate change on temperatures, droughts, and precipitation events, KNMI came up with the KNMI'14-climate scenarios. These are based on the latest scientific insights and give different scenarios of how climate change could have an impact on meteorologic characteristics. In chapter 2.1, these scenarios are listed and explained.

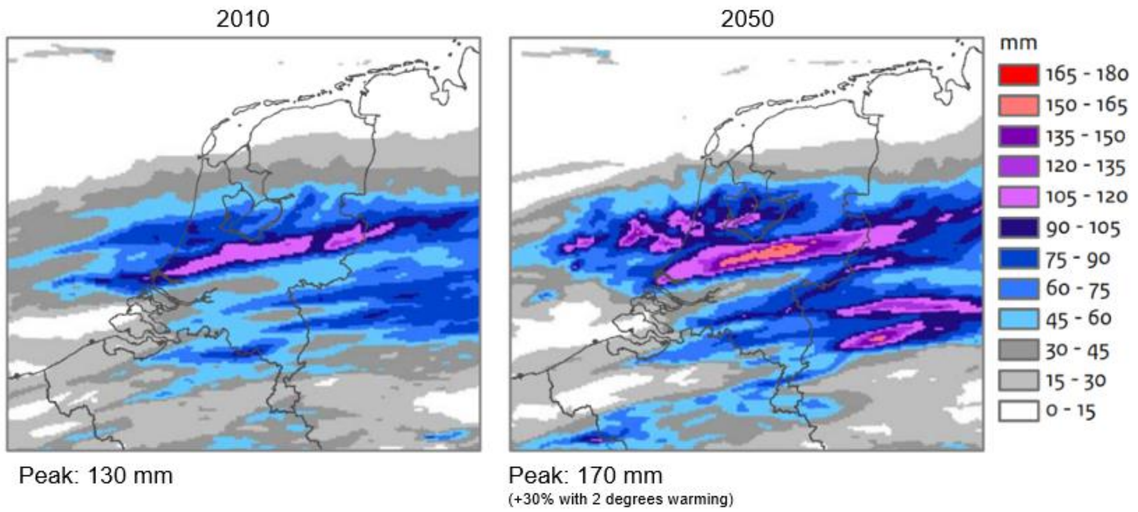

Figure 1 - Situation with more than 100 mm of precipitation in two days in August 2010 (left), and the transformation to a 2 degree warmer climate (right) (Stichting RioNED, 2015)

Besides the continuing threat of extreme precipitation, the population of the Netherlands is growing. Linearly, urbanization - the population shift from rural to urban areas - takes place. This has led to an enormous increase in impervious coverage of the landscape. Impervious surfaces decrease the potential for rainfall to infiltrate and increase the run-off to the streets, surface waters, and sewerage systems. In case of extreme precipitation events, this could lead to catastrophic overflows and consequently serious problems in terms of urban floods and water quality diminution (Bortolini & Semenzato, 2010). To prevent infrastructure to be damaged by water excesses or water shortages, the Dutch government is trying to make urban areas water resilient (Rijksoverheid, 2018). Water resilience would be achieved if the integral water system could anticipate, absorb and respond to shocks and stresses of precipitation events (ARUP, 2017).

The dynamic day-to-day processes, for example, logistics and industrial processes as well as the general health of the Dutch population, are dependent on the water resiliency of our infrastructure. Next to the prevention of water nuisance, a water resilient area can retrieve water in times of drought. Already, several policy shifts have taken place. These have caused that measures in public areas have been applied, both direct (e.g. expanding sewage, increasing street capacity, installation of bioretention swales, etc.) as well as indirect measures (e.g. enhancement of greenery, awareness-raising of stormwater threat). Though, the urgency to enhance the storage capacity of our cities rises.

The threat of climate change and its consequences on the water systems in the Netherlands are widely acknowledged by the government. Several reports have been put together to decentralize the problem and form vertical policy links to effectively battle the threat of extreme precipitation. Since 2000 this new approach has led to paradigm shifts, as described in reports like the *Nationaal Bestuursakkoord Water* (Huizinga-Heringa, Franssen, Jorritsma, & Schaap, 2011) and the strategy posed in *Waterbeleid voor de 21e eeuw* (Tielrooij, et al., 2000). Both reports describe in great detail how the different branches of governmental institutions have to address the urban water management in the public terrains. Though, they both contain the sidenote in which the necessity to take action on the private terrains is emphasized. Municipalities have - based on the Wet Milieubeheer (WM) and the Zorgplicht Hemelwater (article 3.5 in the Waterwet) - the responsibility to gather and control (excess) of urban waste-water. The Waterwet describes how they should cope with ground- and rainwater in the public terrains. Since 2009, Dutch municipalities have been given the legal right to oblige citizens to store rainwater on their terrains. Since then, over 40 municipalities have already introduced guidelines on water storage in private areas. Some of them already implemented legislation in zoning plans and in the Gemeentelijk Rioleringsplan (GRP). In essence, more and more municipalities have recognized the need to include private terrains as an asset to make the urban areas more water resilient.

1.2 Problem description

The combined threats of climate change, sea-level rise, land subsidence, and urbanization are alarming. The excess of water could cause the drainage and sewage systems to saturate, causing large-scale calamities. Subsequently, high economic damages could be the result. For the period 2013-2050, economic damage due to extreme precipitation could rise to 29 billion euros (Deltares, 2012). Besides, the excess water on the street could cause significant traffic delays and pose direct threats towards public health, caused by the intermixing of polluted sewerage water with clean rainwater.

The detachment of the sewage system from the rainwater drainage system would not be structural and only shift the problem. For a proper structural solution to this problem, the storage capacity or (controlled) discharge of urban areas has to be increased. Local policy determines whether the rainwater should be stored or drained. The rainwater surplus that cannot be handled by the drainage and sewage system requires an alternative method to collect. The preferred method is infiltration in the soil, whereas this prevents not only water nuisance, it also maintains a high groundwater level. This could prevent damages in periods of extreme drought. Besides, delayed drainage can also relieve the stress on the sewage systems. Once this cannot be realised due to the extent of paved area, man-made solutions have to be introduced (see Figure 2).

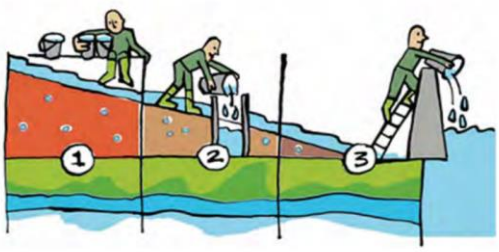

Figure 2 - Categorization of concepts of water storage (Rijkswaterstaat, 2000)

This way a 'sponge'-effect is generated, where the city does not act as an impermeable system, but like an absorbing, storing system. This way, a dynamic and proactive urban water system is created. Municipalities have already implemented a wide range of measures to generate the 'sponge'-effect, like bioretention swales (in Dutch called "wadi's"), reducing the paved areas, and enhancing greenery. A handful of municipalities have introduced a subsidy for those that detach their roofs from the sewage systems into their gardens or guide the rainwater to a separate sewage system.

Others have looked at expanding the sewage charges, paved on the extent of the paved area on a parcel. The introduction of a 'tuintegeltax' was another incentive, where the taxes are increased linearly with the percentage of tiles and stones in a garden. Though, to a large extent, the municipalities are still limited to measure implementation in the public terrains. According to recent reports from the Central Bureau for Statistics (CBS), 48 percent of the built-up areas in the Netherlands are owned by private residents and are not under the direct jurisdiction of the government (CBS, 2019). Though, when a garden is completely paved, around 85 percent of all discharged rainwater ends up in the sewage systems (Deltares, 2017). On the other hand, when a garden is free of pavement, on average just 15 percent will run-off. When 10 percent of all paved gardens are converted to green/unpaved, 30.5 million m^3 less rainfall run-off will flow to the sewage. In the Netherlands, an estimated amount of 56 000 hectares of private gardens exist, of which 34 percent is completely paved (Steenbreek, 2017). Hence, private plots provide great opportunities with regard to stormwater management.

Only until recently, it seems that some municipalities have closed the gap towards stormwater management on private terrains. The Municipality of Amsterdam is exemplary, where they have taken a step out of necessity and introduced a mandatory storage demand for a private parcel. This storage demand is incorporated in the zoning plan and is necessary to get a permit. The storage demand is a specific amount of storage capacity that is assigned to collect (heavy) showers. The Municipality of Amsterdam has made this storage demand mandatory for newly built dwellings and offices. The incorporation of the storage demand on existing buildings is still consulting and stimulating of nature. The legal procedure of the storage demand originates from article 10.32a of Wet Milieubeheer (Rijksoverheid, 2020), which grants the competence to come up with rules with regard to run-off rainwater. However, this is not the course of action that the waterboards and municipalities prefer. A large portion of the Dutch residents is insufficiently acquainted with the posing threat and the consequences of rainfall excesses or periods of drought. Therefore, the preference of the government lies in increasing awareness and creating a social system where the problem can be tackled collectively.

1.3 Knowledge gap

Although the threat of extreme precipitation continues to increase, Dutch residents consider it as being the responsibility of authorities and are not concerned by the threat of water nuisance (Runhaar, Mees, Wardekker, Sluijs, & Driessen, 2012). However, reports from Stichting RioNED indicate that extreme precipitation (> 60 mm/h) occurred 74 times per year during the period 2008 to 2016, based on nation-wide radar data (Overeem & Luitelaar, 2017). To raise awareness, many incentives were launched throughout the Netherlands. For instance, the Municipality of Rotterdam introduced a climate adaptation awareness program, called Weerwoord. Also, Waterschap Rijn & IJssel, Waterschap Vechtstromen, and Waterschap Drents Overijsselse Delta actively participate. Despite the different initiatives, still, a gap can be seen between 'taking notice' and 'taking action'. At the moment, most private residents themselves carry responsibility for rainwater management on their parcels. Those that recognize the threat, are often unfamiliar with how to take action to make their neighbourhood water-resilient (H2O Waternetwerk, 2020).

Witteveen+Bos (W+B) has recognized this and started an internal project to develop an urban stormwater management tool, called IkBenWaterproof. This tool tries to calculate the amount of capacity a certain private parcel requires to prevent overflow of the sewage systems. The capacity of this private parcel is dependent on a wide range of parameters, among others geologic, hydrologic, and dimensional. Despite the local dependency of this required storage capacity, IkBenWaterproof uses a universal storage demand for every location in the Netherlands. The universal demand is used, while the concept is relatively new, and information on the local dependency is scarce. However, it is considered unrealistic to ask the same storage demand for different parcels that carry deviations in (local) characteristics.

1.4 Research questions

The goal of this research is to make an intuitive model that calculates a customized storage demand, based on local characteristics. This model could proactively contribute to the threat that extreme precipitation poses to urban areas, by activating the private resident to take action. This is done through quantification of the storage demand and a direct link to the appropriate measures. The model will be directly offered to the municipalities, water boards, and other authorities.

The target group of these authorities, and therefore the end-user of this product, is the Dutch private resident. The model could be used in the online tool, IkBenWaterproof, which is in development at the moment of writing. To check whether this research is successful, the research objective is as follows:
"In what way can a tailored model be developed that uses local parameters (i.e. geologic, hydrologic, dimensional), to actively contribute to the determination of a storage demand on a private parcel?"

To give a proper answer to this question, the research objective is decomposed into research questions, as listed below:

1. In what way can local data be gathered reliably, to serve as input for the model?
   a) How can future forecasts for extreme rainfall events serve as an input for the prediction of the storage demand, what is the (most relevant) option?
   b) How can a quantitative location assessment be performed, where geographic, dimensional, and contextual local characteristics are collected reliably and accurately?

2. In what types can rainwater storing facilities be divided, what are the appropriate measures to achieve water resilience, and how are these affected by deviations in the local context?
   a) How can different types of rainwater storage measures contribute to the reduction of stress caused by extreme precipitation events?
   b) How do the different rainwater storing measures score on a cost-benefit analysis, and are therefore important to consider for both private residents as well as municipalities (e.g. subsidies)?
   c) What parameters regarding geospatial and hydrologic characteristics are most valuable when evaluating the effectiveness of these measures?
   d) To what extent can the measures realistically contribute to a certain storage demand, both by retention/storage as well as (delayed) drainage?

3. How can a universal model be constructed that determines a tailored storage demand, based on a local assessment?
   a) What key concepts and principles are relevant when determining a tailored storage demand?
   b) How can a realistic tailored storage demand be calculated and in what way is it dependent on local and temporal conditions?
   c) In what way can the local assessment be best gathered using reliable and available databases, and how can they be classified and characterized?
   d) To what extent can the storage demand also contribute to prevent damages in times of drought and what relation does this have to the measures?

4. To what extent does the outcome of the model match with reality, and in what way can this be validated?
   a) What validation techniques are used to check whether the developed model is in line with reality, and fits the demands and requirements?
   b) To what extent can the developed model give realistic advice on the storage demand to the Dutch owner of a private parcel, in several locations with different characteristics?
   c) How sensitive is the outcome - the final storage demand - of the model to the different input parameters?
   d) How does the model score when compared with a similar model that is used in practice?
   e) How can an expert elicitation be used, to validate the model?
   f) To what degree contributes this research to the public interest, where authorities and private residents can collaborate to make the Netherlands a little more water resilient?

1.5 Scope

During this research, a model will be constructed to give the end-users - the Dutch private resident - customized advice on the required storage capacity. For a nationwide validation of the calculated storage demands, the ranges of the local characteristics are investigated. The research is based on the needs of Witteveen+Bos, who currently use a universal storage demand, and would like a tailored approach. The scope of this report is limited to a technical approach. However, the topic enables many more interesting studies.

Briefly, attention will be paid to the 'soft' engineering, which involves the placement of the constructed model on the market. On top of that, the scope of the report is demarcated by the following boundaries:

- IkBenWaterproof incorporates a fully automated model, which can answer to each postal code a specific storage demand. This study, however, is limited to **semi-automated** and the building blocks on which this model is based.
- Several significant **assumptions and simplifications** within the model itself were made. Below a number of these statements are listed with a reference to the chapter that discusses the matter:
  1) Proximity of surface water (chapter 2.3)
  2) Limited lithographic classification (Appendix C)
  3) Broad assumptions surrounding gradient areas and their impact on the behaviour of rainfall running off (Appendix C)
  4) The classifications do not include outlying values. The case studies are selected in such a way that the largest share of the Dutch citizens can find resemblance.
  5) Paved area is considered as impermeable pavement. Whereas permeable pavement would suggest paving, it is considered as being an unpaved area while infiltration is enabled.
  6) Measures installed deeper than 2 meters below the ground surface are barely used on a private parcel scale and hence neglected in this report
- The study focuses on the **relative long-term** solutions, where scenarios from 2050 are used to stress-test urban areas.
- To use and understand the model, **some expertise is required.** This is based on the target group of the model, which are mainly municipalities.
- Prior to precipitation events, **storage capacities are assumed to be fully available.** The different peak precipitation events are assumed to be independent of each other, meaning that the earlier shower will not affect another shower.
- In this research, the case studies are collected in such a way that the largest portion of the Dutch population can find some resemblance between these and their private parcel. Though, there will be outlying cases, which are not accounted for. These boundaries are selected at:
  Lower boundary = Parcel without garden, own roof and balcony
  Upper boundary = Parcel with more than 2000 m^2
  However, parcels that find resemblance or are beyond these boundaries, are unaccounted for. By looking at the outer limits and deducing logically, the actions to take can be derived.

1.6 Report outline

- Chapter 2 Theoretical foundation in which the status quo regarding urban stormwater management is explored and the input for the model is gathered.
- Chapter 3 The framework of methods used to achieve the objective is depicted.
- Chapter 4 Selection of measures, scored on their aim and effectiveness and at last, ranked through a cost-benefit analysis.
  Construction of the model with initial storage demand and factors for the manipulation.
  Conducting two sensitivity analyses, both on the input parameters and based on geo-graphical context.
  Stress-testing of the model through three real-life case studies
  Cross-validation through comparison,
  Proposing outcome model through interviews to private residents of the case studies
  Validation through expert elicitation with two experts

2 THEORETICAL FRAMEWORK

2.1 Consequences of climate change for extreme precipitation

The Delta program is a nationwide plan with the target to prepare the Netherlands for the consequences of climate change. The Deltaplan Spatial Adaptation (DPRA) is a part of this programme since 2018 and focuses on water nuisance, droughts, heat periods, and the prevention of the severe consequences of floods. Among others, extreme precipitation is on the agenda with listed threats due to a changing climate. The phenomenon of extreme precipitation is interpreted differently throughout the Netherlands. This interpretation is dependent on policy aspects, but also meteorologic formulation and regional differences. The Dutch Meteorological Institute (KNMI) has conducted several studies that consider extreme precipitation as being rainfall events where 50 mm falls in one hour. On the other hand, Stichting RioNED maintains a threshold of 60 mm per hour as extreme precipitation. Although many Dutch residents consider extreme precipitation as some far-off phenomenon, in the Netherlands extreme precipitation (>60 mm/h) occurs more than 70 times per year (Overeem & Luitelaar, 2017).

The increase in the intensity of rainfall events has a direct causal connection to climate change. The increase in extreme precipitation is a result from the increase of the moisture in the atmosphere which is predicted by the Clausius-Clapeyron (CC) relation for constant relative humidity. Based on meteorological observations on a global scale, this relation proofs to be sound, where the developing observations of precipitation events are broadly in line with the 6-7 percent per degree of warming (Hartmann, Klein Tank, Rusticucci, & Alexander, 2013). The continuation and impact of climate change are hard to forecast, while this is dependent on many variables and uncertainties. However, KNMI, RioNED, and STOWA (Dutch Knowledge Institution of Waterboards), have tried to simulate future precipitation. First, Stichting RioNED has composed ten artificial precipitation events (bui01-10), that are used to design and test sewerage systems (Stichting RioNED, 2015). To incorporate the expected impact of climate change, a factor of 1.1, 1.2, or 1.5 is applied to these events. The second treated method uses historical data to predict future scenarios. Historical data is gathered and extrapolated, which indicates the future precipitation events. The standard precipitation series of De Bilt (1955-1979) is often used to guarantee mutual comparability and continuity of sewage system plans. This is currently the best available historical dataset, though does not include a climate change correction. Whereas both methods are used, the prediction of the future precipitation data is arguable. For an elaboration of these two methods, see Appendix A.

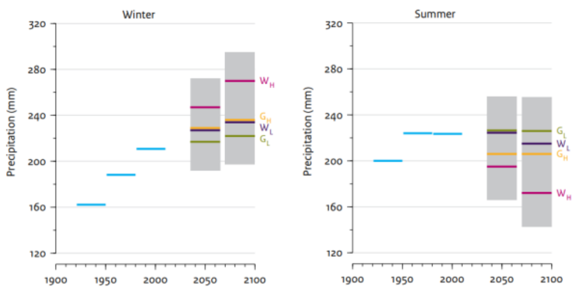

Figure 3 - Precipitation climate in the Netherlands and the expected change with different KNMI'14 scenarios for 2050 (KNMI, 2015)

The last discussed method is based on the combined expertise of KNMI, STOWA, and IPCC. The IPCC published 2013 a research report on the expected impact of climate change on the world (IPCC, 2013). KNMI translated these results to a Dutch version and called them the KNMI'14-scenarios. These scenarios form the upper and lower limits of the prediction of the impact of climate change on different meteorological aspects. They describe the changes around 2050 and 2085 relative to 1981 and 2010, respectively. While designing infrastructure which will be subjected to meteorologic forces, often the worst-case scenario (W_H) is used (Hughes, 2019). This is to guarantee a robust and future-proof system. Figure 3 displays the KNMI'14-scenarios and indicates the increased overall winterly precipitation (potentially causing floods).

It also shows a decrease in precipitation in the summer (potentially causing droughts). Extreme precipitation intensities increase in all future scenarios, even in the W_H-scenario, where the summer precipitation decreases. This is a consequence of an increase in humid air due to a warming climate (KNMI, 2015).

2.2 Consequences of climate change for drought

Besides the increasingly unpredictable behaviour of precipitation, also droughts are occurring more frequently. Climate change is the direct cause of fewer days of precipitation per year, which amplifies the national precipitation shortage. In 2018, a record drought has resulted in an estimated economic damage of 450 million euros, with a potential aftermath of 2080 million euros (Sluijter, Plieger, van Oldenborgh, Beersma, & de Vries, 2018). Water harvesting in the Netherlands relies both on the discharges of the rivers Maas, Rhine, and Waal as well as precipitation. The frequency of extreme drought is increasing, whereas 2018 fell well within the top 5 percent of driest years ever, and 2020 came very near this threshold. Figure 4 displays a maximum precipitation deficit of 298 mm in 2018 and 209 mm in 2020. This cannot be formally assigned as a climate effect, though it is a remarkable development and it suits the development to extremer weather events, posed by the KNMI'14-climate scenarios. The PBL (Netherlands Environmental Assessment Agency) substantiates this claim: *"Effects occur through gradual trend changes, and through changes in weather- and climate extremes such as drought, extreme precipitation, and heatwaves."* (Planbureau voor de Leefomgeving, 2012).

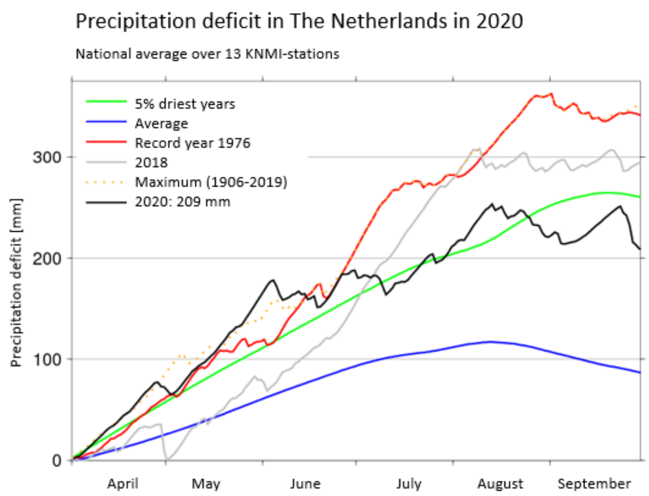

Figure 4 - Annual national precipitation deficit, with the top-8 of driest years, graphed (KNMI, 2020)

Since the Netherlands rates centralized policy highly, tackling multiple targets with one solution is widely appreciated. Where water nuisance is tackled, often drought prevention is incorporated in the plans, through soil infiltration or superficial water storage. The storage of rainwater in (extremely) wet times, is often reused in times of (extreme) drought (Overacre, Clinton, & Pyne, 2006). Through refilling aquifers and maintaining a high groundwater level, the precipitation deficit could be (partly) neutralized. This way economic damages failed crops and drink water shortages could be reduced, possibly even avoided. Storage measures could therefore function - besides the prevention of water nuisances - also as a way to prevent droughts. By infiltrating rainwater, water can percolate into the soil and maintain a healthy balance of the groundwater level. Whereas the average precipitation deficit is given on a national scale, certain locations are often more vulnerable to droughts than others. This local dependency is among others based on the proximity of surface waters, the height of the groundwater level, the soil type, and the degree of vegetation.

2.3 Urban stormwater management in the public sector - Existing drainage methods

Municipalities are working hard to improve water resilience in urban areas. In the public sector, many measures have already been implemented to guarantee water resilient urban areas. Nonetheless, the occurrence of peak showers often causes flooded farmlands, streets, tunnels, and basements. Water nuisance causes the disturbance of infrastructure and transport, leading to material or societal damage. Water nuisance occurs when the sewage systems cannot handle a heavy shower, and the streets transcend a certain level of toleration. This can cause floods on the streets. The overflowing of the sewages can be divided into intrinsic and extrinsic.

Intrinsic overflowing is caused by overflowing in downstream areas due to large run-off upstream. Extrinsic is caused by the direct application of heavy precipitation to the sewage, which cannot be handled. The latter will be discussed during this research. Below, the different types of existing drainage methods are described.

Drainage by sewerage systems

An urban drainage system is divided into dual drainage. First, the minor drainage system is considered to be the subsurface sewage system, which can handle precipitation events with a return period in the range of 2-5 years. Secondly, the major drainage system is considered to be the surface system. This includes buildings, sidewalks, streets, curbs, and gutters. These systems are connected by drains and overflows. When rainwater falls in urban areas, the norm is to drain as quickly as possible to the sewage system. Currently, this is often a mixed system, which drains beside the rainwater also the domestic wastewater. In case of peak precipitation events, and the overflowing of the sewage systems, the polluted municipal wastewater intermixes with the clean rainwater run-off. For this reason, separate sewage systems have been introduced recently, collecting both types of discharged water.

The sewage systems in urban areas are often designed on and stress-tested by artificial precipitation events of bui08 or bui10. These are hydrographs that provide the progress of rainfall 60 and 45 minutes, respectively. The integral of both hydrographs is 19.8 mm, though the peak of bui10 occurs early in the event. This means that the sewage systems have to be able to resist 19.8 mm in that frame of time. In this research, it is considered that all sewages are designed for bui08, meaning that they can resist a shower of 19.8 mm/h, assuming that all infrastructure is optimally connected.

From a municipal point of view, storage on own parcel carries the preference. Considering the threat of climate change, an implicit policy point of municipalities could be to mandate the storage of a day-to-day shower on their parcel. Heavier events will then trigger the maximum draining capabilities of the sewages.

Drainage through run-off to surface waters

Rainfall run-off over the surface is dependent on several variables. Vegetation degree, slope, and soil type are just a few examples. For this reason, there is no straightforward way to determine the run-off to surface waters. Also, not all locations in the Netherlands are near surface waters. Even if a dwelling is next to surface water, the run-off is not always self-evident. In urban environments, many ponds, ditches, and (city) canals will exceed their limits at just a minimal inflow. Municipal policy therefore indicates most often whether water can run off to these surface waters, as indicated in the *preference order* in article 10.29a of the WM.

Water on the street

On a nation-wide scale, water on the street is accepted once every 2 years, provided that no water will flow into buildings or cause traffic delays (Stichting RioNED, 2015). This is supported by reports, like the Gemeentelijk Rioleringsplan Nijmegen 2010-2016 and Standpunt Stichting RioNED. The street can function as a buffer to avoid rainwater damage in buildings. Its capacity could be increased by lowering the street level, (re-) introducing curbs, or heighten the ground level of buildings. This is easier to implement in newly built dwellings rather than existing buildings. The amount of tolerable water on streets is depending on the presence of curbs, deepened street level, or the presence of water storage facilities. Stichting RioNED claims that on average 50 mm is tolerated on the streets. Based on CROW data, the average street width within the city limits is 3.6 meters (Schermers, Stelling, & Duivenvoorden, 2014). Hence, when allocating the street to a parcel and its neighbour on the other side of the street, a total of 0.09 m^3 of (rain)water can be stored per meter length. Therefore, this is the maximum amount of water that is tolerated on street, before the streets overflow. In this report, the threshold lies not at the doorstep, but on street level. This is chosen while the flooding of streets can already cause major traffic delays, pollutions, and other dangerous situations.

Water storage in the public sector

In the last few years, municipalities have recognized the urgency to take action. By increasing the 'sponge'-effect of cities and expanding the storage capacity, cities have become more water resilient. Sewages have been expanded, curbs have been (re-)introduced, street levels have been lowered, and squares and playgrounds have been rebuilt to function as water buffers. However, it has been recognized that room is becoming more scarce, particularly in heavily urban areas. This asks for a different view on improving urban stormwater management.

2.4 Urban stormwater management expanded - Storage demand

Storage capacity in urban areas should neutralize the threat of heavy rainfall events and facilitate the storage of water in times of drought. Whereas municipalities have recognized that the most effective area to implement further measures is on the private parcel level, the concept of storage demand has been introduced. It describes the (obligatory) amount of storage capacity that should be facilitated on a private parcel and is given in millimetres per square area paved area (e.g. dwelling, driveway, terrace, etc.). It is taken over the paved area, whereas the unpaved area is expected to infiltrate, provided the soil is not impermeable. Since 2009, municipalities have the right to include it in the zoning plan and therefore make it obligatory (Gemeente Amsterdam & Waternet, 2013). Once it becomes obligatory and has to be satisfied the storage demand is also called the rainwater ordinance. It is often only relevant when subjected to extreme precipitation. Municipalities could introduce this concept for different purposes. Initially, it is used to prevent water nuisance when an area is subjected to extreme precipitation. On the other hand, it can be used to increase awareness among citizens or to prevent damage due to periods of (extreme) droughts. When looking at the legislation, most municipalities are bound to the Zorgplicht Hemelwater. The responsibility of storing the water is given to each municipality. These can decide how to determine or choose the storage demand. This choice can be based on needs (i.e. currently regular flooding) or desires (i.e. do not tolerate any flooding). A wide range of methods are available and with this a share of in- and output variables to determine the storage demand.

The storage demand has already been introduced by several municipalities throughout the Netherlands. The water board Brabantse Delta uses 7.0 mm storage demand for newly built dwellings (Stigter, Kuiphuis, Wielinga, & Kunst, 2011). In Zwolle, a generic storage demand for a newly built dwelling of 20 mm of paved area forms the norm (Gemeente Zwolle, 2016). The tool IkBenWaterproof uses a universal storage demand of 15 mm for the paved area, independent of local characteristics. The Municipality of Venlo has made the step to a location-dependent storage demand. They use a 4-50 mm storage demand, dependent on the positional and hydraulic parameters (Gemeente Venlo, 2017). These are just a few examples, so it can be recognized that no national consensus on storage demand exists. This fact could be assigned to the fact that different locations can carry great variations with regard to geologic, hydraulic, and contextual characteristics. For instance, the storage demand obliged in a low-lying private parcel with clayey soil cannot be compared with the storage demand obliged to a semi-rural high-lying private parcel with sandy soil. The stress on the latter will be lower due to the run-off and soil infiltration. Hence, to come up with an adequate storage demand, every situation should be assessed, and based on this assessment, a custom storage demand should be given.

To calculate a robust storage demand, an input-buffer-output balance is used. By initially determining the in- and outflow parameters, the outcome of the water balance gives the initial storage demand, provided that all values are given in millimetres per square meter. The water balance for the water system is shown in equation 1 and visually clarified in Figure 5. The water balance is assumed to be used on a detached dwelling, situated in an environment without gradient, and not on case studies lying beyond the boundaries of this study.

$$\Delta S = P - D_{sew} - D_{ro} - S_s - S_p - I \qquad \text{Eq. 1}$$

Here,
- ΔS = Initial storage demand (m^3)
- P = Normative precipitation event (m^3)
- D_{sew} = Drainage through sewage systems (m^3)
- D_{ro} = Drainage through surface runoff to surface water (m^3)
- S_s = Tolerated storage on streets (m^3)
- S_p = Existing storage on a private parcel (m^3)
- I = Natural infiltration in the soil (m^3)

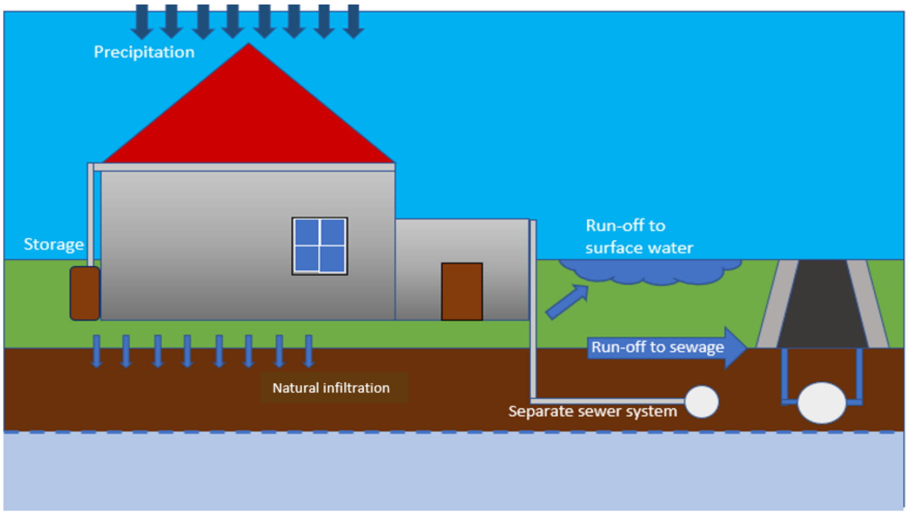

Figure 5 - Rainfall-runoff model

The required storage capacity is calculated through the water balance and is then divided over the total area. In Table 1, an exemplary calculation is given that shows the determination of the storage demand, through the use of the water balance.

Table 1 - Example calculation of storage demand

Characteristic	Value	Unit
Total area residential plot	200	m^2
Paved area (i.e. house, driveway, terrace)	120	m^2
Unpaved area (i.e. garden, pond)	80	m^2
Setting of initial storage demand		
$\Delta S = P - D_{sew} - D_{ro} - S_s - S_p - I = ST_{initial} = 6{,}8\,mm = \frac{6{,}8}{1000} * 200 = 1.36\,m^3$		
Manipulation of storage demand		
$ST_{new} = ST_{initial} * factors$		
Storage demand converted to required storage capacity		
$ST_{new} * 120\,[m^2] = 1000 * \ldots liters$		

2.5 Areal analysis through local parameters

The use of a tailored storage demand is not often used in Dutch policy. Many local parameters are required to construct the tailored storage demand, for which not always all data is available. If the data is available, it is often outdated, covers not all locations, or is inaccurate. In this section, the different parameters on which the storage demand is dependent are selected and investigated. The parameters are arranged in classes, depicted in Appendix C. Figure 6 displays the large deviations in storage capacity throughout the Netherlands, graphed by Atlas Natuurlijk Kapitaal. The local differences are a clear indication that it is unreasonable to impose a universal storage demand for all locations in the Netherlands.

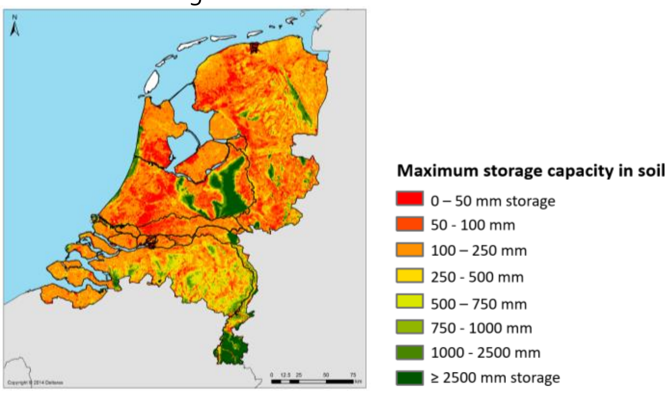

Figure 6 - Water storage capacity (Nationaal Georegister, 2014)

Through a sensitivity analysis in chapter 4.4.1, these parameters will be ranked, based on their impact on the storage demand. In Table 2, the most relevant parameters for this study are selected. They are ranked on their respective phases throughout the report. For a complete overview of all hydraulic, geologic, and positional parameters, see table 9-11 in Appendix B. In these tables, the parameters are divided into subcategories: hydraulic, geologic, and dimensional, respectively. Hydraulic parameters involve all hydrologic water-related parameters. The geological parameters are location-dependent and comprise properties of the soil. The dimensional properties are assigned as being positional.

Table 2 - Overview with most important parameters

#	Parameters	Brief explanation	Unit
1 Initial derivation of dummy storage demand			
1.1	Precipitation	The amount of rainwater that falls in a certain location, often framed in a certain period, like an hour.	mm/h
1.2	Discharge	The amount of rainwater that flows from the location on which it falls. The water can be discharged both subsurface and superficial. Besides the natural discharge, water can also be discharged manually	m^3/h
1.3.1	Infiltration	The water that flows into a porous medium, could be both naturally (percolation through sandy layer) as well as artificial (infiltration well/tube/crates)	mm/h
1.3.2	Hydraulic conductivity	The rate at which water passes through a porous medium, dependent on the intrinsic properties of the soil (could be both horizontal as well as vertical), scaled by hydraulic conductivity k (in m/day)	m/day
1.3.3	Infiltration depth	The maximum depth relative from the ground level where soil can infiltrate. The depth of the sand layer provided that the top layer is not clay or peat. This parameter becomes important when infiltration is possible to a certain depth, causing infiltration crates and bioretention swales to be a plausible measure, but infiltration wells impossible.	m
1.4	Storage capacity	The amount of (rain)water that can be stored in both a natural or an artificial way.	m^3
2 Manipulation of dummy storage demand			
2.1	Proximity surface water	The water that runs over the surface towards surface water of the sewage when the soil cannot infiltrate sufficiently (anymore)	m^3/sec
2.2	Pavement degree	The extent to which a certain location is urban, scaled through a pavement rating. The pavement degree describes all hardened surfaces, like terraces, driveway, walkway, etc.	%
2.3	Potential degree of precipitation deficit	The extent to which a certain location is vulnerable to drought, scaled in the deficit of rainwater	mm
2.4	Development	Type of state of the parcel. Could be a new building, an expansion or rebuild, or the improvement of the existing situation.	-
3 Coupling the final storage demand to the measures			
3.1	Groundwater level	The depth of the height of groundwater relative to the ground level	metres
3.2	Soil type	Certain type of soil class that falls within a distinctive set of characteristic properties	-
3.3	Size of paved area	The number of square meters on a private parcel that is paved, including a terrace, dwelling, drive-way, etc.	square metres (m^2)
3.4	Square size of flat roof	The number of square meters that has a flat roof, on which potentially a green roof could be constructed	square metres (m^2)
3.5	Slope	The surface that is higher on one side than the other	m/m

These parameters are selected based on the requirements of IkBenWaterproof and its existing programming, but extended with the parameters that could be added in the near future. The responsibility of assigning values to the parameters is divided. Firstly, location-specific parameters can be found based on the address of the dwelling and are fixed. Examples are *3.1 Groundwater level* and *3.2 Soil type*. Then, the policy-based parameters are variable and can be adjusted by the authorities as a boundary condition. These parameters give the municipalities the option to introduce policy points in the model. Examples are *2.2 Pavement degree* and *2.5 Proximity surface water*. For a full overview of where the policy-based and location-specific parameters are depicted, see chapter 4.3.2.

Classification is used to sharpen the research and give the model its boundaries. On the other hand, the classification allows expanding this study. While the classification is now based on a limited amount of parameters, and a limited range and amount of classes, the model offers the basis on which is expanded. This could be done by expanding the number of parameters on which the storage demand is scored. For instance, vegetation level, pavement type, and dependency on surrounding areas are aspects that could be involved easily. The classifications are placed in chapter 4.3.2 and elaborated Appendix C.

2.6 Model quality

Scientific models are used to explain and predict the behaviour of (future) applications of systems. Scientific models have the unique character to represent the real world, within the limits of (digital) technology. Models have opened many doors, given us many insights and predicted many future phenomena. Though, it is important to remember the importance of model quality control. This massively reduces the risk of errors which on their turn can lead to biased results. To check the quality of a model, the terms that determine proper model quality are described in this section. The quality concepts of a model are listed below:

- The extent of understandability;
- Effectiveness of the model;
- The soundness of the model;
- Robustness of the model

To test the model quality, verification and validation of the model are valuable processes that assure that the model is sound, robust, and adequate in the used context. Often, the quality of constructed models is tested through calibration or validation by experts.

3 METHODOLOGY

This chapter describes and decomposes the different methods and steps used to give a robust answer to the research objective. The methodology is graphically depicted in Figure 7, which shows the separation of the phases throughout this project. The phases are directly linked to the research questions. The graph also shows the sequence of steps and the interdependency of each step on another. Below, the steps are elaborated upon for every phase of the research.

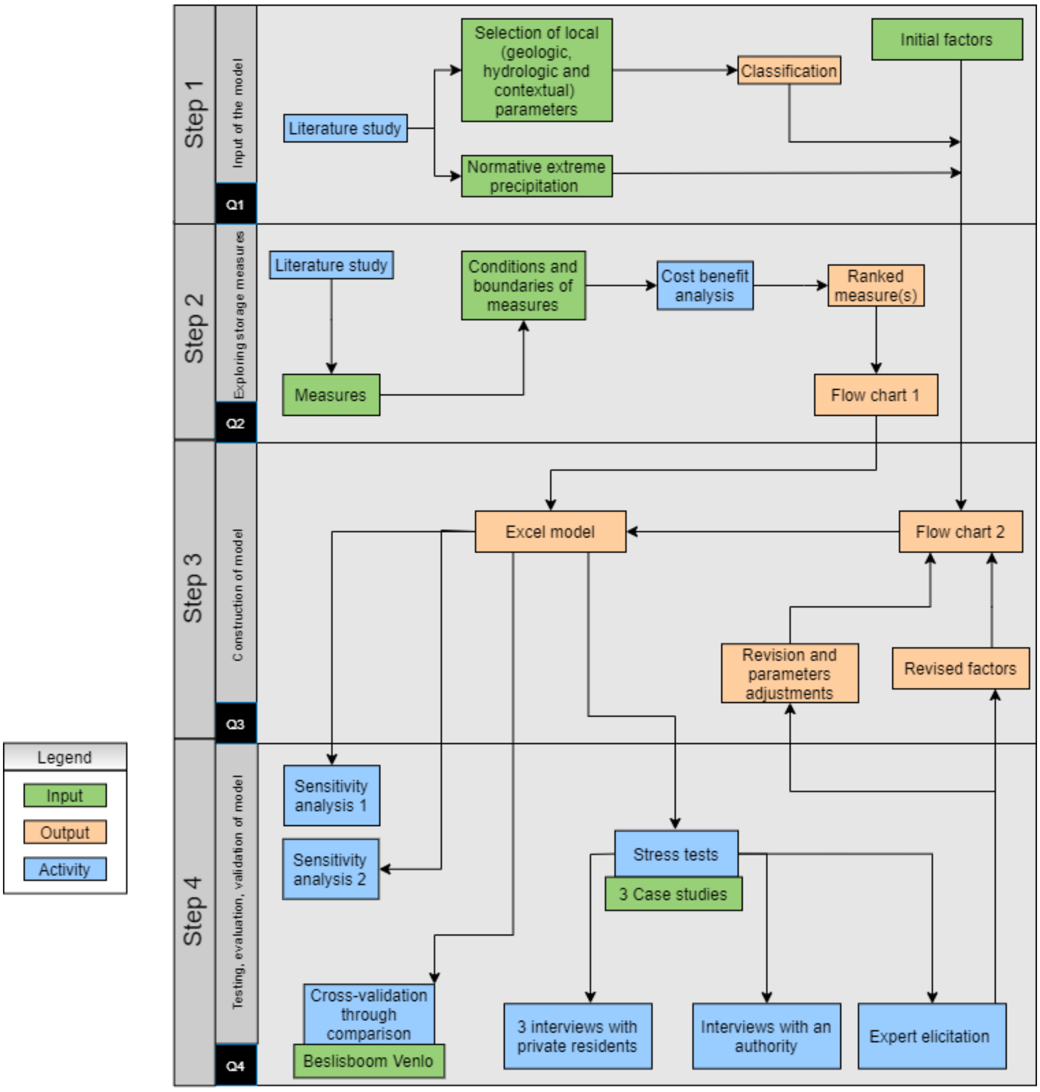

Figure 7 - Methodology visualized through an interdependency model

3.1 Step 1: Identification of input parameters

A literature review was carried out to gain expertise and insight into the current urban water management system. Where the different relevant future precipitation events are indicated in chapter 2.1, in this phase the precipitation that was used as input for the model was chosen. Then, the input parameters and their related classifications were set up, which formed the building blocks of the model. The parameters on which the storage demand would depend were selected, in accordance with the aspects that influence rainwater run-off. After these parameters were set, their quantitative limits and the linked (degree of) classification were determined. The set-up for the local assessment was then identified, which formed the set-up for the construction of two flow charts. The first flow chart was set up quantitatively and directs the user to its tailored storage demand. The second flow chart describes a qualitative way to find adequate (a combination of) measures for the specific location of a private resident. The flow charts provide a graphical guideline that shows, independently of each other, the build-up of the model.

Besides the identification of the opportunities, the determination of a tailored approach to the storage demand, this step was used to identify the challenges. Whereas the main challenge is composed in the research objective, a lot of sub-challenges were identified throughout the process of developing the model:

- Defining the conditions for all selected measures, based on the type of storage and its dependency on groundwater and soil type;
- Determining the influence of the extent of pavement in a neighbourhood on the required storage capacity;
- Determining what influence sloping has on the surface run-off;
- Dividing the responsibility of the input parameters over the municipality, the private owner, and the model expert;
- Defining how a newly built dwelling manipulates the storage demand and if this must be incorporated in a zoning plan;
- Finding accurate, up-to-date open-source databases from which the input parameters can be determined per private parcel.

The end-user of this model is expected to take action in the near future. Therefore, there is chosen to look at the expected climate change for 2050. Several input parameters were reviewed to see how they behave in the year 2050. When the scope would lie further in the future, say 2100, the measures are more stringent, though it is not expected that the end-users will look at these long-term investments of their house.

A literature study has been conducted to identify the relevant parameters when determining a storage demand. In chapter 4.3.2 the different parameters and their classifications are explained.

3.1.1 Data acquisition

In this chapter, the method of data gathering that is used for this research is described. Also, the way how the parameters are quantified is described briefly. Data was gathered through the expertise of the expert, knowledge of private residents, and boundaries set by municipalities. An example of such a variable parameter is the precipitation shower. The municipality can impose the type of precipitation event by selecting the frame of time they look. Dependent on the purpose of acquiring the model, the municipality can deviate several variable input parameters. Private residents themselves give the characteristics of their private property, provided that they agree to collaborate. To get an insight into their specific storage demand, they were asked to contribute contextual and dimensional characteristics.

Hence, the data is gathered through close contact between the model expert and the client. The choice for the precipitation event can depend on the context of an inquiry, possibly different per case. However, the data gathering is demarcated to a large extent. Those input parameters that are expected to have a major impact on the outcome were selected. The parameters related to a certain location are collected from freely accessible databases. This gives great advantages with regard to the general accessibility and inclusiveness of the model. A disadvantage is that these sources are not all accurate and up-to-date. The challenge arises to identify that data that is accurate enough to use in this research. In Table 3, the different databases, their respective information provision, and their source is listed.

Table 3 - Database sources for the local assessment

Obtained data	Source	Reference
1) The classification of the degree of pavement on a certain location 2) The drought vulnerability	Klimaateffectatlas	*https://www.klimaateffectatlas.nl/nl/*
Dimensions parcel	KadastraleKaart Perceelloep Vastgoedloep	*https://kadastralekaart.com/* *perceelloep.nl* *vastgoedloep.nl*
Groundwater level (infiltration depth)	Grondwatertools	*https://www.grondwatertools.nl/grondwatertools-viewer*

1) Ground level (m+NAP) 2) Slope	ArcGIS online AHN viewer	*https://ahn.arcgisonline.nl/ahnviewer/*
Soil type (infiltration depth)	DINOloket	*https://www.dinoloket.nl/ondergrondgegevens*

3.2 Step 2: Exploration of storage and infiltration measures

Measures that facilitate a degree of storage capacity when being subjected to an extreme shower were divided into three types: (1) store, (2) delayed drainage and (3) infiltration. The latter is most desirable from a climate-adaptation perspective, where it battles drought and heat stress besides the key driver which is the prevention of water nuisance. The measures were selected based on relevance and needs on the private parcel, where industrial-scale measures were neglected. Also, the aim of each measure is investigated. Several measures are multi-functional with regard to water nuisance, heat stress, and drought prevention. (see Table 5). For a complete overview of the measures, and their respective conditions and boundaries, see Appendix D1. These measures have in practice a heavily dynamic character, where the in- and outflow are typologically and contextually bound (Vergroesen, Brolsma, & Tollenaar, 2013). The dynamic character is neglected and there is assumed that the measure is empty when subjected to extreme precipitation. Hence, the measures are described statically, insinuating that the measures have always the same effect. The gathered measures were then rearranged on their financial effectiveness, through a cost-benefit analysis. The outcome is relevant for both the municipality and the private resident. See chapter 4.2.2 for a full elaboration.

3.3 Step 3: Construction of the model

The literature study of Step 1 forms the input for this phase, where the computational model was constructed in Excel. The following steps were required to construct the model:

- Define the relevant parameters;
- Providing the boundaries and conditions of the (different types of) measures;
- Define the model input variables, based on the parameters, and their classification;
- Explore the technical part of the model, with the expanded water balance;
- Define the initial factors for the manipulation of the initial storage demand;

During the construction of the model, several choices were made. Initially, the choice was made to construct the model in Excel, whereas this software was familiar to both the user and the constructor. The model can be seen as a black-box model that hides calculations and gives an intuitive value for the storage demand, the related storage capacity, and the quantified advice on the measures. This model combined the gained knowledge from the literature study with an input-buffer-output method to determine the initial storage demand. Through reverse engineering, the model found its shapes. Data from the initial phase and the real-time case studies tested the model, forming the stress-test for the trial-and-error process leading to the final model. The working of the model is visually explained through the flow charts discussed in chapter 4.3.1.

The final storage demand is then determined, through manipulation of the storage demand that uses a local assessment of geologic, hydraulic, and contextual characteristics. The most impactful choices were made during the manipulation of the initial storage demand, with the initial factors. Most factors were scientifically substantiated, though the remaining factors were determined by estimating their expected relative impact. This disputable method of estimation formed the basis for the trial-and-error process of these factors, concluding with the confirmation through expert elicitation.

On top of that, location-specific measures were advised, extended with a quantification. This advice was based on the conditions and characteristics of the measures, as well as the performed CBA. This storage demand was then connected to the conditions and characteristics of the measures. For every measure, it is indicated to what extent (in percentage) the measure can provide for the required storage capacity.

3.4 Step 4: Model evaluation and validation

To test the model quality, the model is evaluated through the use of several validation techniques. Initially, the model was tested on the sensitivity of its input parameters, through two sensitivity analyses.
Then, real-time stress tests, in combination with the input of the artificial precipitation event from STOWA, were used to check the model in a realistic environment. The model was qualitatively validated through an iterative trial-and-error method. Besides that, the expert elicitation with the Gemeente Oisterwijk and the water manager gave feedback on the influence of different location-related properties on the final storage demand.

3.4.1 Sensitivity analyses

Models are used to simulate phenomena in the past or predict phenomena in the future. According to Loucks & Van Beek, the usefulness of models depends in part on the accuracy and reliability of their output. Though all models are imperfect abstractions of reality, and because precise input is rarely if ever available, all output values are subject to imprecision (Loucks & van Beek, 2017). It is therefore important to limit the uncertainty of input variables, to increase the reliability of the output of the model. Though, not all variables have a similar impact on the output. To check what parameters can be adjusted and to what extent they are uncertain, two sensitivity analyses were performed. The Sensitivity Analysis (SA) is a method that measures how the impact of uncertainties of one or more input parameters can lead to uncertainties on the outcome (Pichery, 2014). An example of such a factor of uncertainty is the precipitation event, possibly subject to a changing climate. By taking the parameters and looking at their respective boundaries of uncertainty, and implementing this in the model, there is checked what impact this would have on the storage demand. Two sensitivity analyses were performed, which could give valuable information to both private residents and municipalities. A distinction was made between fixed (e.g. areal analysis) and variable (e.g. water balance) parameters.

Sensitivity analysis 1 - Relative change of input parameters

The first sensitivity analysis tested the input parameters of the constructed model. Through manually adjusting the different input parameters in the Excel model, by reducing and increasing the factor with a factor of 0.9 and 1.1, respectively. As a reference situation, one of the real-time case studies was selected. All factors that contribute to the water balance (e.g. run-off to surface water, run-off through the slope, etc.) were investigated through this analysis.

Sensitivity analysis 2 - Different urban contexts

Another sensitivity analysis tested the model on its geohydrological characteristics in a similar urban context. Several cases were manually selected throughout the Netherlands, where all dimensional and contextual parameters were uniform. Examples of this uniformity were the type of parcel (> 750 m^2), the degree of pavement (< 40 %), the (absence of) proximity to surface waters, and the type of development.

3.4.2 Climate stress tests

To check whether the constructed model was sound and realistic, several real case studies served as stress-test. The case studies are private parcels. A total of three private parcels is selected, based on their geologic (e.g. pavement degree, soil type), hydraulic (e.g. groundwater level), and dimensional characteristics. These specific cases are selected, whereas the largest share of Dutch citizens can find (some) resemblance with their parcel. Each private resident was interviewed to review whether the model is user-friendly and the outcome is realistic. Also, the interviewees were asked what motivates them to take action, and if this tool could support them. Outlying case studies are left out of the scope of this research. These outlying cases were given by a parcel with no garden, roof, or balcony forming the lower limit. Parcels with more than 2000 m^2 formed the upper limit. The upper limit is determined after investigating these limits in reports from among others Waterschap de Dommel and the Municipality of Breda. These describe how people are obliged to finance the storage facilities themselves unless their parcel is larger than 2000 m^2. Between these boundaries, the model can be interpreted in the same way as the most resembling case study described below. For a more technical description of all case studies, see Appendix F. For the summaries of the interviews conducted with the owner of these parcels, see Appendix G3.

Table 4 - Overview case studies

Case study 1 *Amersfoort (Utrecht)*	**Case study 2** *Sneek (Friesland)*	**Case study 3** *Harich (Friesland)*
Environment = semi-urban	**Environment** = semi-urban	**Environment** = rural
Parcel area = 267 m^2	**Parcel area** = 135 m^2	**Parcel area** = 750 m^2
Unpaved area = 20 m^2	**Unpaved area** = 132 m^2	**Unpaved area** = 509 m^2
Installed measure(s) = 30 m^2 detached roof	**Installed measure(s)** = **-**	**Installed measure(s) =** 6 m^2 detached roof
Soil type = Sand **Groundwater level** = Low	**Soil type** = Clay **Groundwater level** = High	**Soil type** = Sand **Groundwater level** = Low
Remarks: Average dimensions of a Dutch parcel (CBS, 2018)	**Remarks:** -	**Remarks:** Located on a slope
 Figure 8 - Case study 1 parcel	 Figure 9 - Case study 2 parcel	 Figure 10 - Case study 3 parcel

The model was validated through real-time testing with these cases as stress-tests. The output was among others proposed during the two expert elicitation that were carried out, both with an expert from Witteveen+Bos and an expert from the Municipality of Oisterwijk.

3.4.3 Cross-validation through comparison

Besides the stress-test of the model in a realistic environment, the model is tested in a comparable environment, by comparing it with the "Beslisboom" of Municipality Venlo. The "Beslisboom" is a step-by-step plan, intended as an aid while determining which demands and rules are handled when applying for an environmental permit or a request for a sewage application. Cross-validation is the process where the constructed model is validated by comparing the simulation results with empirical evidence. In this case, the empirical evidence is the model that is used in practice. This comparison will give insight into the choices made during the construction of the model and compares it with a successful model. The similarities and the differences and mapped, forming a part of the validation process of the model. The raised questions through this cross-validation are listed below:

- What are the differences and similarities regarding the purpose of both systems?
- Are the options from the nodes of this system binary and how does this differ from the model from this research? What is the better alternative and why?
- Are the model applicable and aimed at a nation-wide basis?
- To what extent make the systems use categorization, and which gives the most accurate outcome?
- What is the outcome of both models and how is this output given?

An extensive comparison between the "Beslisboom" and the model from this research is restricted by time. Hence, there will be made a technical comparison with the three real-time case studies that give an insight into the differences and similarities. This comparison is drawn up in chapter 4.4.4.

3.4.4 Interviewees

The model validation took place through conducting interviews with different key actors. Three interviews were conducted with private residents to check the outcome of the model and the user-friendliness of the model. Two expert elicitations were conducted with two parties with both a different perspective on the concept. The following people were interviewed:

Market inquiry - Private residents
These four owners of a private parcel were asked where they live so that a representative stress test for their private parcel can be conducted. It was also asked what would stimulate them to take action, whether it was subsidies, participating neighbourhoods, or the experience of water nuisance on their parcel. After that, they were imposed whether the outcome - the storage demand - was realistic, understandable and whether it would motivate them to take action. Questions were posed concerning the understandability of the model, and how the effectiveness (address -> final storage demand) was rated. This target group formed the market inquiry, where the response functioned as a test of the model on the market.

Expert elicitation - Municipality Oisterwijk
The first expert elicitation is used to pose questions focussed on the policy around the storage demand on private parcels, and specifically on the experiences in Oisterwijk. The target of this interview was to gather information on the perspective of a municipality towards the concept storage demand and the tailored approach discussed in this report. The interviewee was selected while he already had some experience with the new concept. The interviewee was asked if the step towards private parcels should be made and if this model could help with that. Several questions were raised with regard to the motivation/willingness of private owners to take action. This interview is important and framed in such a way, while the target group of the model is Dutch municipalities. Via interviews, this target group was asked for the existing problem and the expected solution. For the determination of the storage demand, several assumptions have been made. The soundness of these assumptions is checked. The interviewee was asked if the assumptions would affect the considered reliability of the study.

Expert elicitation - Water manager
In the second expert elicitation, the interviewee was asked if the technical design of the model was sound. The interviewee is asked what could be done to improve or elaborate on the model. The outcome will form a part of the iterative process of the construction of the model. The interviewee is asked in particular the technical components of the model, the manipulation of the basic storage demand, and the reliability of the (free) database sources. Also, questions were posed that were focussed on the assumptions and simplifications that were made during the set-up and construction of the model. The feedback will be important for the soundness of the model and say something about the coverage of the model.

3.4.5 Interview structure
First, the subject was introduced after which the interviewees were asked to introduce themselves. Then, questions were asked concerning the basic concept of the (need for a) storage demand and the linked measures. When this generic introduction was concluded, the questions were arranged on the (expected) expertise of the interviewees. The structure of the model, its reasoning, and its share of assumptions were then discussed, whereafter the outcome of the model was proposed to them. After discussing this outcome, the interviewee was asked for points of improvement and whether or not the model has potential for future application.

The interview was carried out with two people, the interviewer, and the interviewee, with a total duration ranging from 20 to 40 minutes. The interviews were conducted in Dutch. Due to the impossibility of interviewing in person, considering the situation around Covid-19, Microsoft Teams was used. Semi-structured interviews therefore enable a more interactive and intuitive interview, with room to stray. This method was chosen, to give the best impression of the knowledge and opinion of the interviewees. Besides the closed questions, interviewees can bring up other topics that are interesting for this study.

3.4.6 Privacy and approval
- An audio recording is made, provided that the interviewee approves;
- The interviewee is questioned for the permission of being mentioned in the report, this enables a reliable base, especially with the expert elicitation;
- The interviewee is asked whether it is fine to use their parcel for exemplary calculations, otherwise suggest discrete processing of the data;
- During the processing of the real-time case studies, the addresses will be treated discretely and will not be published.

4 ANALYSES & RESULTS

4.1 Identification of input variables

Initially, the options regarding the input variables are explored. In combination with the conditions of the measures, this would form the basis for the construction of the model. The first research question was:
Q1 - How can future forecasts for extreme rainfall events serve as an input for the prediction of the storage demand?

4.1.1 Normative precipitation event

While precipitation has many variables, like intensity, frequency, and duration, there is no unambiguous definition of an extreme precipitation event. Organizations like KNMI and RioNED, therefore, like to use standardized precipitation events. These precipitation events are chosen, to guarantee a sound comparison of results. For stress testing urban areas, often standardized peak rainfall events of 1-2 hours are used, based on the controlled run-off to surface waters. Different methods of data gathering regarding precipitation events are available. As discussed in chapter 2.1, three methods are mainly used in the field of urban stormwater management. In Appendix A, these methods are explained in greater detail. Historical data is highlighted, data extrapolated with a climate change factor is reviewed, and standardized artificial precipitation events (bui08-10) from Stichting RioNED are treated in this section.

The general opinion is that rainwater in the house is unacceptable. If the chance of overflowing rainwater in 60 years would be reduced to maximally 20 percent, a return period of 1000 years should be used (Overeem & Luitelaar, 2017). The Deltaplan Spatial Adaptation (DPRA) makes use of a large return period to come up with an extreme rainfall event. The nation-wide programme (used for all municipalities) uses T= 100 years, which results in a precipitation event on the scale of 70 mm/h. This shower is based on the 2050 W_H scenario (Deltaplan Ruimtelijke Adaptatie, 2018). Besides DPRA, also STOWA uses return periods to determine extreme precipitation events. With the use of historical data, STOWA has managed to quantify the precipitation sum as output, with the return periods and precipitation duration as input variables (STOWA, 2019). Appendix A describes the rainfall events, as a product of the return period and the duration of the shower. This data is subjected to a climate change factor (W_H upper scenario), which describes the expected influence of climate change. For the model, this artificial peak rainfall event is used as input for the stress tests. These so-called Precipitation Series are used as input for this research, whereas it is considered this is the most accurate data source. It also provides great opportunities to (manually) switch the return period and hence, look at the nearer or further future. Based on a return period of 25 years, the assigned precipitation event releases a total precipitation sum of 47.9 mm in one hour on the system (see Table 13). A return period of 25 years is chosen, while it is based on the future perspective of the end-user. Private residents are expected not to look beyond a period of 20-25 years regarding investing in their parcels (Rijkswaterstaat, 2014). In the model, the option is given to select different return periods. This way, the precipitation event becomes a policy aspect, where each municipality can indicate their policy goals with regard to stormwater management. If it turns out that the recommended storage capacities cannot be met (resulting from cost-benefit analyses), it can be chosen to scale down the return period.

The purpose of municipalities for using the model could differ largely from that of parcel owners. The aim of municipalities could be to try and find the bottlenecks of certain neighbourhoods. With the use of relative comparison between parcels, they could find the locations on which to focus. When comparing, the identification of the normative precipitation event is not as valuable as for parcel owners themselves.

4.2 Water resilience measures on a private parcel level

Q2 - What are the appropriate ways and measures to achieve water resilience and how do different geospatial and hydraulic parameters impact these initiatives?
The Climate Proof Cities research (Rovers, Bosch, & Albers, 2014) has concluded that within the urban areas, a great spatial variety exists regarding the vulnerability of persons and objects. Therefore, the choice for (a combination of) measures is heavily dependent on the local context.

While noticing the shrinking space for opportunities in the public domain and the potential of the private terrains, several initiatives have already been raised. To increase the awareness of Dutch citizens, municipalities have introduced plans like Amsterdam Rainproof, Rotterdam Weerwoord, and "Huisjeboompjebeter". Plans with a similar feel to IkBenWaterproof are the Maatregelen-Toolbox (developed by Amsterdam Rainproof) or waterlabel.net (, which is an initiative by RioNED and STOWA).

4.2.1 Collection of measures

Table 5 provides a qualitative overview that includes all selected and relevant measures that can be taken to prevent water nuisance or drought damages, on a private parcel level. The measures are assessed based on their function, effectiveness, and type. The column 'Aim' describes the intent of the measure and against which meteorologic threat it is effective. While the scope of this research stays within the prevention of water nuisance, this column assesses every measure on its multi-functionality. The column 'Effectiveness' then describes the extent to which each measure is effective. The effectiveness is rated through the results of the CBA (see Table 6), the relative storage capacity, difficulty of implementation and maintenance, and finally the multi-functionality. The column 'Type' addresses the conditions and prerequisites attached to each measure, and whether the measure is dependent on several (local) characteristics.

Table 5 - Overview measures (Rovers, Bosch, & Albers, 2014)

Code	Measure	Aim*	Effectiveness**	Type***
Infiltration				
1.1	Bioretention swale	W	++	T
1.2	Rainwater pond	W	++	T
1.3	Infiltration well	W	+	T
1.4	Permeable pavement	W	+	G
1.5	Open pavement	W	+/-	G
1.6	Infiltration trench	W	+	T
1.7	Infiltration crates	W	++	T
1.8	Infiltration tubes	W	+	T
Storage				
2.1	Water bag	W	+	C
2.2	Rain barrel	W	+	G
2.3	Rainwater tank	H/W	+	T
2.4	Rain blocks	W	+	C
2.5	Detention basement	W	+/-	C
Delayed drainage				
3.1	Extensive green roofs	H/W	+	C
3.2	Intensive green roofs	H/W	+/-	C
3.3	Water roof	W	+/-	C
3.4	Detaching rain pipe	W	+	C
3.5	(emergency) drain	W	-	-

*) H = prevention heat stress ; W = prevention water nuisance
**) Effectiveness based on the CBA, sheer size, and target (H/W)
***) G = generic ; T = typology bound ; C = context bound

4.2.2 Cost-benefit analysis

In Table 6 a quantitative overview is depicted and the measures are ranked on their effectiveness through a Cost-Benefit Analysis (CBA). An important sidenote with this analysis is the fact that the measure with the highest score in terms of effectiveness, is not necessarily the best in every context. For instance, the bioretention swale tops the charts, though cannot be implemented in a small garden with clayey soil. The outcome of this analysis is important to interpret for both the private residents as well as municipalities.

Table 6 - CBA-ranked storage measures

Rank	Type of measure	Alt1 [L]	euros	Alt2 [L]	euros	Alt3 [L]	euros	€ per L
1	**Bioretention swales**	500	6,1	500	5,17	-	-	0.008
2	**Rainwater pond**	500	20	250	73	1000	215	0.182
3	**Infiltration well**	1000	152	5000	1600	-	-	0.197
4	**Permeable pavement**	1000	120	1000	175	500	175	0.215
5	**Infiltration trench**	400	122	-	-	-	-	0.306
6	**Infiltration crates**	200	78	272	160	200	70	0.443
7	**Extensive green roofs**	59	50	25	30	-	-	0.682
8	**Water bag**	3000	201	2000	1500	4000	1950	0.435
9	**Rain barrel**	240	140	320	149	210	67,5	0.457
10	**Open pavement**	90	140	-	-	-	-	0.519
11	**Rainwater tank**	15000	3410	1000	805	1000	396	0.476
12	**Infiltration chambers**	70	130	-	-	-	-	0.619
13	**Intensive green roofs**	55	60	80	120	-	-	0.864
14	**Rain blocks (in a boarding/fence)**	165	209	350	400	330	419	1.226
15	**Water roof**	1000	2100	-	-	-	-	2.100

4.3 Construction of model

Q3 - How can a universal model be constructed that determines the storage demand based on classification?
To use the input data as building blocks for the model, and give an answer to the research question posed above, the five steps below are discussed is in the upcoming sections:

1. Through a literature study identification of relevant input and opportunities
2. Through a literature study, the collection of the initial factors used to manipulate the storage demand
3. Through identification of the boundaries and conditions of the measures, the construction of the first flow chart
4. Through the classification and the initial factors identified previously, the construction of the second flow chart
5. Based on the second flow chart, the construction of the computational model in Excel.

The provisionally calculated storage demand is a result of the water balance in the closed system of the parcel. This value for the storage demand is then manipulated by factors, based on its geographic, hydrologic, and contextual characteristics. The initial factors that are incorporated in the model are described in Table 7. Initially, the factors are determined by estimation of the consequences of such a change in parameter on the final outflow. This was estimated through scientific research and relative comparison. The exact factors are manually adjusted by expert elicitation. The reconfigured values are indicated between brackets in bold, and the added options are also indicated this way. The calibration of this model takes place through trial-and-error, a manual approach where the outcome is constantly checked. The outcome is realistic and plausible when it is approved by the expert. If the outcome is unrealistic, adjustments are made within the scientific boundaries so that the model improves.

Table 7 - Factors for the manipulation of the dummy storage demand

Type of flow	Option #1	Option #2	Option #3	Option #4
Proximity surface waters	"Yes, but more than 50 metres"	"No"	"Next to a surface water"	-
Factor (before expert elicitation // after expert elicitation)	*0.8 // **(*0,8)**	*1.0 // **(*1,0)**	*0.5 // **(*0,6)**	-
Development	"New"	"Existing"	**(Redevelopment)**	-
Factor (before expert elicitation // after expert elicitation)	+10mm // **(+10mm)**	+0 // **(+0)**	... // **(+5 mm)**	-
Degree of pavement	"Rural (<40 %)"	"Moderate (40-70 %)"	"Dense (70-90 %)"	**(Very dense (> 90 %))**
Factor (before expert elicitation // after expert elicitation)	*0.9 // **(*0,8)**	*1.0 // **(*0,95)**	*1.2 // **(*1,1)**	... // **(*0,3)**
Parcel size	"Small (<20 m^2)" **(<150 m^2)**	"Average (20-100 m^2)" **(150-750 m^2)**	"Large (> 100 m^2)" **(750-2000 m^2)**	**(Very large (> 2000 m^2))***
Factor (before expert elicitation // after expert elicitation)	*0.9 // **(*0,7)**	*1.0 // **(*1,0)**	*1.1 // **(*1,3)**	... // **(*1,3)**
Drought vulnerability (criteria APD)	"Low (<270 mm)"	"Moderate (270-300 mm)"	"High (300-390 mm)"	-
Factor (before expert elicitation // after expert elicitation)	*0.9 // **(*0,9)**	*1.0 // **(*1,0)**	*1.1 // **(*1,1)**	-
(Groundwater level)	**(< 0.5m)**	**(0.5-1.0m)**	**(1.0-1.5m)**	**(1.5-2.0m)**
Factor (before expert elicitation // after expert elicitation)	*0.9 // **(*0,8)**	*0.95 // **(*0.9)**	*1.0 // **(*0.95)**	*1.1 // **(*1,0)**

** In close consultation with the local municipality*

4.3.1 Flow charts

Subsequently, two independent flow charts were composed. Respectively, they display the determination of the final storage demand (see Figure 11), and the advice on which measures to take (see Appendix E1). The first flow chart shows the influence of different dimensional and geohydrological properties and their respective influence on the final storage demand. To each flow, a certain factor is added, which indicates the impact of each property parameter on the output. Each flow indicates an answer to a question that is included in the nodes. This flow chart functions as the guideline, which was used to construct the computational model.

The second flow chart (see appendix E1, Figure 24) is constructed for the coupling of the final storage demand to the different measures. For this step, first, the conditions and prerequisites for every measure are inventoried, see *Dimensions and conditions* in Appendix D1. This flow chart was used as a guideline for the conditions and boundaries of the different measures, and the quantified advice on the measures. Both flow charts make use of classes and are therefore not as accurate as of the computational model.

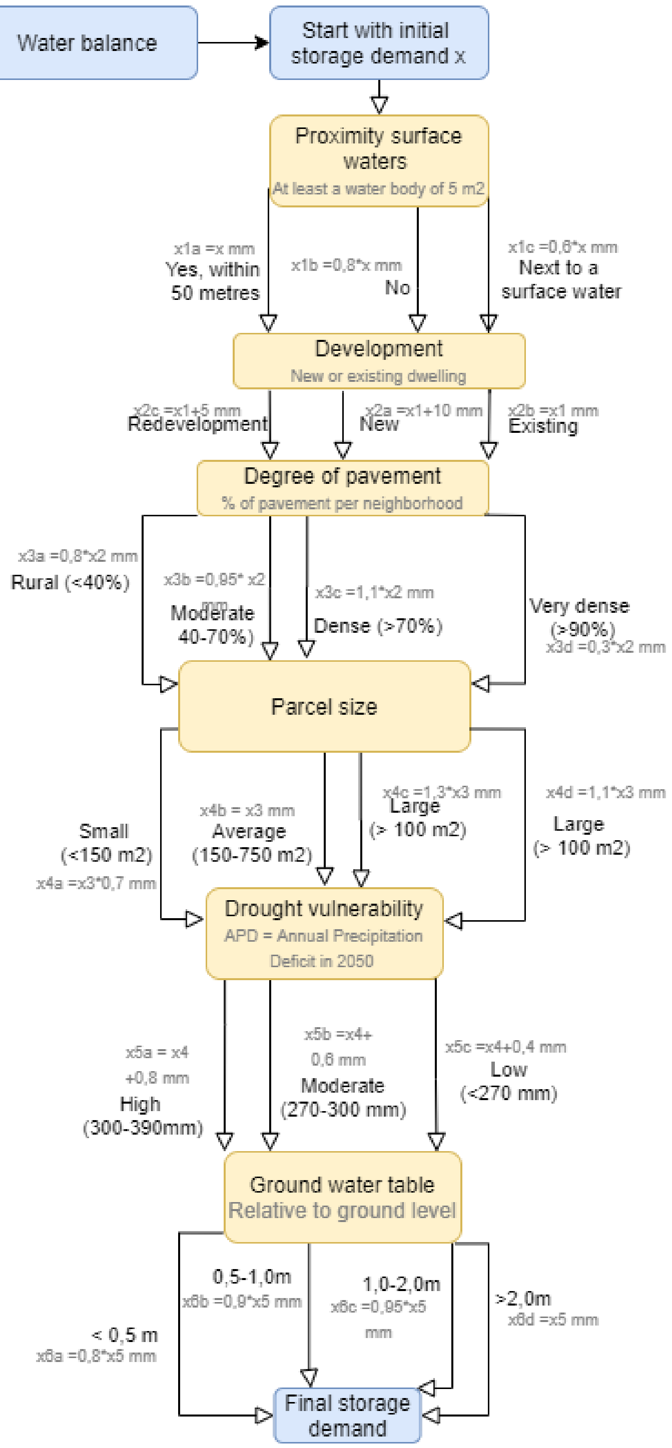

Figure 11 - Flow chart to derive the final storage demand

4.3.2 Local assessment and classification

Serving as the input for the model, there is made a local assessment. This assessment is performed through the semi-automated configuration of open-source databases into the computational model. During this assessment, all dimensional, geologic and contextual parameters are analysed. To simplify the process, classes were made. For an overview of the boundaries and the choices made while setting these classifications, see Appendix C. All nodes from the flow chart in Figure 11 are based on the classifications of this research. Below, each step of the flow chart is decomposed and the most important choices are elaborated.

Proximity surface waters
Policy-wise, the municipality determines whether or not rainwater may/will flow into the near surface waters. For this reason, this will also be incorporated in the tool as a boundary condition. The municipality is asked whether rainwater run-off may flow into the surface waters. Besides the policy-dependent boundary condition, a physical condition is added. While checking whether the water will run off, first the availability of such a body is checked. The surface body should be near or at least within 50 meters and have minimum dimensions of 5 m^3. This threshold is based on the peak precipitation falling on an average parcel. Also, the parcel is assumed to be optimally situated so that it is sloped with the target to drain water directly to surface water. If a dwelling is considered to lie within significant proximity, it is checked whether the municipality allows the drainage to this surface body. Once these boundary conditions are all met, it is assumed that (a large portion of) the rainwater will flow directly to this surface water. This causes a decrease in the required storage capacity.

Development classification (open, policy-dependent)
The model distinguishes between three development classes, which are “newly built” dwellings, “redeveloped” dwellings, and “existing” buildings. Their respective influence on the outcome of the model is depicted in Appendix C. Newly built dwellings give greater opportunities to incorporate demands within the zoning plan and the Rioleringsplan (GPR+), where most municipalities can make the storage demand a requirement before granting a permit. Therefore, there will be made a distinction between existing and newly built dwellings. Based on reports from municipalities Venlo and Apeldoorn, newly developed parcels are given a further 10 mm to the storage demand. Redevelopment projects lend themselves perfectly for the construction of water storage measures and are therefore given a higher storage demand.

Pavement classification (open, policy-dependent)
The amount of pavement in a neighbourhood indicates how much water can infiltrate the soil. A densely paved neighbourhood causes to gives the sewages the responsibility of draining, which could lead to overflow situations. Therefore, the denser paved the neighbourhood, the higher the storage demand. This is arranged in four different classes This classification uses an upper limit, where neighbourhoods that are paved higher than 90 % (for instance city centre) are expected to carry a lower storage demand.

Dimensional classification (fixed, location-specific)
Based on the parcel size, the storage demand is adjusted. This choice is made so that unreasonably large dwellings, often occupied by a wealthy private resident, get a fair storage demand. Hence, four classes were made. Real-life case studies are selected in such a way that they fall into three different classes. Also, the upper threshold forms a class, where the parcel size is larger than 2000 m^2. This threshold is chosen whereas parcel sizes larger are considered as industrial plots. Also, several zoning plans (of among others Waterschap de Dommel and the Municipality of Breda) use a boundary of 2000 m^2 for which a regular storage demand can be asked and the residents are expected to finance the facilities themselves. For parcels larger than 2000 m^2, often close contact with the municipality can result in a collective approach, where the storage demand is (partly) compensated through subsidies.

Drought vulnerability (open, policy-dependent)
Periods of drought are increasing, with 2018 and 2020 as recent examples with a precipitation deficit of over 250 mm. To compensate for this deficit, private residents should store rainwater for times of drought. Another method is to enable infiltration for the groundwater level to be controlled. Based on data from the Klimaateffectatlas, three classes are made. The expected annual precipitation deficit with T=10 years for 2050 determines the options and boundaries of the classes. The storage demand is increased based on this deficit, where a compensation is encapsulated in the final storage demand. The installed facility should store a sum ranging from 130 to 250 mm on an annual basis. This means a surplus of the storage demand, ranging from 0.4 to 0.8 mm/day, depending on the specific location.

Groundwater level classification (fixed, location-specific)
Throughout the Netherlands, the groundwater level ranges from 10-20 cm below surface to 30-40 meters below the ground level. This variability in groundwater is incorporated in the tailoring of the storage demand. The higher the groundwater level, the less water can infiltrate the soil.

This causes an enhanced surface run-off and also, a lower storage demand. Through location-specific data of the groundwater level, the online database Grondwatertools is accessed. The soil layer WVP2 - which is the first water-carrying soil layer that is covered by soil - is constructed based on measurement points from DINOloket, where interpolation with the use contour lines (isohypses) is used to deduce intermediate groundwater levels. The data should not be older than January 2018, to give a tolerable, contemporary estimation. This class influences the storage demand, as well as the advice of the type of measure. Based on the scope of this research, the threshold of the groundwater level lies at 2.0 meters. Aquifers situated deeper in the soil will not have any influence on infiltration. Also, the selected measures have a maximum height of 2.0 meters subsurface.

Lithographic classification (fixed, location-specific)
The lithographic classification is not incorporated in the flow chart, where it does not have an impact during the manipulation of the storage demand. The soil type determines the infiltration depth, and with that, the type of measures can be selected. Five soil types and their respective conductivity are separated. The type of soil will influence the storage demand, as well as the advice on (the type of) measures. For a location that is situated in a clayey environment, infiltration is hard, which causes a reduction of the storage demand and infiltration measures are neglected. The hydraulic conductivity of each soil type determines the degree of natural infiltration. Heavy showers (> 10 mm/h) overwhelm the infiltration capacity (3-10 mm/h) of soils, resulting in excess rainwater run-off over the surface (Worm, de Louw, van Bakel, & Massop, 2019). In one hour, soil can therefore store up to 10 mm, before saturation is reached. In Table 17, the values for the hydraulic conductivity and hence the maximum infiltration capacity of each soil type are depicted.

Slope classification (open, policy-dependent)
Whereas the slope is not incorporated in the flow chart, it does influence the water balance in the model. Besides that, when it is indicated that the dwelling is placed on a slope, a sidenote will be added to raise the awareness of rainwater running in or off the parcel. In this research, a slope of 1.0 % is seen as the threshold at which water will run in or out of a private plot. A slope of 1.0 percent results in a reduced maximum infiltration capacity of 4.4 percent, investigated by Haggard in a laboratory environment (Haggard, Moore, & Brye, 2005). This surface run-off is incorporated in the model and reduces the required amount of storage capacity on the private plot. While the model will not recognize placement on the top, halfway, or down a slope, it is important to consider that every dwelling requires a tailored approach. Parcel boundaries are often facilitated with fences or ditches to prevent in- and outflow. Hence, a side-note will be added to the imposed storage demand that suggests actively consider the dependency on the actions of the upstream neighbor and the dependency of the downstream neighbour on your actions.

To see further expansion on all classifications, see Appendix C.

4.3.3 Constructed computational model
The tailored storage demand is determined by a constructed model which was made in Microsoft Excel. The input of the model can be provided by the end-users (e.g. municipalities, private parcel owners), but can also be deduced completely from a single address. In the latter case, the information is gathered from open-source databases. In Figure 12, a screenshot of the user interface of the model is depicted. The full sheets, with exemplary calculation, are placed in Appendix F (see Figure 25 and Figure 26). In three sheets, the storage demand is calculated. In the first (input) sheet (1-RA) the Regional Assessment takes place. This sheet configures all data and provides the input for the second sheet (2-WB). The second sheet provides the content of the 'black-box' and gives all (intermediate and end-) calculations. Adjustments made during the validation process have to be performed in this sheet. The end-user is only interested in 1-RA, and the experts of the model are interested in sheet 2-WB, as well as the third and last sheet (3-CM). This sheet provides all conditions and boundaries of the measures, to be implemented. This sheet is used to give a quantitative advice on the (type of) measures to take, which is based on the CBA.

1 - Regional Assessment (FILL IN)

This model uses a regional assessment to come up with a tailored capacity that should be stored in case of an extreme precipitation event.
The model can be used by both municipalities - to get an idea which parcels require most attention - as well as private owners, to give an indication what the best measures are to take.
Fill in the data in the first sheet and your storage demand is automatically calculated!

All parameters in this sheet are variable/adjustable

1 Personalia	
Applicant name	Y. Ypma
Adress	Frederik Hendrikstraat 29
City	sneek
Max budget (€)	500
Date	29-1-2021
I want to tackle	Solely water nuisance

Final overview (DO NOT CHANGE ANY VALUES)			
Storage demand		12,9	mm
Required capacity		1741	liters
Advised measures	**Type**	**Contribution to required capacit**	**Price (€) for contribution**
		19	1,92
		34	81,68
		8	20,39
		5	17,20
		2	14,93
		23	122,00
		13	76,17
		1	13,86
			ABOVE BUDGET
	Rain barrel	15	117,25
			ABOVE BUDGET
	Rain blocks	16	414,53
		2	11,74
	Intensive green roof	3	35,82
	Water roof	3	126,00
	Detaching rainpipe	2	0,00
Extra advice			

2 Location specific (fixed) parameters*				
2a Dimensional			Unit	Source
Total area	135		m^2	*Kadastralekaart/Maps*
Paved area (house)	56		m^2	*Kadastralekaart/Maps*
Total area (garden)	44		m^2	*Kadastralekaart/Maps*
Paved area (garden)	41		m^2	*Kadastralekaart/Maps*
Unpaved area (garden)	3		m^2	*Kadastralekaart/Maps*
Area flat roof	24		m^2	*Kadastralekaart/Maps*
Length adjacent street	7		m	*Kadastralekaart/Maps*
2b Contextual			Unit	Source
Existing storage	Nothing	0	m^3	Own expertise
1			m^3	
2			m^3	
3			m^3	
4			m^3	
Existing storage	Nothing	0	m^2	Own expertise
1			m^2	
2			m^2	
3			m^2	
4			m^2	
Crawl space			m^2	Own expertise
2c Geographic	Value		Unit	Source
Slope	0,001		%	*ArcGIS online AHN viewer*
Max depth permeable soil	Clay	0	m	*DINOloket*
Estimated k_v value	0,42		mm/h	
Ground water level	-0,7		m+NAP	*GrondwaterTools*
Ground level (GL)	1,158		m+NAP	*ArcGIS online AHN viewer*
Ground water level	1,858		m - GL	
Infiltration depth	0		m - GL	

3 Policy based (open) parameters**		Unit	Source
Pavement degree	Semi-urban (40-70%)	%	*Klimaateffectatlas*
Drought vulnerability	Moderate (270-300mm)	mm	*Klimaateffectatlas*
Proximity surface water	No	m	*Google Maps*
Development	Improving existing situation		*Own expertise*

Figure 12 - User interface (1-RA) of the input sheet of the computational model

Based on the conducted CBA, the final storage demand is coupled to a specific type of measure. This specific advice on the measures indicates the contribution of a certain measure (per piece or m^2). Also, the price for this contribution is directly indicated, as can be seen in an example in Table 8 which is the outcome of the real-time stress test of Case study 2 - Van den Heuvel. This table shows not only the type of measures that could be selected but also the contribution to solve the required storage capacity in percentage. It also gives the price for this percentage of contribution.

Table 8 - Final advice from the model on for Case study 2 - Van den Heuvel

Code	Type	Contribution to required capacity [%]	Price (€) for contribution
Infiltration			
1.1	Bioretention swale	22	1,92
1.2	Rainwater pond	38	81,68
1.3	Infiltration well	9	20,39
1.4	Permeable pavement	5	17,20
1.5	Open pavement	2	14,93
1.6	Infiltration trench	26	122,00
1.7	Infiltration crates	14	76,17
Storage			
2.2	Rain barrel	17	117,25
2.4	Rain blocks	18	414,53

4.4 Evaluation and validation

After the construction of the model, it should be tested in a realistic environment and scientifically validated. Hence, the following research question is posed:

Q4 - To what extent does the outcome of the model match with reality, and in what way can this be validated?

To give a sound answer to this question, four methods were used to evaluate and validate the model. These are discussed in the upcoming sections in the following order:

1. Using a sensitivity analysis
2. Through a quantitative comparison of model outcomes
3. Through a relative comparison of the model outcomes with the "Beslisboom" of Municipality Venlo
4. Through interviews and expert elicitation

4.4.1 Sensitivity analysis of input parameters

The sensitivity of the model outcome (storage demand) to a change in the input parameters is tested in this section. By comparing the results, conclusions can be drawn regarding the parameters that should be focussed on or which can be considered in a (policy) decision regarding the battle against urban stormwater. Using local characteristics of Case study 1 - Amersfoort as the reference situation, the reference storage demand is determined. Then, all relevant selected input parameters are reduced and increased by 10 percent. In Table 9 the outcome of the sensitivity analysis is shown. The most sensitive input parameters are ranked highest, ending with the parameters with the lowest impact on the outcome.

Table 9 - Sensitivity analysis outcome

Input	Storage demand [mm]	Storage demand (-10 % Δ)	-10 % Δ	Storage demand	+10 % Δ	Rank

				(+10 % Δ)		
Reference situation "Case study 1 - Amersfoort"	7,21	-	-		-	
Precipitation +/-10 %	-	4,49	-60,58 %	9,86	+36,76 %	1
Run-off to sewages +/-10 %	-	8,47	-14,88 %	5,94	+17,61 %	2
Natural infiltration +/- 10 %	-	7,64	-5,63 %	6,77	+6,103 %	3
Run-off to surface waters +/-10 %	-	7,41	-2,70 %	7,00	+2,913 %	4
Storage streets +/-10 %	-	7,48	-3,61 %	6,93	+3,88 %	5
Run-off due to slope +/-10 %	-	7,39	-2,43 %	7,03	+2,50 %	6
Existing storage +/-10 %	-	7,24	-0,41 %	7,18	+0,42 %	7

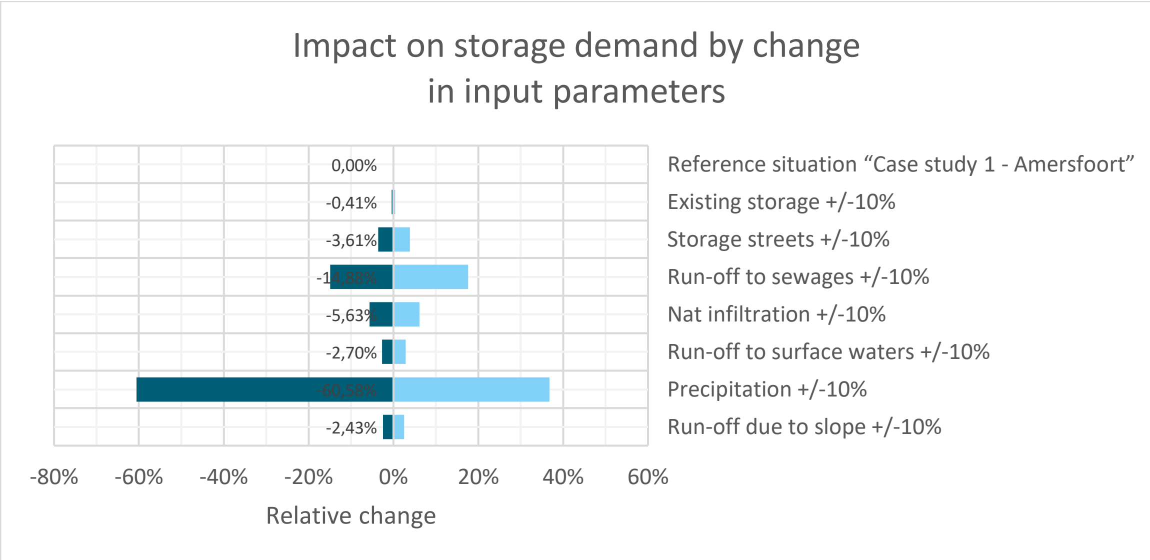

Figure 13 - Sensitivity analysis

From this sensitivity analysis, it can be concluded that precipitation influences the outcome most significantly. This is an important conclusion to draw when municipalities would use the model. Based on the return period, they can select the type of precipitation event that serves as the main inflow for the stress tests. To get an idea of the degree of sensitivity of the storage demand on the precipitation input, a different return period is chosen. When a municipality would choose T=20 years instead of T=25 years, this would result in a reduced value for the storage demand with 26 percent. The policy of the municipality is therefore of great influence on the demanded storage capacity.

Another expected conclusion that can be drawn in response to the outcome of the SA, is that an expansion of the sewage systems would have a significant impact on the reduction of the storage demand. While this expansion is effective in all contexts, it remains a relatively drastic and expensive implementation. Whereas the public measure of expanding sewages would significantly benefit urban stormwater resilience, an expansion of the existing storage on the streets (e.g. lowering street plain, raising of curbs) would have a minor influence on the storage demand.

At last, another remarkable conclusion can be drawn. The model showed that an exemplary implementation of a measure on parcel-level (infiltration crate) in the same price scale had a greater influence on the final storage demand than the lowering of the street level. This suggests that the implementation of measures on private-parcel - for at least the infiltration crate - is more effective than the lowering of the street level.

4.4.2 Sensitivity analysis based on geographic context

Then, a second sensitivity analysis is performed that finds its differentiations related to the geographic environment. Several cases are selected with the same contextual parameters (i.e. degree of pavement, parcel size), though in a different city. The variable parameters, therefore, are groundwater level and soil type. Table 10 displays the selected cases. In this table, similar parameters regarding areal analysis can be seen, and the deviations regarding geographic context can be seen.

Table 10 - Overview city case studies

City	Areal analysis			Geographic context		
	Total area [m^2] *All parcels larger than 750 m^2*	Paved area [m^2]	Degree of pavement	Soil type	Infiltration depth [m]	Groundwater level [m- GL]
Delft	972	429	Rural (<40 %)	Marine clay	0	6,32
Enschede	856	334	Rural (<40 %)	Sand	2	2,49
Zaandam	765	451	Rural (<40 %)	Peat	0	0,10
Nijmegen	1035	532	Rural (<40 %)	Riverine clay	0	3,62
Maastricht	1321	423	Rural (<40 %)	Loam	2	16,42

Figure 14 presents the dependency of geographic context on the storage demand. The parcels are selected for most parameters to remain relatively constant, except for soil type and groundwater level. The cases are all located in exclusive residential areas, with a parcel size larger than 750 m^2, and a pavement degree below 40 percent. Besides that, the amount of paved area is all selected similarly.

From Figure 14 can be concluded that a parcel placed on loam or sand soils (i.e. Maastricht, Enschede, respectively) requires significantly less storage capacity. The permeable character of the sandy soil provides storage of the precipitation event through (delayed) soil infiltration. Also, the case from Maastricht - low groundwater level and loam as soil type - is especially remarkable, where it is even lower than the storage demand of Enschede, though located on a less permeable soil. Although loam infiltrates less than sand, the (minor) advantage in storage demand is caused by the enhanced opportunity to store rainwater on the streets. Hence, it can be concluded that the soil type has the largest influence on the outcome. The reduced storage demand can be attributed to the fact that the water balance shifts in favour of water drainage. On top of that, the manipulation of the storage demand in cases of permeable soils is favourable.

The measures per case can also be analysed and support the conclusion posed above. Whereas all parcels are located in a spacious, green neighbourhood, almost all measures are recommended. The clear deviations are found in the measures that should be placed on a flat roof (i.e. water, green roof), and measures that have the main target to infiltrate. For the cases of Maastricht and Enschede, infiltration is strongly advised and possible. For the other cases, this is not suitable and storage or (delayed) drainage measures are advised.

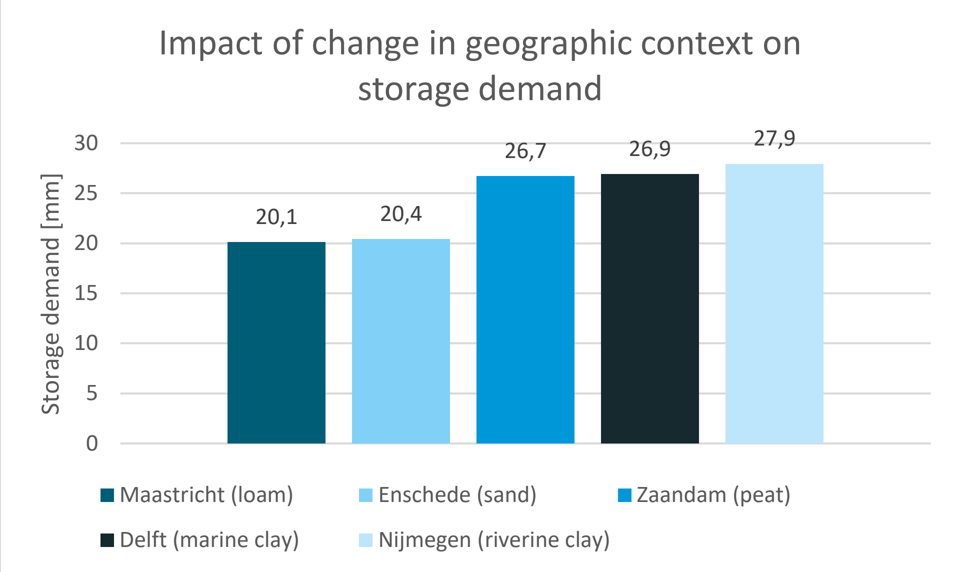

Figure 14 - Sensitivity analysis based on the geographic context

4.4.3 Climate stress tests - comparison and evaluation

To give a proper assessment of the model in different contexts, a quantitative comparison is made. Three comparisons are distinguished, where first the real-life case-studies (see Table 11) are compared. The main variable parameter between these parcels is the pavement degree and parcel size, meaning a different urban context for each. These parcels are validated through private owner elicitation, to check the input and verify the output.

Table 11 - Parcel characteristics real-time case studies

City	Areal analysis		Main varying parameters			Other
	Total area [m2] *All parcels over 750 m^2*	Paved area [m2]	Soil type	Infiltration depth [m]	Groundwater level [m- GL]	Degree of pavement
Harich	750	292	Sand	2	4,58	Rural (<40 %)
Amersfoort	262	100	Sand	2	2,40	Semi-urban (40-70 %)
Sneek	135	132	Clay	0	1,86	Semi-urban (40-70 %)

Based on Figure 15, several conclusions can be drawn. The storage demand is not scaled with the storage capacity, whereas the storage demand is given per m^2 and the storage capacity over the total area of the paved area. Whereas De Jong has the largest share of paved area, the value for the storage capacity on this plot is the largest. The values for the storage demand are comparable, whereas there are just slight deviations in the local parameters that exist. Remarkable is the fact that the values are all relatively near the storage demand posed by Witteveen+Bos for the smaller parcels of Ypma and Van den Heuvel (, respectively 4 and 2 percent). Ypma and Van den Heuvel also require a similar storage capacity, whereas Van den Heuvel has almost twice the room available to implement measures. This is caused by the clayey placement and high groundwater level of Ypma.

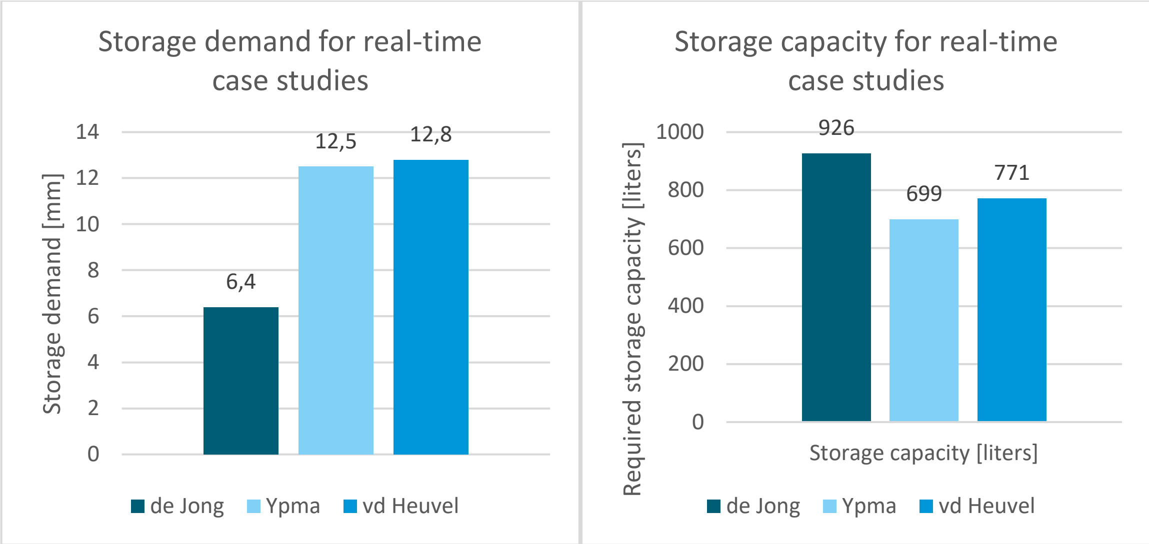

Figure 15 - Analysis case studies with real-case studies and main variable parameter pavement degree

The suggested measures for each case study are selected, and given in each successive model. An overview of the measures and their direct contribution to the required storage demand is placed in Table 26 (see Appendix F). Later in this research, this outcome is proposed to the respective private residents through the conduction of semi-structured interviews.

4.4.4 Cross-validation through comparison

The "Beslisboom" is a graphical clarification of the tailored storage demand that is used by the Municipality of Venlo. It finds a great resemblance with the model that is constructed during this research. Though, where the constructed model is mainly quantitative, the "Beslisboom" uses a qualitative flow-chart. Cross-validation is used to predict the outcome of the model, through testing the "Beslisboom" on the three real-time case studies. In Table 12, the outcome of this validation process is displayed.

Table 12 - Results of cross-validation through model comparison

		De Jong	Van den Heuvel	Ypma
		750 m^2	*267 m^2*	*135 m^2*
"Beslisboom" municipality Venlo	Storage demand [mm]	20	20	20
	Required storage capacity [litres]	5800	1400	2000
	Advice on type of measure	-) Infiltrate (without run-off to municipal sewage) -) Place permeable bottom soil passage to enable infiltration	-) Infiltrate (without run-off to municipal sewage) -) Place permeable bottom soil passage to enable infiltration	-) Storage facility with a maximum of 4,86 mm/h to municipal sewage
Constructed model	Storage demand [mm]	13,8 (-31 %)	15.7 (-21.5 %)	12.9 (-35,5 %)
	Required storage capacity [litres]	4019	1099	1251
	Advice on type of measure	-) Infiltration -) Waterbag, detention basement (Crawl space) -) Green roof	-) Infiltration is suggested	-) No infiltration possible -) 24 m^2 of a flat roof, providing room for green roof

Noteworthy is that the model - which is designed to catch a peak shower with T= 25 years - gives for every case a lower storage demand than the "Beslisboom". The choice of Venlo to use a significantly higher storage demand could be an implicit policy-point to focus on a further horizon. It could also be purposefully set too high, whereas this ensures that the safety regulation is always on the safe side. This is in line with the claim of Van der Meijden (2021) - expert from Municipality Oisterwijk - that the storage demand is not always in line with the design precipitation event, stating that often a higher demand is posed than needed. This suggests that a lower storage demand would be sufficient to catch off a shower with T=25 years, and limits the costs of an unnecessary amount of storage facilities. In the overview below, the differences, the similarities, and the (expected) motivations behind major choices are listed.

Purpose
The aim of the "Beslisboom" is to inform those living in this region, whereas the constructed model from this research tries to span nation-wide. Also, the "Beslisboom" addresses solely water nuisance, where the constructed model also looks at drought prevention. At last, the purpose of the "Beslisboom" is to be incorporated in the zoning plan, whereas the constructed model is solely advisory and consulting of nature.

Input
The input of the models is relatively similar, though the accuracy of this input deviates largely. The input in the "Beslisboom" is composed of the soil permeability, the groundwater table, proximity of surface waters, and development type. The constructed model incorporates also the drought vulnerability, parcel size, pavement degree (in the neighbourhood), and the run-off due to gradient ground level.

Classification and accuracy
The flow chart of Venlo uses mostly a binary choice system, whereas every node starts and ends with two options. The constructed model of this research tries to use as many options as possible, having at least three options at every node. The options of both models are limited, whereas the method of giving options shows flows with values slightly below the upper boundary of an option and slightly above the lower boundary of the successive option. An improvement would be the increase of classes or the removal of categorization.

Output
The flow chart of Venlo uses 6 categories as output for the storage demand, whereas the constructed model calculates a direct quantitative storage demand. The flow chart of Venlo has incorporated a difference between statical and dynamic storage, which addresses the emptying of the storage facility. The constructed model, however, indicates directly the best type of measures and a quantification. This is a step beyond this flow chart of Venlo.

4.4.5 Interviews

The case studies that are used for stress-testing are extensively elaborated in Appendix F. These case studies form the input for the different interviews. The response from the interviews will form part of the validation process, whereas there is checked whether the outcome of the model is sound and realistic. Interviews with different involved key stakeholders were conducted. Where all interviews gave different outcomes and discussions, the most outcome of these interviews is composed below. In Appendix G3, the summaries of the transcripts of all interviews were placed.

Interview 1 - Market inquiry
None were subjected to floods on a private parcel level. All have noticed, however, the effect of heat stress, to different extents. De Jong mentions the drought in the summer and the subsidence as a result. Nonetheless, they are not planning on taking action regarding water storage in the near future. Both Ypma and De Jong consider it unacceptable when the doorsteps overflow. Van den Heuvel mentions that the street adjacent to his parcel floods on average two times per year, which he considers acceptable. Besides the fact that no experiences with water nuisance occurred, also the fact that Ypma and Van den Heuvel live in a rental house is important when considering water storage facilities. Owning a parcel is for all respondents a clear reason to invest in the measures, which is supported by De Jong, who is most eager to take action.

Both De Jong (2021) and Van den Heuvel (2021) have already detached their rain pipe, with 6 and 20 m^2 respectively.

All respondents think the model is user-friendly and, with the help of an expert, can be filled intuitively. All respondents think the advised storage capacity is realistic. Also, the measures that are suggested are considered sensible options. Though Ypma emphasizes that the storage demand in mm is hard to imagine, especially while the consequences of extreme precipitation have not (yet) been noticed. This is supported by De Jong, who is unfamiliar with the concept of storage demand, though recognizes the measures which create a better feel for what to do. For future applications, all participants agree on the fact that automatization of the tool would improve the reliability and user-friendliness. Van den Heuvel mentions that there should be work with what there is, and make the best of this.

Interview 2 - Expert Elicitation Municipality Oisterwijk

Van der Meijden mentions that people are only willing to take action when they are acquainted with the consequences of the problem. This model could help with that. In comparison with the universal storage demand used in Oisterwijk, Van der Meijden responded positively to the tailored approach to the storage demand, especially considering the local geologic and hydrologic differences. A universal 60 mm storage demand is currently used for the whole municipality. Van der Meijden explains that this is considered unreasonably high, where often complaints are dropped.

For future applications, Van der Meijden is curious about the effectiveness of the first millimetres regarding the collection peak showers. This could form a recommendation for later studies. He also mentions his interest in superficial and surface water storage and how this can also help against drought and heat stress.

Interview 3 - Expert Elicitation Water Manager W+B

To intrinsically motivate private residents to take action, Roeleveld explains that people have to be addressed personally, while Dutch residents are acquainted with the problem but do not know what to do.

Through their own experiences with an unreasonable storage demand at Ring Utrecht of 45 mm, he questions the use of a storage facility that is filled once in 10 years.

The factors used in the model seem reasonable, though several remarks are made. A parcel size should be included in the manipulation of the storage demand. Other factors were also slightly adjusted (see Table 7), forming a part of the iterative calibration of the model. Also, the expert advised to test the model in different contexts, where all parameters are in a similar range, and one contextual factor was changed.

The expert questioned the effectiveness of approaching private residents on taking small measures, considering the installation costs and increased effectiveness of centralized larger facilities. He also describes the knowledge gap, and the need for private residents to help out municipalities with water storage (both financially as practically)

In addition to the opinion of the private residents, also Roeleveld mentions that private residents should be directly given the type of measures. Besides the technical calculation, also the socio-economic aspects are important while considering the implementation. The output should be fair and reasonable, otherwise, it will not be accepted. Another view of Roeleveld towards this model is the use of subsidies. If the model gives a relatively high storage demand, more subsidies are granted to reach the required storage capacity.

5 DISCUSSION

This research shows great opportunities to implement a tailored storage demand. Based on the technical, local assessment, each parcel can be assessed as a variable case and therefore, also its storage demand. Regarding the need for the tool and its implementations, the interviews and expert elicitation proved valuable confirmation that the tailored storage demand could be an important building block towards a water-resilient Netherlands. In contradiction with the current situation, where a universal storage demand is used, this study shows that the tailored storage demand could be both reasonable as well as robust in terms of water resilience. While the model is subjected to several limitations, the model shows great expansion potential. Given the fact that the model is constructed in Microsoft Excel, the model can be easily read and extended by those that are interested.

The results from the report indicate that the storage demand is still fixed in most legislation throughout the Netherlands. The concept is only recently incorporated in the Zorgplicht Hemelwater (article 3.5 in the Waterwet), where much room for opportunities concerning the tailoring of the storage demand exists. The non-universal application per municipality and the unreasonably high storage demand imposed in several municipalities, ask for an improved approach. According to Van Der Meijden (2021), many complaints were received asking for a reduced storage demand. In combination with the skeptic view towards the effectiveness of the storage demand, this asks for a more contemporary, updated review. This shows there is a clear interest in the tailoring of the storage demand, depending on several location-specific parameters. The open-source, free availability of the databases indicates that information on a nation-wide scale is available, making the tailored storage demand a relatively easy switch. This research contributes to the knowledge gap currently in the field of water retention on the private parcel level. Whereas a lot of legislation on the storage demand is available, local variability is mainly untouched in the field of both public and private water retention. This study contributes to the insight into the possibilities and limitations around (the obligation of) private water storage.

However, there are still uncertainties regarding a tailored approach to the storage demand involving data management. The data provision falls in some cases short of accuracy, where some data is outdated or uncertain. Examples of these data uncertainties are listed below:

- The use of schematic estimation instead of location-specific measurements, to determine parameters like pavement degree, and drought classification;
- Data from DINOloket is often outdated by several decades, though is expected to remain of similar composition during this period;
- The classification of the degree of pavement based on the neighbourhood, whereas the pavement degree on parcel scale, would be more accurate;
- The uncertainty of the precipitation data, both due to the unpredictable course of climate change, as well as the course of precipitation intensity during exposed hour;
- The most common measures are selected as the norm, though in practice a lot of differences regarding storage facilities exist. Hence, the advice on the measures should be interpreted with a grain of salt;
- The interpretation of outdated measurements at monitoring wells as being contemporary, and the linear interpolation of groundwater levels between two monitoring wells;
- The lack of nation-wide coverage of soil and groundwater measurements;

The latter two points can be improved by enhancing the drill samples throughout the Netherlands. Also, the increase in the use of monitoring wells could result in improved coverage.

Besides that, the model makes some major assumptions that would significantly impact the outcome. The use of categorization, though being in line with the existing models (e.g. “Beslisboom” Venlo), does not show a sound output. Categorization is doubtful when looking at two values that fall in the proximity of the boundary between two classes. Concerning the construction of the model, several assumptions and simplifications were made to come up with a sound model. The sensitivity of the model to these data choices makes the model not necessarily unsound. It is, however, an important focus point when making a local assessment. When implementation is desired, the tool can form a guideline and may be improved by

local (hence more accurate) measurements. When using and analysing the results of the model, the following assumptions were made:
- To make the system robust, the W_H upper scenario is used through this research;
- The output factor of natural infiltration does not incorporate local vegetation degree, a mixture of soils, or compressibility;
- The interpretation that sand and loam are permeable, and peat and clay are impermeable in case of a heavy shower;
- The slope will cause the run-off of rainwater of the parcel, and no water retaining artificial defenses (e.g. fence, wall) were placed.
The uncertainties, simplifications, and assumptions made are caused by the limited time and resources. To improve the system, automatization of the tool is required. While the integration of several GIS-maps for the soil types, groundwater levels, elevation profiles, and pavement degree is already possible nowadays, the resolution, date, or accuracy of the available data still lacks significantly or is too expensive. With this update, the system would improve largely regarding efficiency, readability, and possibly even accuracy.

At last, while the characteristics of the linked measures were tried to estimate as well as possible, some uncertainties are inevitable. The limited time and the demarcated scope resulted in several choices during the development of the model. The emptying of storage facilities is not incorporated, whereas most facilities require 24 to 48 hours to fully infiltrate the soil. This aspect is also arguable, whereas the model is constructed with the eye on an independent precipitation event with a return period way beyond the scale of the outlet of water from the facility. Nonetheless, overflow of facilities due to constant high groundwater, a long period of showers briefly before the peak shower, or silting of the facility could be a considerable focus point for further research. On top of that, the spillway of a measure is not considered in the final to advice. Where a measure could not provide room for the amount of water to be stored, it was considered unsuitable. This would deviate in practice. reality.

6 CONCLUSION

This research aimed to provide a more reasonable, and scientifically substantiated approach towards rainwater storage on a private parcel, through tailoring the storage demand. This was achieved by constructing a computational model that gave a tailored storage demand for all Dutch residential owners. This aim was founded on the needs and desires of Witteveen+Bos, who are, at the moment of writing, busy developing a tool that uses still a universal storage demand.

Initially, the status quo in urban stormwater management was investigated through a literature study. Then, through another literature study, the different parameters were investigated, forming the input for the computational model. Four artificial precipitation methods were compared. The Precipitation Series of STOWA, based on the WH-upper scenario and with a return period of 25 years, proved to be the most reliable and relevant for this study. After the input for the model was selected, the classification and its boundaries were determined. The parameters were quantified per case through open-source databases. These sources proved to be of sufficient reliability, at least for the scope of this research, as could be concluded from the expert elicitation. Though, automatization and more accurate and up-to-date data sources would increase the validity of the model. The feedback from the expert elicitations, in combination with the performed research, formed the credibility of the constructed model.

Through the analysis of the current availability of infiltration and storage measures, the model could directly advise on the type and quantity of measures. Through a cost-benefit analysis, the bioretention swale and rainwater pond proved to be best regarding the effectiveness. Whereafter, the aim of each measure was mapped, which concluded the collection of all conditions and boundaries of the measures. The soil type and groundwater level turned out to be a clear driver in the type of measures. Infiltration measures were selected and preferred, in the case studies with low groundwater levels and a sand or loam soil.

This model determined the amount of storage capacity a parcel should facility per square meter paved area, and was built in MS Excel. The calculation of the storage demand included the required water storage to catch a peak precipitation event, but also facilitate water storage for times of drought. The storage demand was constructed for a parcel to withstand an extreme precipitation event with a return period of 25 years. The model was improved through trial-and-error, in combination with the expert elicitation. Two sensitivity analyses were performed to analyse the sensitivity of the outcome to the input parameters. The first analysis showed that the type of precipitation, the expansion of sewage, and the run-off to surface waters had a significant influence on the storage demand. Another remarkable outcome showed that an exemplary implementation of a measure (infiltration crate) on parcel-level in the same price scale had greater influence than the lowering of the street level. This suggests that the implementation of measures on private-parcel - for at least the infiltration crate - is more effective than the lowering of the street level. The second sensitivity analysis, based on the geographic location, proved that the model behaved as desired, whereas it was clear that the soil type and the high groundwater table had the most influence on the outcome of the model. Therefore, both the precipitation input as well as the soil type are important parameters when considering implementing the model in real life, particularly by the municipality. This actor can select the area that requires the most attention, subsidies, or prudence legislation.

As a result of the validation process, the model tested positively in a realistic environment. Through stress-testing the model with three real-time case studies, the model gave a tailored storage demand lower than comparable models, but still able to catch a significant peak precipitation. This was supported by the responses from the interviews and the expert elicitation, forming a part of the validity and credibility of the model. The interviews proved the feasibility of the model, its user-friendliness, and the reasonability of the final outcome, the storage demand. Based on these interviews, it could be induced that the model outcome was reasonable. The interviews proved that the step from 'abstract' storage demand to 'specific' (infiltration) measures was vital in the interpretation of the model. Besides the advice on the type and quantity of measures, the private residents indicated that action will only be taken when water nuisance is often experienced, or subsidies are granted by the municipality. The comparison between the real-time case studies turned out to be in the same range of the universal storage demand currently used in the tool IkBenWaterproof. This suggests that the model is sound, and can be placed in a realistic context for average Dutch dwellings. The model finds similarities with the universal storage demand employed by Witteveen+Bos. Though, the sensitivity of the water storage demand to local characteristics causes a requirement for a tailored approach, to cover a wide range of varying parcels. At last, cross-validation was used to verify and compare the demand claimed by constructed model with the local demands states by a model which is being used by Municipality Venlo, the "Beslisboom". The comparison gave a lot of similarities, but also deviations where the constructed model excelled. The user-friendliness and the simplicity of the "Beslisboom" were notable. However, through the use of a limited amount of options and final classes, a limited degree of tailored approach remained. Also, the link to the measures gives the constructed model an advantage, where this addresses the private residents directly. This opinion was shared by the respondents De Jong, Ypma, and Van den Heuvel (2021).

The model required some adjustments, which were mainly made after the expert elicitation. The parcel size had to be added, several more options had to be expanded, and the model was tested based on geographical context. Also, the expert elicitation asked for a more user-friendly link to the coupled measures. Roeleveld (2021) also addressed the inaccuracies and uncertainties that are related to the open-source databases, like the interpolation between two monitoring wells to determine the groundwater level and the erroneous use of AHN3 without fences, and other water retaining objects. Roeleveld also prompted the testing of the model in different contexts. At last, Roeleveld suggested a different use of the model, by stating that the model could be used by municipalities to find the regional bottlenecks that require extra encouragement, attention, or subsidies.

This research shows that the model could have a contribution to improving the concept of storage demand in the world of urban stormwater management. Through the tailored approach, Dutch residents are treated more fairly, and unnecessary costs are avoided in terms of unused space of storage facilities.

7 RECOMMENDATIONS

This study is limited to a technical review on the storage demand on the private parcel level but could be the start of a wide range of new studies. When this study was to be improved, several aspects could be enhanced. Due to time or research constraints, these are (purposely) neglected. For instance, where Roeleveld (2021) indicated the need for a socio-economically supported model, new opportunities arise for future studies. For instance, a socio-economic approach to the concept of storage demand could give many new interesting output variables. Examples for future applications of the model are listed below:

Investigating the support and collaboration among private residents

The interests of private residents are beyond the scope of this study. Though, it is in the same range of importance regarding implementation as the technical calculation of the storage demand, maybe even more important. The interviews with the private residents pointed out that it taken action on their terrain is not high on the agenda unless water nuisance is experienced (regularly). Also, the use of subsidies is subject to fraud, according to Van Der Meijden (2021), which makes it a sub-optimal means to help private residents to take action. This social study could be expanded, by investigating what moves people to make sustainable investments, when aiming at the greater good (e.g. solar panels, electric vehicles,

Incorporation of drought and heat stress

This is limited to a slight adjustment to the final storage demand and a link to the (type of) measures that should be taken. However, the scope of this study stays within the research of water nuisance due to extreme precipitation.

Incorporation of consequences of drought, in form of soil subsidence.

In the model, drought vulnerability is incorporated briefly to enlarge the storage demand and motivate people to infiltrate. However, soil subsidence forms a topic that became interesting when De Jong (2021) indicated his experiences with the phenomenon in times of extreme drought. Although soil subsidence lies beyond the scope of this report, it is interesting when looking at among others the infiltration rate, making it an excellent topic for future research.

Financial effectiveness of the storage demand

The storage demand is not a linearly effective value. The first millimetres that should be stored are often the most effective and can catch most precipitation events. The question to what degree the first degree is fully effective and on the other hand, the last millimetres are cost-effective are fascinating and promising for future research.

Use of emptying of a storage facility

In the current model, the storage facilities are considered to be fully empty and therefore entirely useable when stressed with an extreme precipitation event. Van der Meijden (2021) stated these facilities are seldom fully empty when stressed, for different reasons. Both the slow infiltration of rainwater, as the silting of the facilities raises interesting questions.

Automation of (components of) the model

Automation could massively enhance the model. Aspects like user-friendliness, ease of use, ease of operation, could positively impact the effectiveness, time consumption, and useability.

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APPENDICES

Appendix A1 - Methods of extreme precipitation statistics

Method 1 - Historical data

A common method is to use historical data on extreme precipitation. Historical data are difficult to gather, while there is a limited amount of (accurate) weather stations available. The maximum hourly precipitation sum ever measured at De Bilt was 44.1 mm in 1953. Based on the national trend of climate change in the Netherlands and the future development (W_H-upper scenario), a similar shower as the one in 1953 in De Bilt would result in a precipitation sum of 72.2 mm (Stichting RioNED, 2015). The heaviest local historical peak rainfall events were recorded in 2011 in Herwijnen with 94 mm in 70 minutes. This data source is considered unrealistic to serve as input in the constructed model. The rainfall event is not considered to be representative on a national scale, due to its local character. This also goes beyond the aim of the model, while the largest portion of the Dutch citizen is desired to be approached. The shower from Herwijnen had an expected return period of 250 years, while the model is designed for a lower return period.

Method 2 - Extrapolation historical data to account for climate change

Another method to give the precipitation event is the use of (local) historical data and extrapolate this data into the future. This extrapolation is often subjected to a climate change factor. The historical data could be both from weather stations, as well as from historical radar data. The latter being the most accurate, but also the most expensive and contemporary. A sidenote of this method is that there is a wide range of uncertainty, both in the measurements of historical data (due to lack of national covering and accuracy) and extrapolation of climate change.

Method 3 - Artificial peak precipitation events of Stichting RioNED

The third data source is used often to stress-test sewage systems. Stichting RioNED has designed 10 artificial hydrographs, called bui01-10 (Stichting RioNED, 2019). These graphs give ascending statistical return periods and have become the Dutch standard for determining the hydraulic capacity of the sewer systems. To comprise the effect of climate change, often a factor (110/120/150 %) is used. The most commonly used are bui08 (see Figure 16) and bui10 (see Figure 17) with a return period of 2 and 10 years, respectively. They have a different shape, where bui08 has its peak late in the event and bui10 early in the event. In this report, this artificial precipitation is maintained as an option to serve as the input for the stress-tests of the model. The stress-test bui08 is traditionally used for the technical design of sewage systems. In the coming years, municipalities would like to test the current sewage systems on bui10. The stress implemented by bui10 causes an earlier saturation of the subjected systems, due to the early peak.

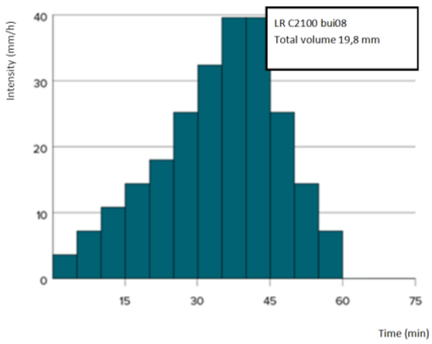

Figure 16 - Hydrograph bui08

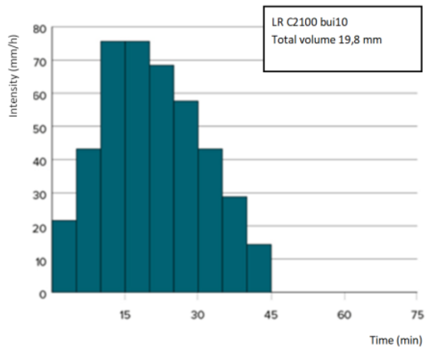

Figure 17 - Hydrograph bui10

Method 4 - Artificial peak precipitation events based on the KNMI'14-scenarios

STOWA collected historical data and gathered this in the latest version of Precipitation Statistics. Then, based on the expected climate change which was collected in the climate-scenarios of KNMI, set in 2014. This is considered to be the most accurate data source. In the following section of Appendix A, the data sets from STOWA are given.

Appendix A2 - Extreme precipitation statistics of STOWA

The basic statistics from STOWA, based on the W_H-upper scenario from KNMI'14-scenarios are considered the best option to form the input for the constructed mode. In Table 13 the Basic Statistics are composed and the relation between the precipitation duration and the return period T is shown.

Table 13 - Basic statistics for precipitation sum for Wh upper climate scenario

	Neerslagduur							
T [jaar]	10 min	30 min	60 min	2 uur	4 uur	8 uur	12 uur	24 uur
0.5	9.8	12.7	15.2	18.6	22.4	26.4	28.8	34.1
1	12.3	16.3	19.7	23.7	28.2	33.0	35.9	41.7
2	14.8	20.1	24.3	29.0	34.2	39.8	43.1	50.1
5	18.3	25.7	31.2	37.2	43.4	49.9	53.6	62.5
10	21.2	30.7	37.5	44.6	51.7	58.8	62.8	72.9
20	24.6	36.6	45.2	53.6	61.7	69.5	73.7	84.4
25	25.8	38.8	47.9	56.8	65.3	73.4	77.6	88.4
50	30.0	46.4	57.8	68.6	78.3	87.0	91.3	101.4
100	34.8	55.6	69.9	83.0	94.2	103.5	107.6	115.8
200	40.5	66.7	84.8	98.6	107.2	114.1	117.2	131.6
250	42.5	70.8	90.3	104.9	113.5	120.2	123.0	137.0
500	49.5	85.3	110.0	127.3	135.7	141.3	143.1	154.9
1000	57.8	103.0	134.2	154.8	162.6	166.4	166.6	174.6

Appendix B - Expanded overview parameters

Table 14 - Hydraulic parameters

#	Parameters	Brief explanation	Unit
1.1	Baseflow	Between storms and runoff events, streamflow is maintained by groundwater discharge known as base flow, as long as the water table remains above the stream bottom	m^3/sec
1.2	Groundwater level	Distance between ground level and upper level of an underground surface in which the soil or rocks are permanently saturated with water	metres
1.3	Surface run-off	Water, from rain, snowmelt, or other sources, flows over the land surface and is a major component of the water cycle. Urbanization increases surface run-off	m^3/sec
1.4	Discharge	The amount of water flowing in the stream or river, commonly expressed in cubic metres per second	m^3/sec
1.5	Hydraulic conductivity (k)	Defines how easily pore fluid escapes from the compacted pore space. The conductivity depends on the type of soils that are found in the region	m/s
1.6	Evapotranspiration	The sum of transpiration through plant canopy and evaporation from soil, plant, and open water surface	m^3/sec

Table 15 - Geologic parameters

#	Parameters	Brief explanation	Unit
2.1	Permeability/ Infiltration rate	A measure of the ease of passage of liquids or gases or specific chemicals through the material	m^3/sec
2.2	Plasticity	The ability of a material to undergo permanent deformation under stress without cracking	%
2.3	Compressibility	The contribution of rock deformation to fluid production for a given pore pressure variation	$-\Delta V/V_0$
3.1	Elevation level (AHN3)	The height of a garden, relative to the New Amsterdams Peil (+NAP)	metres
3.2	Slope	The ground that forms a natural or artificial incline	m/m
3.3	Pavement degree	The extent to which a certain location is urban, scaled through a pavement rating. The amount of paving indicates all hardened surfaces, like houses and expansions, but also terraces, driveways, and walkways.	m/year
3.4	Precipitation intensity	The ratio of the total amount of rain (rainfall depth) falling during a given period to the duration of the period. In The Netherlands, this intensity is graphed through the classification "Low", "Moderate" and "High".	%
3.5	Potential precipitation deficit	The extent to which a certain location is vulnerable to drought, scaled in the deficit of rainwater	mm
3.6	Infiltration depth	The maximum depth to which infiltration is possible, based on the groundwater level and the soil type (infiltration only possible in loam, gravel, and sandy soils)	m

Table 16 - Positional parameters

3	Spatial	Brief explanation	Unit
4.1.1	Distance to nearest surface water	The distance takes before rainwater travels from the point of precipitation to the surface water (e.g. pond, channel, lake, ditch)	metres
4.1.2	Distance to the nearest sewer	The distance - as the crow flies - of the place of precipitation to the nearest sewage system inlet	metres
4.2.1	The sheer size of the paved area	The number of square meters on a private parcel that is paved, including the terrace, dwelling, drive-way, etc.	square metres (m^2)
4.2.2	Square size of flat roof	The number of square meters that has a flat roof, on which potentially a green roof can be constructed	square metres (m^2)
4.2.3	Square size of unpaved area	The number of square meters of garden and other unpaved areas, from which there can be assumed that it fully infiltrates or will occasionally leave an accepted puddle	square metres (m^2)

Overview sources:

1.1 Delleur, J. W., 1999. The handbook of groundwater engineering. Boca Raton, FL: CRC Press

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Appendix C - Overview classifications

1. Development classification

Newly built dwellings provide greater opportunities to incorporate demands within the zoning plan and the Rioleringsplan (GRP+). Most municipalities have made the storage demand a hard requirement before granting a permit to build a new dwelling. Several municipalities have already made the step towards existing buildings, though this sector is harder to reach policy-wise. Therefore, there will be made a distinction between existing and newly built dwellings. In the zoning plan for newly built dwellings, there is often a check called 'watertoets' incorporated that checks whether the increase in paved area is compensated through some storage capacity. This ranges from 4 to 60 mm and is often customized per neighbourhood. The easiest and most effective method is to increase the foundation level of the newly built dwellings, by increasing the height of the doorstep. Also, typical measures for newly built dwellings are the installation of a retention basement (maximum of 500 mm), water- or green roof (maximum of 60 and 8 mm, respectively), or the detachment of the rain pipe (maximum 20 mm). For this research, the choice is made to incorporate a higher storage demand for new build than for existing buildings. Based on the reports from Venlo and Apeldoorn, as well as the minimalization of typical measures for newly built dwellings, an extra 10.0 mm storage demand is given. Redevelopment purposes also provide an improved opportunity to facilitate measures and increase the storage demand by 5.0 mm.

2. Lithographic classification

The lithographic classification is determined by checking the type of soil. This classification checks the type of soil and couples this to the parameter hydraulic conductivity (also permeability or infiltration rate). The hydraulic conductivity of soil can be scaled with the variable K, which describes the vertical distance (in meters) that water can travel in a day through the soil under a hydraulic gradient. Throughout the Netherlands, there are in general five types of soil: gravel, sand, loam, clay, and peat (Römkens & Oenema, 2004). The different soil types have different properties concerning infiltration and will therefore also form the classes in this category of the classification.

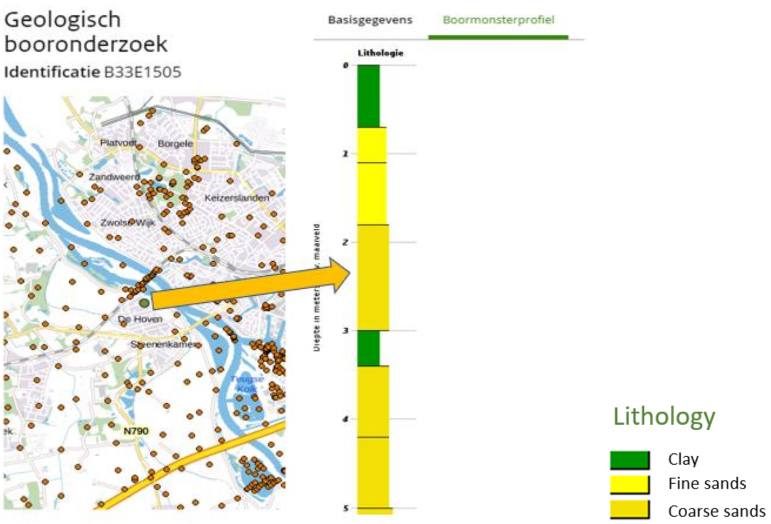


Figure 18 - Example of geologic drill sample (in Deventer) (TNO , 2020)

When the private parcel is solely made up out of (dense) clay, infiltration options become limited. If infiltration in clay or peat is desired, the water has to be given more time to infiltrate and therefore a larger storage facility is required. When the private parcel contains a mixture of different soil types, the extra boundary layers make infiltration harder. DINOloket is an online database that has gathered all drill samples throughout the Netherlands. Figure 18 displays an example of the different soil layers in a specific location Deventer, gathered from a drill sample. The hydraulic conductivity is quantified through the vertical k-value. The reference value is 1.0 m/day and is for pure sand. The model will assign k_v-values to the chosen types of soils. There is assumed that no infiltration will occur for the soil types peat and clay. The minimal infiltration makes it a suboptimal option regarding stormwater management.

Table 17 - Soil characteristics of the lithographic classes (van de Ven, Brouwer, Horstmeier, & Hartjes, 2004)

Soil type	Infiltration?	hydraulic conductivity k [m/day]	Maximum infiltration capacity (mm/h)
Gravel, humus	Yes	5.0	
Sand	Yes	1,0	41,7
Loam	Yes	0.4	16,7
Peat/turf	No	0.02	0,83
Clay	No	0.01	0,42
Mixture (sand+loam)	Little	0,5	

The infiltration depth is the parameter that encompasses these characteristics and can be given in as one value. This depth indicates the extent to which water can infiltrate the soil. This is based on the groundwater level and the soil type. The infiltration depth is never more than the groundwater level in that location. The infiltration depth is also characterized by the fact whether gravel, sand, or loam is the top layer. Once, the soil type of peat, clay arises, this sets the boundary for the parameter infiltration depth.

3. Pavement classification

In the model, the input parameter of pavement degree is filled in through classification. The classes are formed based on the amount of square paved area. The classification will be based on data from Klimaateffectatlas, an independent database controlled by Stichting CAS. Several large knowledge institutions are closely related and collectively provide (data) information, such as Rijkswaterstaat, Deltares, W+B, DPRA, and Tauw. The different classes are (1) very dense, (2) dense, (3) moderate, (4) rural. In Table 18, the different ranges per class are described. These intervals are based on data from CBS and chosen for representative locations, which are urban areas.

Table 18 - Overview of classes of pavement degree

Class	Percentage of paved area
Very dense	> 90 %
Dense	70-90 %
Moderate	40-70 %
Rural	< 40 %

The Rural class can be visualized typically as a farm or detached dwelling with a significant amount of unpaved plot. This area facilitates infiltration easily and will therefore not form a bottleneck. However, it is important that this class also takes action. By implementing measures, water storage could prevent damages inflicted by long dry periods. The Dense class can be visualized as an apartment (or a flat) in a dense city, where there is no room for the implementation of measures. These two classes form the outer boundaries and the bandwidth in between - the Moderate class - is the most opportunity-rich group. Therefore, the end-user of this model is likely to lie within the boundaries of the Moderate class. In Figure 19, the classification is depicted in the city centre of Deventer, which is used to get some perspective.

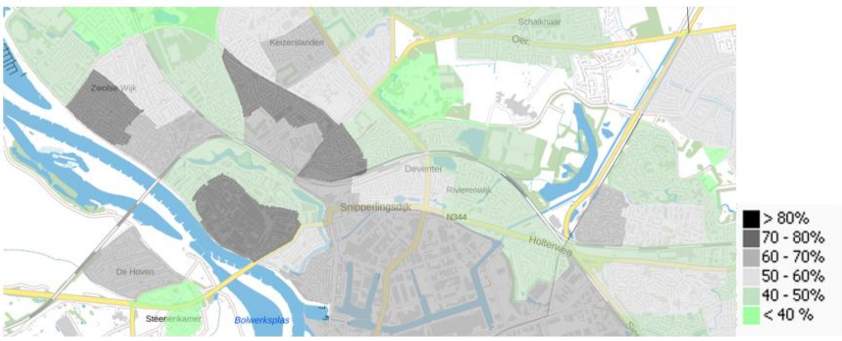


Figure 19 - The degree of paved area in the city centre of Deventer (TOP10NL, 2020)

4. Slope classification

Whereas the Netherlands is often considered an entirely flat country, there are some (regional) elevation differences. To investigate whether water will flow from or inside an area, the slope is investigated per specific location. This class is scaled concerning the elevation level relative to NAP. For the extraction of the data for the relative elevation, data from Algemeen Hoogtebestand Nederland v3 (AHN3, published by ArcGIS online viewer) is used, see Figure 20.

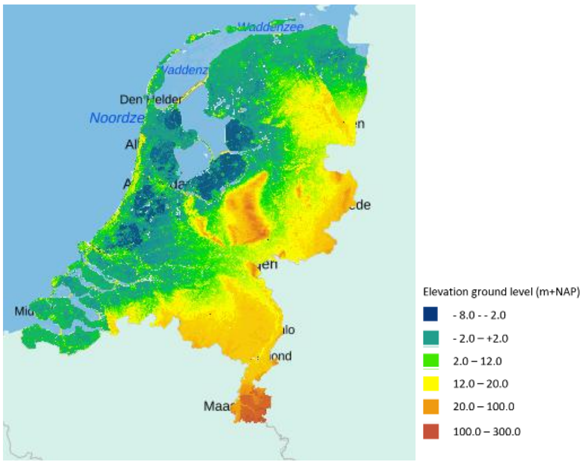


Figure 20 - Algemeen Hoogtebestand Nederland (AHN) on a national scale

The slope parameter is rather difficult to classify, whereas there is an enormous range of variables. Just a few examples are the (degree of) vegetation, degree of slope, roughness coefficient, infiltration during run-off, and the dependency on neighbours whether they take action or not. To get an idea of the complexity, there is looked at the city centre of Apeldoorn where the height difference between east and west is (100+NAP and 5+NAP making it) 95 meters. Though, extra storage upstream and controlled and limited drainage to downstream locations is effective for the prevention of water nuisances downstream.

In this research, the slope classification is assessed qualitatively. To assess the elevation characteristics of a certain location, the online map layer AHN3 is accessed through ArcGIS Online. The map layer "*AHN3maaiveld blauw/groen/oranje statische opmaak*" is the most topical and accurate database, and therefore the most reliable. Also, this update carries advantages in the fact that it has filtered buildings and trees. This advantage can be found back in the fact that the study of rainwater flow should be located at ground level. Water will move dynamically once the location carries a (local) gradient of 1 percent (ARTBA, 2018). Once there is recognized that there is such a height difference, a portion of the rainwater from the neighbour flows on the parcel. This will be not quantitatively incorporated into the tool. The model recognizes the presence of the slope and automatically adds a side note to the advice. In the model, the elevation profile depicted in Figure 21 is used to check whether or not the study location is located on a gradient. Several peaks can be distinguished, which are trees, buildings, or other vegetation or infrastructure.

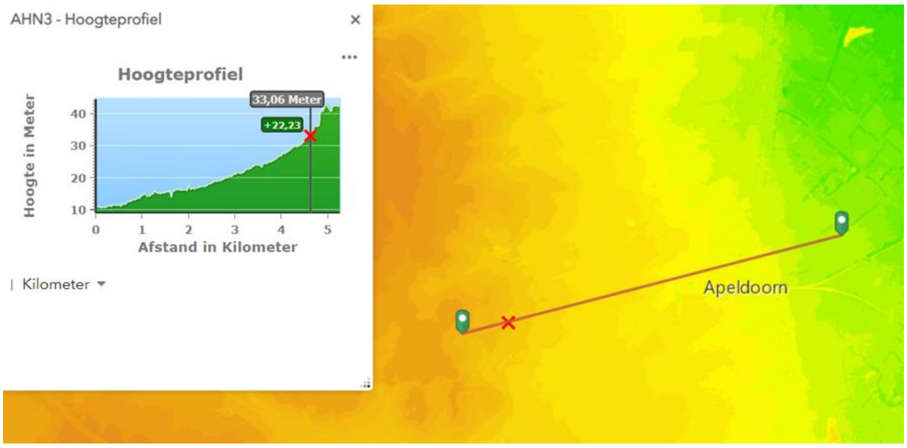


Figure 21 - Example of an elevation profile in AHN3 in Apeldoorn city centre

Important to consider is the fact that certain measures are less effective when placed on a slope. While this is not considered in the report, it is valuable to consider for future research.

5. Groundwater classification

Besides the ground level, the groundwater level beneath this ground level is also considered. The groundwater level of a specific location indicates whether the soil is saturated yet. Saturation prevents infiltration and percolation. Also, it causes seepage through the capillary rise. While the Netherlands seems flat, the groundwater level differs substantially, from 20-30 cm below the surface to 30-40 meters below the surface. In the model, the height of the groundwater level is assessed. The storage demand is reduced when the groundwater table is relatively high. The high water level prevents that infiltration measures from being implemented. The threshold of groundwater level assessment is at 2 meters, because this is considered the maximum depth at which homeowners are likely to take measures on their property. To get an insight into urban groundwater dynamics, the online database Grondwatertools is used. The groundwater levels are presented as groundwater contour lines (isohypses). These lines connect locations with the same groundwater level. Between contour lines interpolation is used to estimate the groundwater level. They show the spatial pattern of groundwater levels and also indicate the direction in which groundwater flows. Grondwatertools combines the measurement data from DINOloket with the Nederlands Hydrologisch Instrumentation (NHI) from Deltares. While DINOloket proves an excellent source for exact location, interpolation with Grondwatertools gives a great advance in national coverage of data through interpolation between all measured points. While WPV1 gives the subsurface layers, the WVP2 layer is used. This layer indicates the first phreatic subsurface layer. While this data covers the whole of the Netherlands, the data is not in all cases up-to-date. To come up with contemporary data, data older than January 2018 is neglected. Moreover, the measurement locations are sometimes far apart and therefore carry some factor of uncertainty. Nevertheless, it is the most accurate (free) accessible data source with regard to the national groundwater level and is therefore used in this research.

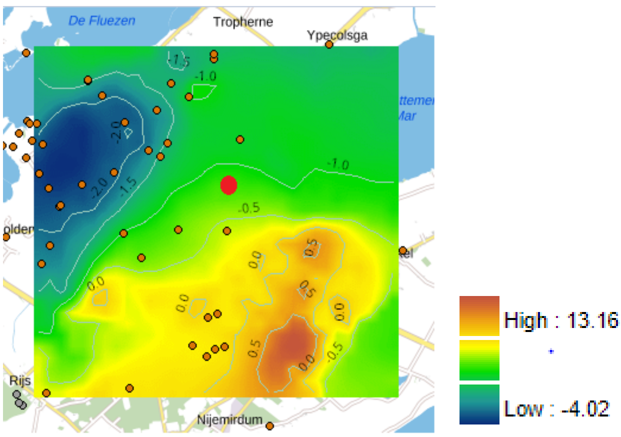


Figure 22 - Exemplary groundwater levels in Friesland through Grondwatertools (TNO, 2020)

6. Drought vulnerability classification

For the classification of drought vulnerability, the Netherlands is divided into three regions. This is visualized in Figure 23. The classification is also depicted in Table 19 below and is based on the potential annual precipitation deficit. It was decided to assume the worst-case climate scenario (W_H upper) in combination with a T = 10 years drought event. These assumptions are in accordance with the scenario and temporal horizon chosen for precipitation events. The urgency to take action with regard to the threat of drought is based on these classes.

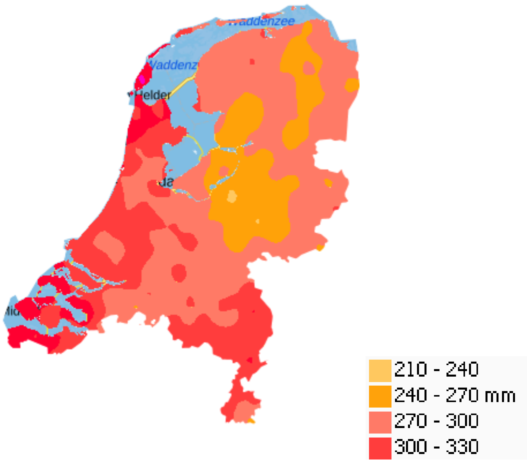


Figure 23 - Potential precipitation deficit throughout the Netherlands

Every year, the Netherlands suffers a precipitation deficit, most often late in the summer period. On average, this maximum deficit reaches a height of 110 mm (KNMI, 2020). It was therefore decided that this height is tolerated, and is generally neutralized. Water boards and Rijkswaterstaat proactively try to maintain a proper groundwater level. However, for the last few years, this height was exceeded more and more often. In 2018, the maximum precipitation deficit was 309 mm. To be able to be drought-resistant in the future, there should be stored at least the difference between the tolerated and potential precipitation deficit. Based on Figure 23, a facility/measure must be installed that can collect a sum ranging from 130 to 250 mm on an annual basis. This means that every day, to come up with a buffer to prevent drought damages, there should be collected at least 0.4 and a maximum of 0.8 mm/day, depending on the location. This functions as a surplus on the storage demand.

The required storage capacity to reduce drought stress is significantly smaller than the required storage capacity to prevent water nuisances. Though, only infiltration measures help against the threat of drought. If the end-user wants to battle drought-stress, they will be advised solely on infiltration measures. Storage or delayed draining measures are then neglected, due to their limited capacity and the lack of heightening the groundwater level. Also, these measures would require regular maintenance and manual emptying and are therefore neglected as a method to prevent drought. Hence, an infiltration facility of 2 mm over the total parcel is recommended.

Table 19 - Classes for the drought vulnerability through the potential precipitation deficit

Class	Elaboration	Bandwidth	Extra storage demand
Low	where drought is least likely to occur, indicated with the color 'orange' in Figure 23.	0-270mm	0.4 mm/day storage capacity through infiltration
Average	The largest share of the Netherlands at which drought will occur indicated with 'pink' in Figure 23.	270-300mm	The storage capacity of 0.6 mm/day through infiltration
Upper	The region where drought is most likely to occur is indicated with the color 'dark-red' in Figure 23.	300-390mm	Storage demand of 0.8 mm/day through infiltration

7. Dimensional classification

The dimensions of the parcel are important for both the size of the paved area, as well as the options with regard to the amount of square area of flat roof. With a large dwelling with the adjacent pavement, there is a relatively high run-off, either to surface waters or the sewage system. Based on the amount of paved area, there should be demanded a higher storage demand. In this research, to determine the storage demand, there is made a distinction in the amount of paved area. The paved area classification is based on reports from several municipalities throughout the Netherlands, like Zwolle, Apeldoorn, and Uden. Also, the target group is those that have a moderate living area (20 - 200 m^2). The classification is scaled as drawn up in Table 20.

Table 20 - Parcel size classification

Area of parcel size [m^2]	Elaboration	Storage demand [mm]
< 150 m2	The small plot, often an apartment or terraced house, often located in a highly urban environment	+0
150-750 m2	The average plot, situated in an urban environment	+10
750-2000 m2	The above-average plot, situated in a slightly rural environment	+20
> 2000 m2	Large plot, often situated in a rural environment	tailored

Next to the classification of the parcel size, the square area of pavement is asked. The more pavement, the more rainwater will flow into the sewer and therefore, the higher the storage demand. When the storage demand is determined, the amount of unpaved area defines the options or limitations of specific measures. For instance, a wadi is hard to install with a garden smaller than 5 m^2 and a rain barrel proves less effective when there is a garden of more than 200 m^2. Also, the total area of a flat roof is asked and with this information, the chance for water- or green roof is advised.

Appendix D1 - Expanded overview measures

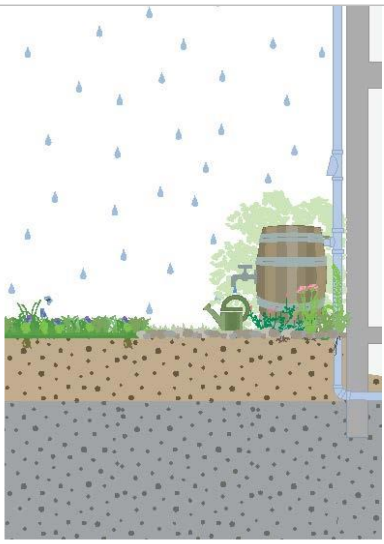
First, this report describes the individual measures, gives the average dimensions and conditions for implementation. This section includes a short description of the measures and gives their dimensions and conditions. The measures are discriminated through the type of water storage. Infiltration, storage, and (delayed) drainage are the distinctive categories. These characteristics are vital for determining what measures can be installed in specific locations.

While advising on the possible measures, the emptying of the storage and infiltration measures are not considered. The peak precipitation events in this research behave independently of each other and assume an empty facility in all cases.

1. Detention measures

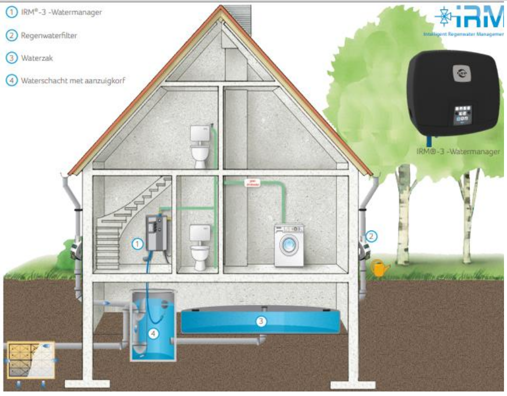
Detention is the (temporary) storage of rainwater. It is often used when the collected rainwater can be harvested. The harvested water could be reused in domestic operations where no drinking water is required. Examples are flushing the toilet or watering the plants. Besides that, the detention of rainwater could be an (energy) efficient way to deal with times of drought.

Measure 1.1 - Rainwater tank	
Similar to infiltration-well but without holes. The concrete container placed subsurface and often used for rainwater harvesting.	
	**Dimensions and conditions** 1. Quantity: maximum of 1 2. Minimum/maximum parcel dimensions: The Garden has to have at least a size of 4 m2. 3. Groundwater level: The groundwater level has to be below the underside of the tank. 4. Measure dimensions: The minimum required depth is 1.35 meters and the maximum depth is 2.0 meters 5. Others:

Measure 1.2 - Rain barrel	
Wooden/plastic barrel attached to for instance roof, collecting water. This water could be reused for domestic uses (grey water) or watering in the garden. It is the easiest measure to install when detaching the rain pipe. The size of the barrel is limited (several 100 litres) and therefore it has to have an overflow. For long showers, this could form a problem.	
	**Dimensions and conditions** 1. Quantity: - maximum of 3 2. Minimum/maximum parcel dimensions: Minimal garden size of 10 m^2 required 3. Groundwater level: 4. Measure dimensions: 5. Others:

Measure 1.3 - Waterbag

Large watertight bag, often stored beneath the house (in crawl space). Rain pipe is often connected to this bag and water can be reused as greywater



Dimensions and conditions

1. Quantity:
maximum of 1
2. Minimum/maximum parcel dimensions:
Assumed to be no larger than 80 percent of the square size of the house (basement is often smaller than a house);
3. Groundwater level:
4. Measure dimensions:
- Minimum size is 20 m^2
- Minimum height of 50 cm of the crawl space
5. Others:

Measure 1.4 - Rain blocks (in a boarding/fence)

Plastic boxes are used as both building blocks of the fence but also as detention buckets.

Dimensions and conditions

1. Quantity:
2. Minimum/maximum parcel dimensions:
Minimal length of 1.0 meters.
3. Groundwater level:
4. Measure dimensions:
The average height is between 1.8 and 2.0 meters
5. Others:

Measure 1.5 - Detention basement

Subsurface basement (in the crawl space underneath the house) in which water can be stored, drained, or reused. Often connected to rain pipe. Requires a significant amount of initial investment and/or maintenance.

Dimensions and conditions

1. Quantity:
2. Minimum/maximum parcel dimensions:
Takes up a maximum of 80 percent of the area of the dwelling
3. Groundwater level:
4. Measure dimensions:
Maximal depth of 500 mm
5. Others:

2. Infiltration measures

Infiltration is the collection of water at one location and delayed drainage into the ground, starting the process of percolation. This way the rainwater can be absorbed by the soil, or run-off subsurface to surface waters. Common examples are a (rainwater) pond, infiltration crates.

The application of infiltration systems is best suited on moderate to highly permeable soils. Though, infiltration systems can also be applied in locations with less permeable soils, provided that the detention values and infiltration areas are larger. In this report, there is assumed that peat and clay will not facilitate infiltration. In this chapter, there is also tried to find for each measure the minimal required infiltration depth. This is the minimal permeable soil depth, for the measure to become effective.

Measure 2.1 - Infiltration well

Concrete well without a bottom, with holes in the side to enable infiltration. If infiltration is not possible, due to the high groundwater level or the impermeable character of the soil, this measure will not be recommended.

Dimensions and conditions

1. Quantity:
maximum of 3
2. Minimum/maximum parcel dimensions:
3. Groundwater level:
Groundwater level at least 20 cm beneath this underside of the well
4. Measure dimensions:
The minimum required depth is 0.5 meters and the maximum depth is 2.0 meters
5. Others:

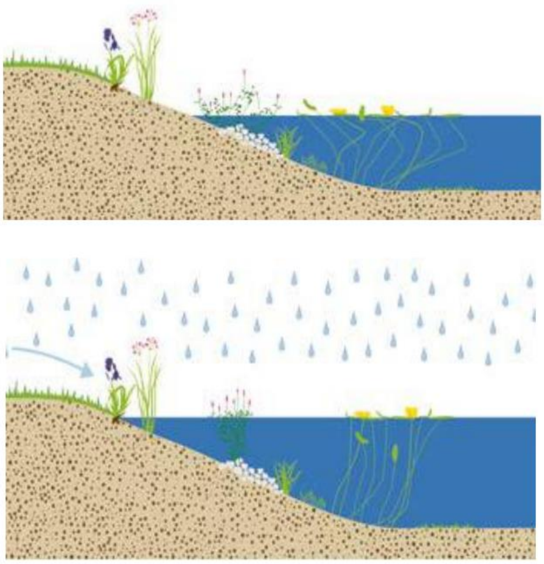
Measure 2.2 - Infiltration crates

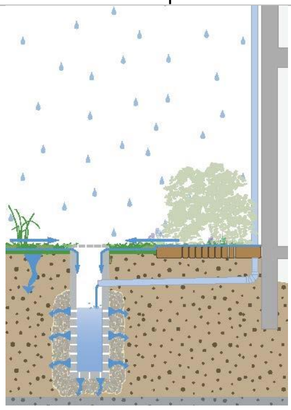
Permeable plastic crates placed subsurface in the garden, enabling storage and slow infiltration. Often geotextile is used to prevent soil and roofs from entering the crates.

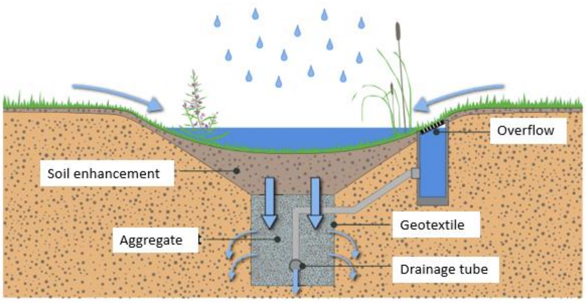
Dimensions and conditions

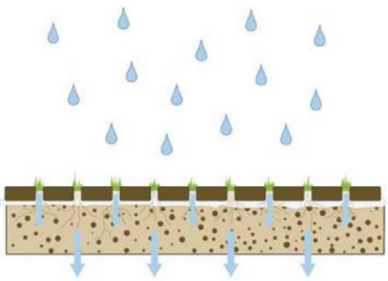
1. Quantity:
Unlimited quantity, possibly stacked (with a max of 80 percent of area garden)
2. Minimum/maximum parcel dimensions:
placed at least 30 cm below the ground level and should be not near buildings
3. Groundwater level:
Groundwater level should not be too high
4. Measure dimensions:
The minimal infiltration depth is 0.3 m
Max depth is 0.4m.
10-15 litres for every m2 detached roof surface
5. Others:

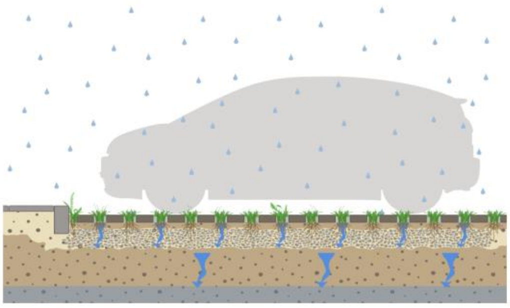
<table>
<tr><th colspan="2">Measure 2.3 - (IT) Infiltration tubes</th></tr>
<tr><td colspan="2">Vertical or horizontally placed permeable tubes, that enable (slow) infiltration. If infiltration is not possible, due to the high groundwater level or the impermeable character of the soil, this measure will not be recommended.</td></tr>
<tr><td>
Source: brochure fotoboekKAS</td><td>Dimensions and conditions
1. Quantity:
2. Minimum/maximum parcel dimensions:
Placed at least 30 cm below ground level
3. Groundwater level:
Groundwater level lower than the depth of the tubes
4. Measure dimensions:
5. Others:</td></tr>
</table>

<table>
<tr><th colspan="2">Measure 2.4 - Rainwater pond</th></tr>
<tr><td colspan="2">Rainwater ponds can proactively function as a buffer, emptied in winter and filled in summer. They also increase the aesthetic appeal of the garden and boost the ecosystem. Besides working as a buffer through storage, it can function as infiltration measure. If infiltration is not possible, due to the high groundwater level or the impermeable character of the soil, this measure will not be recommended.</td></tr>
<tr><td>
Source: Atelier Groenblauw</td><td>Dimensions and conditions
1. Quantity:
2. Minimum/maximum parcel dimensions:
The pond has to be at least 2 m^2, to have some impact as a water buffer.
The pond can be at most 20 percent of the garden
3. Groundwater level:
The groundwater level should be lower than the depth of the pond.
4. Measure dimensions:
The average depth of a pond is 30 cm for every square meter.
5. Others:</td></tr>
</table>

Measure 2.5 - Infiltration trench	
Hole in the ground filled with gravel, packed with an anti-root fabric to prevent soil to intermix with the gravel in which water can be stored and drain slowly in the surrounding soil. The trench could also function as a filter where the clean rocks gather the hydrocarbons from the water, which would increase the effectiveness of the infiltration crate(s) below. - If infiltration is not possible, due to the high groundwater level or the impermeable character of the soil, this measure will not be recommended.	
 Source: Atelier Groenblauw	**Dimensions and conditions** 1. Quantity: Unlimited quantity 2. Minimum/maximum parcel dimensions: For every m2 of the roof, there has to be 0.03 m3 of trench available 3. Groundwater level: 4. Measure dimensions: The minimal required depth of the trench is 0.6 m The maximal depth is 1.8 m. Assuming a porosity of 40 percent, the trench can store 400 litres per m^3. 5. Others:

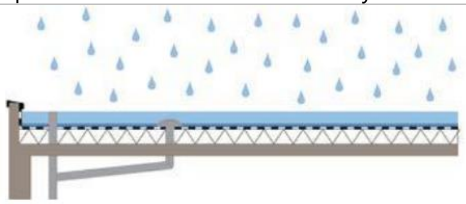
Measure 2.6 - Bioretention swales	
Bioretention swales (in Dutch “wadi’s”) Sloped deepening in the garden, comparable to empty ditch. Often filled with gravel or sand to enable infiltration, where sometimes a storage/infiltration crate is installed below. This makes it an excellent buffer. If infiltration is not possible, due to the high groundwater level or the impermeable character of the soil, this measure will not be recommended.	
 Source: Atelier Groenblauw	**Dimensions and conditions** 1. Quantity: 2. Minimum/maximum parcel dimensions: For the construction of a bioretention swale, the garden has to have a size of at least 153.6 m^2 with a minimal length of 4 meters. Per meter in length, 4.8 m^2 surface area is required. Should minimally 40 cm deep and have a talud of 1:4, meaning that the width should be four times as large as the depth. 3. Groundwater level: Should not be a high groundwater level 4. Measure dimensions: 5. Others: -

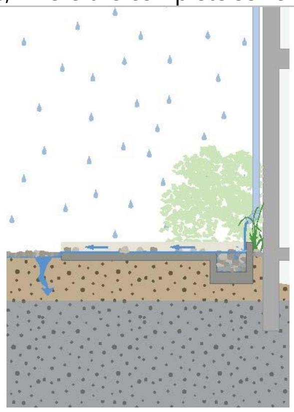
Measure 2.7 - Permeable pavement	
(rain)water is more likely to infiltrate the soil without a paved surface, by replacing it with wood chips/gravel/sand as pavement. The rainwater can infiltrate easier, the sewage is relieved and the groundwater level is maintained. The porous character of the pavement (ranging from 15 percent to 40 percent) enables the water to flow through, while maintained a walkable (aesthetically pleasing) topsoil layer. If infiltration is not possible, due to the high groundwater level or the impermeable character of the soil, this measure will not be recommended.	
 Source: Atelier Groenblauw	**Dimensions and conditions** 1. Quantity: 2. Minimum/maximum parcel dimensions: 3. Groundwater level: Groundwater level should be 30 cm below ground level or lower. 4. Measure dimensions: 5. Others:

Measure 2.8 - Open pavement	
Open pavement (terrace, walking path, or parking lot) is designed to enable infiltration of the rainwater in the soil. There is often chosen to use pavement whereas subsidence would be a logical result, due to re-petitive loading. This type of pavement is especially effective with low precipitation intensity. Besides the open pavement displayed below, the most common open pavement is Zeer Open Asfalt Beton (ZOAB) in the Netherlands. Most highways use this concrete that is permeable and facilitates infiltration. On (less intensively used) parking lots, the open pavement can reduce the heat island effect. If infiltration is not possible, due to the high groundwater level or the impermeable character of the soil, this measure will not be recommended.	
 Source: Atelier Groenblauw	**Dimensions and conditions** 1. Quantity: 2. Minimum/maximum parcel dimensions: 3. Groundwater level: Groundwater level should be 30 cm below ground level or lower. 4. Measure dimensions: 5. Others:

3. Draining measures

Delayed drainage is the (in)direct (steering of) flow towards surface waters or sewage systems. This helps the private parcel to become water resilient, though has disadvantages. It shifts the problem to the sewage systems, which are easily stressed. After all, most sewage systems in the Netherlands are designed according to bui08 (approximately 20 mm/h).

Measure 3.1 - Water roof	
Flat roofs can carry a load of 1 kN per m2 and are therefore suitable to be reshaped for buffering precipitation. The water is carried away in a delayed manner, through a small drainage opening.	
 Source: Atelier Groenblauw	**Dimensions and conditions** 1. Quantity: 2. Minimum/maximum parcel dimensions: The roof has to be larger than 10 m^2. The depth of the layer often not more than 60 mm. 3. Groundwater level: 4. Measure dimensions: Can store 100 litres of water per square meter 5. Others:

Measure 3.2 - Detaching rain pipe	
By detaching the rain pipe, the sewage systems are relieved from the stress. In general, there are two options. The first option is to let the rain pipe(s) exist in the garden. This way the water can be harvested. The second option is the attachment to a separate rainwater sewage system. This prevents pollution due to overflows, where the complete sewer (including human waste) falls on the streets.	
 Source: Atelier Groenblauw	**Dimensions and conditions** 1. Quantity: - 2. Minimum/maximum parcel dimensions: The rain pipe can only be detached, provided that roof < 10 m^2 3. Groundwater level: If the groundwater table is at a high level (0.5m - ground level), this measure is not very effective. 4. Measure dimensions: 5. Others:

Measure 3.3 - Intensive green roofs	
Vegetation is placed on a roof, to enable indirect drainage. Has the ability to cool and isolate buildings. Also, the large extent of greenery makes the measure aesthetically pleasing. Intensive green roofs have natural plants and therefore require some maintenance (e.g. cutting, weeds picking). In the Netherlands, there is an estimated 200 million square meters of flat roofs (Deltares, 2017). Therefore, there is great potential to install green roofs on houses, factories, shed roofs, etc.	
 Source: OptiGroen	**Dimensions and conditions** 1. Quantity: 2. Minimum/maximum parcel dimensions: Flat roofs with a size of at least 5 m^2 3. Groundwater level: 4. Measure dimensions: height of 60 mm 5. Others: OFten provided with subsidies when more than 10 m2 is installed Green roofs can be installed on roofs with a slope ranging from 0 to 30 degrees

Measure 3.4 - Extensive green roofs

The specific type of green roof, where sedum plants are used, which are particularly good in holding water. Is not as maintenance demanding as intensive roofs. Exist out of a substrate layer to store the water on which little sedum plants grow. The water can stay for a long time on the roof, but can also be drained manually.

Source: Atelier Groenblauw

Dimensions and conditions

1. Quantity:
2. Minimum/maximum parcel dimensions:
3. Groundwater level:
4. Measure dimensions:

The average depth of 3.0 cm, where they lie on a substrate of 2.0 cm which functions as a water buffer

5. Others:

- There is assumed that green roofs cannot be installed on sloped roofs. In practice, this is possible, though considerably less effective.

Appendix D2 - Cost-Benefit Analysis (CBA)

The measures will be assessed on their efficiency. This way there is made a ranking on which measures give the most benefits in terms of quantity, for the least amount of money. The homogenization of the different units is converted through gives the final score in terms of euros per litre storage. The unit of litre is chosen whereas this is an approachable unit for the Dutch citizen. The measures that are scaled in a certain period, are homogenized to one hour, while this is the period of the shower that will be used in the stress tests. First, there is made a selection of the measures for different sizes and prices, and the average score is determined. This score is then multiplied with the scaling factors. To comprise feasibility, effort, initial costs, and maintenance in the evaluation, a scaling factor is added. In the tables below, these factors are shown and form the input for the full overview of the CBA in Table 21.

An important conclusion from the cost-benefit analysis is that natural ponds and bioretention swales have the largest impact for the least amount of money and impact. Though, it is important to consider that these are not necessarily the best option for all situations, whereas there could be reasons that could prevent the construction of these measures (e.g. low-lying cables, aesthetic reasons, insignificant room, etc.). It is valuable information, however, for the municipalities whereas they now get an indication of the cost-optimal measures. What should be recognized from this analysis is the fact that homogenisation is not bulletproof. The factors are simply estimated and the life span of the measures is not incorporated.
To get a proper insight into the way how the model will link the measures to a certain storage demand at a certain location, the methodology is constructed.

Table 21 - Expanded cost-benefit analysis

		Alt1 [L]	euros	Alt2 [L]	euros	Alt3 [L]	euros	Initial CBA in euros/L	Initial costs	Maintenance	Installation	Aesthetics	Final CBA in euros/L
1	Bioretention swales	500	6,1	500	5,17			0,008	0,8	1	1,2	0,8	0,006
2	Rainwater pond	500	20	250	73	1000	215	0,182	0,8	1	1,2	0,8	0,140
3	Cistern	1000	152	5000	1600			0,157	1	0,8	1,2	1	0,151
4	Wood chips/ gravel	1000	120	1000	175	500	175	0,215	1	0,8	1,2	1	0,206
5	Infiltration crates	200	78	272	160	200	70	0,443	0,8	0,8	1,2	1	0,340
6	Extensive green roofs (sedum)	59	50	25	30			0,682	0,8	0,8	1,2	0,8	0,419
7	Water bag	3000	201	2000	1500	4000	1950	0,435	1	1	1	1	0,435
8	Rain barrel	240	140	320	149	210	67,5	0,457	1	1	1	1	0,457
9	Permeable terrace	90	140					0,519	1	0,8	1,2	1	0,498
10	Rainwater tank	15000	3410	1000	805	1000	396	0,476	1,2	1	1	1	0,571
11	Infiltration chambers	70	130					0,619	1	0,8	1,2	1	0,594
12	Intensive green roofs	55	60	80	120			0,864	0,8	1,2	1,2	0,8	0,796
13	Rain blocks (in a boarding/fence)	165	209	350	400	330	419	1,226	1	1,2	1	1	1,472

Bonus scores	Reference (rain barrel)	Lower than rain barrel	Higher than rain barrel
Initial costs	1.0	0.8	1.2
Maintenance	1.0	0.8	1.2
Installation	1.0	0.8	1.2
Aesthetics	1.0	0.8	1.2

Appendix E1 - Flow chart 'selection of type of measure'

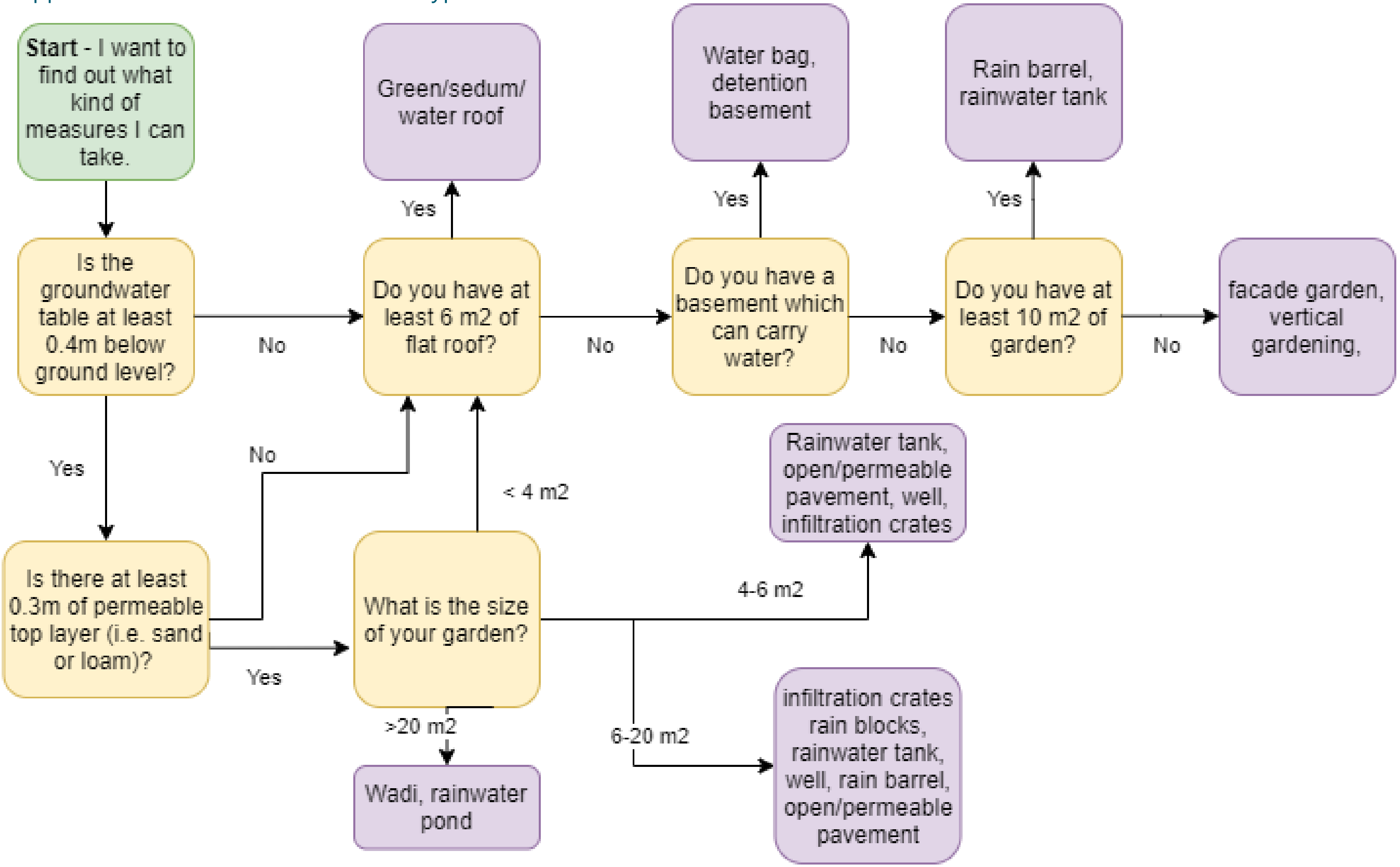


Figure 24 - Second flow chart for determining type of measure to take

Appendix E2 - Computational model

1 - Regional Assessment (FILL IN)

This model uses a regional assessment to come up with a tailored capacity that should be stored in case of an extreme precipitation event.
The model can be used by both municipalities - to get an idea which parcels require most attention - as well as private owners, to give an indication what the best measures are to take.
Fill in the data in the first sheet and your storage demand is automatically calculated!

All parameters in this sheet are variable/adjustable

1 Personalia	
Applicant name	Y. Ypma
Adress	Frederik Hendrikstraat 29
City	sneek
Max budget (l)	500
Date	16-1-2021
I want to tackle	

Final overview (DO NOT CHANGE ANY VALUES)			
Storage demand		12,5	mm
Required capacity		699	liters
Advised measures	**Type**	**Contribution to required capacit**	**Price (l) for contribution**
		48	1,92
		84	81,68
		19	20,39
		12	17,20
		4	14,93
		57	122,00
		32	76,17
		3	13,86
	No waterbag		ABOVE BUDGET
	Rain barrel	37	117,25
	No rainwater tank		ABOVE BUDGET
	Rain blocks	40	414,53
	No detention basement		
		4	11,74
	Intensive green roof	6	35,82
	Water roof	9	126,00
	Detaching rainpipe	4	0,00
Extra advice	*You live in a flat area and are not subjected to rainfall running off*		
	0		

2 Location specific (fixed) parameters				
2a Dimensional			Unit	Source
Total area	135		m^2	*Kadastralekaart/Maps*
Paved area (house)	56		m^2	*Kadastralekaart/Maps*
Total area (garden)	44		m^2	*Kadastralekaart/Maps*
Paved area (garden)	41		m^2	*Kadastralekaart/Maps*
Unpaved area (garden)	3		m^2	*Kadastralekaart/Maps*
Area flat roof	24		m^2	*Kadastralekaart/Maps*
Length adjacent street	7		m	*Kadastralekaart/Maps*
2b Contextual			Unit	Source
Existing storage	Nothing	0	m^3	Own expertise
1			m^3	
2			m^3	
3			m^3	
4			m^3	
Existing storage	Nothing	0	m^2	Own expertise
1			m^2	
2			m^2	
3			m^2	
4			m^2	
Crawl space			m^2	Own expertise
2c Geographic	Value		Unit	Source
Slope	0,015		%	*ArcGIS online AHN viewer*
Max depth permeable soil	Clay	0	m	*DINOloket*
Estimated k_v value	0,01		m/day	
Ground water level	-0,7		m+NAP	*Grondwater Tools*
Ground level (GL)	1,158		m+NAP	*ArcGIS online AHN viewer*
Ground water level	1,858		m - GL	
Infiltration depth	0		m - GL	

3 Policy based (open) parameters		Unit	Source
Pavement degree	Semi-urban (40-70%)	%	*Klimaateffectatlas*
Drought vulnerability	Moderate (270-300mm)	mm	*Klimaateffectatlas*
Proximity surface water	No	m	*Google Maps*
Development	Improving existing situation		*Own expertise*

Figure 25 - Overview computational model sheet 1 '1-RA' filled in for case study Ypma

2 - Water balance (RESULTS)

All parameters in this sheet are fixed and should NOT be changed

Water balance					
Initial storage demand					
Water balance: $\Delta S = Precip. - runoff\ - current\ storage$					
Initial storage capacity [m3]			#DIV/0!		
Initial storage demand [mm]			#DIV/0!		
Initial storage capacity [liters]			#DIV/0!		
Manipulation of water balance			Steps	Final	
Degree of pavement	Rural (<40%)	0,8	0	0,0	
	Semi-urban (40-70%)	0,95	0		
	Urban (70-90%)	1,1	0		
	Highly urban (> 90%)	0,3	0,0		
Drought vulnerability	High (300-390 mm)	1,1	0	0,0	
	Moderate (270-300 mm)	1	0,0		
	Low (0-270 mm)	0,9	0		
Development	Redevelopment	5	0	0,00	
	New development	10	0		
	Improving existing situation	0	0,00		
Size parcel	Parcel size larger than 2000 m2	1,3	0	0,00	
	Parcel size between 750-2000 m	1,3	0,00		
	Parcel size between 150-750m2	1	0,00		
	Parcel size smaller than 150 m2	0,7	0,00		
Proximity surface waters	Next to surface body (> 5 m3)	0,6	0	0,00	
	Within 50 metres from open wat	0,8	0		
	No open waters in proximity	1	0		
Ground water level	Very high	0,8	0	0	
	High	0,9	0		
	Moderate	0,95	0		
	Low	1	0		
Final storage demand				0,0	mm
Final required capacity				0,00	m^3
YOU SHOULD FACILITATE STORAGE FOR				0	liters

Output/outflow					
Run-off (sewer)	19,8	mm	Drainage by the sewage systems		
Natural infiltration	#DIV/0!	mm	Hydraulic conductivity determinates natural infiltration		
Run-off (slope)	0,00	mm/h	When a slope is indicated, water will run-off over the surface		
Surface water	0	mm/h	When near surface water, the rain water will run off		
Tolerated storage					
Storage on streets	0	m^3			
Existing storage	0	m^3		0	m^3
				0	m^3
				0	m^3
				0	m^3
				0	m^3

Figure 26 - Overview computational model sheet 2 '2-WB'

3 - Conditions of measures

	Infiltration?	Min. infiltration depth	Max. infiltration depth	Min required water table	Min depth	Max depth	Min volume [m3]	Max volume [m3]	Min garden size	Min size house	liters per m2	liters per piece	Average price in euros/L
Infiltration													
Bioretention swale	Yes	0,4	1	0,5	0,4	1	0,05	8,96	96	-	333,33		0,00577
Rainwater pond	Yes	0,3	1,2	0,4	0,3	1,2	0,10	0,60	20	-	583,3		0,140032
Infiltration well	Yes	0,5	1,6	0,9	0,5	1,6	0,07	0,2	4	-		135	0,15104
Permeable pavement	Yes	0,1	0,3	0,2	0,1	0,3	-	-	1	-	83,33		0,2064
Open pavement	Yes	0,1	0,3	0,2	0,1	0,3	-	-	1	-	30		0,497778
Infiltration trench	Yes	0,6	1,8	0,7	0,6	1,8	0,06	0,40	1	-	400		0,305
Infiltration crates	Yes	0,2	0,4	0,6	0,2	0,4	0,14	0,29	1	-		224	0,340028
Infiltration tubes	Yes	0,4	2	0,8	0,4	2	-	-	4	-		23,33	0,594286
Storage													
Water bag	No	-	-	-	-	-	0,20	4,50	-	40		3000	0,434833
Rain barrel	No	-	-	-	-	-	0,21	0,32	10	-		256,67	0,456796
Rainwater tank	No	-	-	-	-	-	0,69	2,88	4	-		5666,67	0,571333
Rain blocks	No	-	-	-	-	-	0,30	1,60	6	-		281,67	1,471688
Detention basement	No	-	-	-	-	-	0,10	0,60	-	40	600		
Delayed drainage													
Extensive green roof	No	-	-	-	-	-	-	0,03	-	10	28		0,419319
Intensive green roof	No	-	-	-	-	-	-	0,05	-	10	45		0,795927
Water roof	No	-	-	-	-	-	-	0,06	-	10	60		2,1
Detaching rainpipe	Yes	-	-	-	-	-	-	-	10	-	30		0,00001

Figure 27 - Overview computational model sheet 3 '3-CM'

Appendix F - Real-life case studies

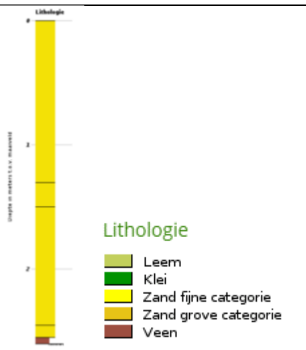
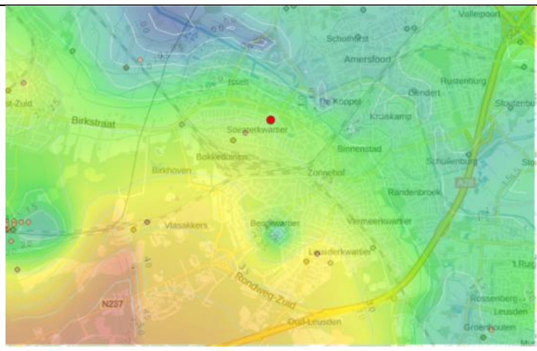
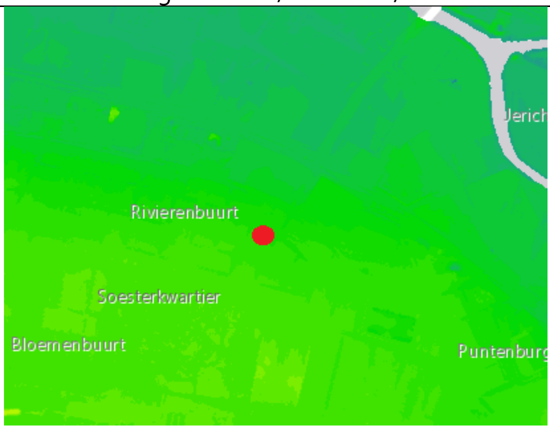
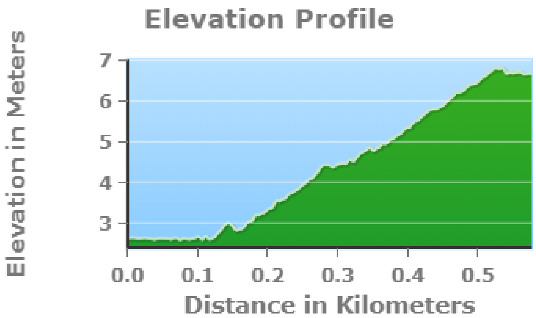
In this research, there is tried to find an answer to these challenges. Next to the substantive challenges, also the chosen case studies could form a challenge. The case studies have the target to test the model and see whether the outcome is legitimate. While the target is therefore not to shape but check the correctness, a few case studies are enough. However, the case studies should include the outer limits of the research objective of this study and should stay within the boundaries of the scope. The model will be tested based on the weak and strong features it carries, which is giving directly the storage capacity on a private parcel and checks whether it is necessary or not. This study provides insight through several case studies and provides this guidance towards this nation-wide covering. A single-family residential parcel is explored, based on its surface-subsurface hydrology. Later in this research, interviews will be conducted in which representative residential owners of private terrains are asked whether the outcome of the model is realistic.

On average, the urban areas of the Netherlands consist out of 33 percent paving (de Graaf, Roeffen, den Ouden, & Souwer, 2013). The case studies are chosen by looking at the classification of CBS, where case study 1 describes an area with more than 2500 addresses per square kilometre. 70 percent of Dutch house owners have a garden. 3 percent does not have a garden. The measurements of the different cases are derived from perceelloep.com, which is an online free database giving real estate data.

1. Case study 1

Semi-urban dwelling with average plot dimensions
D. van den Heuvel (3812 HB, 43, Amersfoort)

Table 22 - Local assessment real-time case study 1

Land registry *Source: perceelloep.nl*	**Pavement degree** *Source: Klimaateffectatlas*
	
Soil type *Source: DINOloket*	**Groundwater level** *Source: Grondwatertools.com*
 	
Elevation profile parcel Source: ahn.arcgisonline.nl/ahnviewer/	
 	

2. Case study 2

Semi-urban environment with below average parcel size

Y. Ypma (Sneek, Friesland)

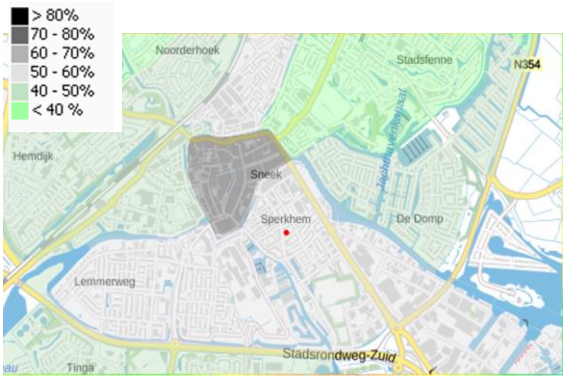
Table 23 - Local assessment real-time case study 2

Land registry

Source: perceelloep.nl

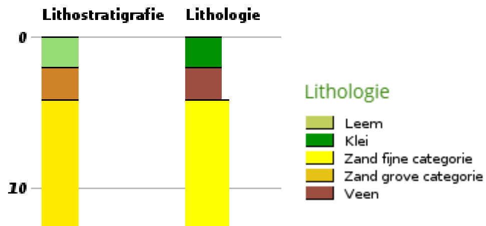
Pavement degree

Source: Klimaateffectatlas



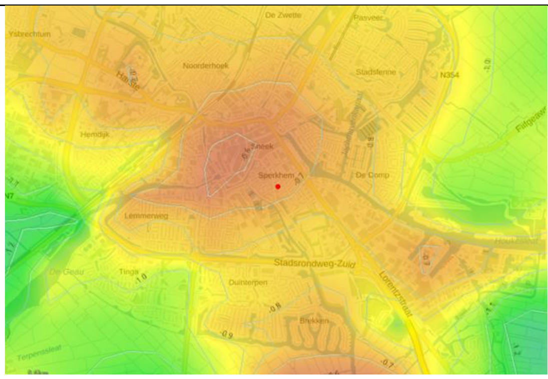
Soil type

Source: DINOloket



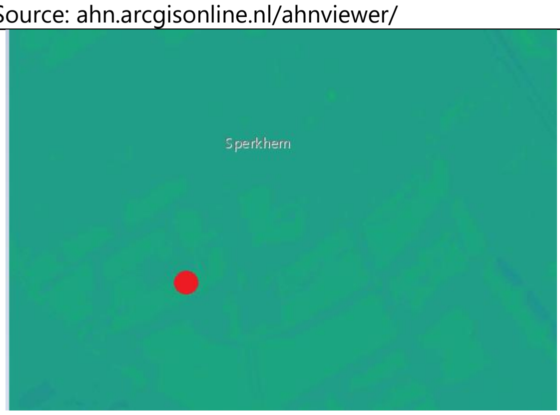
Groundwater level

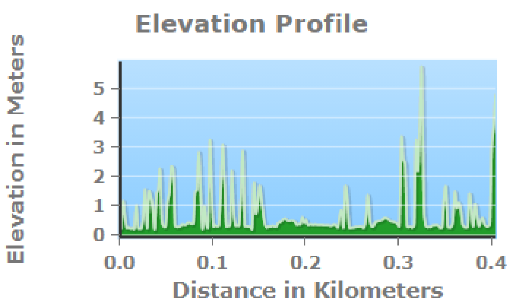
Source: Grondwatertools.com



Elevation profile parcel

Source: ahn.arcgisonline.nl/ahnviewer/



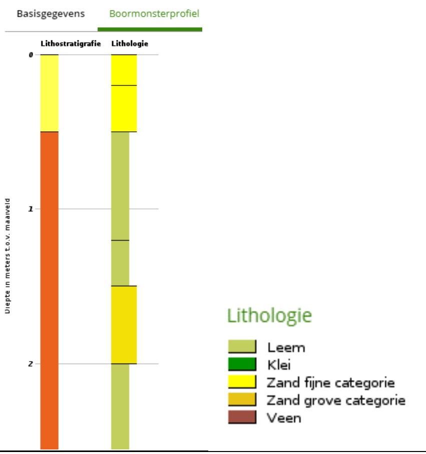
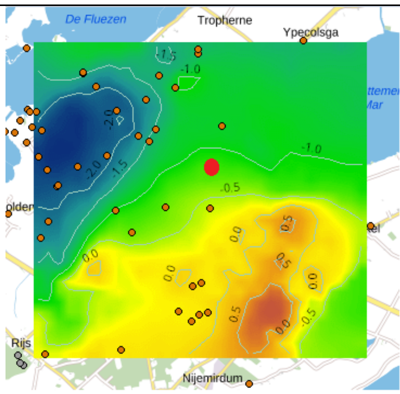
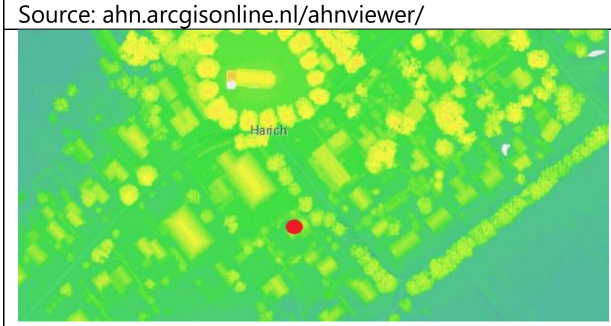
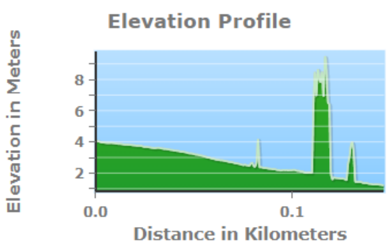


3. Case study 3

Rural environment with parcel size well above average dimensions

J. de Jong (Harich, Friesland)

Table 24 - Local assessment real-time case study 3

Land registry *Source: perceelloep.nl*	**Pavement degree** *Source: Klimaateffectatlas*
	
Soil type *Source: DINOloket*	**Groundwater level** *Source: Grondwatertools.com*
	
Elevation profile parcel Source: ahn.arcgisonline.nl/ahnviewer/	
	

From the databases posed in the tables 23-25 and the expertise of the parcel owner, the following parcel characteristics were listed:

Table 25 - Overview parameters real-time case studies

Parameters	Case study 1	Case study 2	Case study 3
General properties			
Total area of parcel [m^2]	267	135	750
Area dwelling [m^2]	60	56	144
Area garden [m^2]	30	79	656
Area pavement in garden [m^2]	10	41	147
Area unpaved in garden [m^2]	20	3	509
Flat roof [m^2]	0	24	36
Slope over 500 meters [%]	0.76	0,015	Yes
Proximity to surface water (of at least 5 m^3)	No	No	No
Special features:	Detached roof to infiltration trench: 30 m^2		Detached rain pipe of 6 m^2
Geohydrology			
Ground level [m relative to NAP]	4.70	1,158	3.778
Soil type [m - ground level]	Sand (2m)	Clay	Sand (0-0.5m) Loam (0.5-1.0m) Sand (1.2-2.m)
estimated k_v-value [m/day]	0.5	0,01	0.5
Groundwater level [m+NAP]	2.3	-0.7	-0.8
Groundwater level [m - ground level]	2.398	1,858	4.578
Max. infiltration depth [m - ground level]	2	0	2.0
Demographic			
Degree of pavement in neighbourhood [%]	50-60	40-70	< 40
Drought vulnerability [mm]	Moderate (270-300 mm)	Moderate (270-300 mm)	Moderate (270-300mm)
Development	Improving existing situation	Improving existing situation	Improving existing situation

Link to measures

In Table 26, the different measures that can be used for the real-time cases are placed in an overview. Indicated with green are the measures that are adequate and in red, those that are not suitable or feasible.

Table 26 - Link real-time case studies to suggested measures

Advised measures	Type	Case study 1		Case study 2		Case study 3	
		Contribution to required capacity [%]	**Price (€)**	**Contribution to required capacity [%]**	**Price (€)**	**Contribution to required capacity [%]**	**Price (€)**
Infiltration	Bioretention swale	8	1,92	19	1,92	3	1,92
	Rainwater pond	14	81,68	34	81,68	6	81,68
	Infiltration well	3	20,39	8	20,39	1	20,39
	Permeable pavement	2	17,20	5	17,20	1	17,20
	Open pavement	1	14,93	2	14,93	0	14,93
	Infiltration trench	10	122,00	23	122,00	4	122,00
	Infiltration crates	6	76,17	13	76,17	2	76,17
	Infiltration tubes	1	13,86	1	13,86	0	13,86
Storage	Water bag	-	-	-	-	75	ABOVE BUDGET
	Rain barrel	6	117,25	15	117,25	2	117,25
	Rainwater tank		ABOVE BUDGET		ABOVE BUDGET		ABOVE BUDGET
	Rain blocks	7	414,53	16	414,53	3	414,53
	Detention basement					93	ABOVE BUDGET
Delayed drainage	Extensive green roof	1	11,74	2	11,74	0	11,74
	Intensive green roof	1	35,82	3	35,82	0	35,82
	Water roof	1	126,00	3	126,00	1	126,00
	Detaching rainpipe	1	0,00	2	0,00	0	0,00
Extra advice		-		*You live on clayey soil with a relatively high groundwater level, therefore infiltration measures are not advised*		*You live on a slope and could therefore be compromised by run-off from neighboring areas*	

Appendix G1 - Interview schedule: Market inquiry

Questionnaire 1

Instructions for the interviewer

- Ask whether the interviewee wants to stay anonymous
- Ask permission to record
- Provide interviewee with the knowledge that the results are processed and published
- Stay objective throughout the whole interview
- Ask all questions, in this order, and do not skip any

Interview introduction

- Introduction of the interview
    - -) Concept of storage demand
    - -) Current use: no local dependency
    - -) Contribution of this study to the knowledge gap
- Contribution of the interviewee to this study
- Explanation of the type of questions
- The explanation that the interview is processed through summarization of recording
- Mention duration of the interview: 20-30 minutes

Set-up interview

Before we go into detail, I would like to ask you some personal questions.

6 Could you maybe introduce yourself and explain your function?

Now I would like to ask you some questions that are related to the overarching theme of this interviewee, which is urban stormwater management.

7 On a scale of 0 to 10, how do you rate your expertise with regard to this theme?

8 What are your experiences with regard to water nuisance and heat stress on a parcel level?

9 Did you already do something to prevent damages due to these threats? Or are you planning to do so in the near future?

10 What do you consider as being the boundary of unacceptable with regard to urban flooding? Is that flooding of streets, or overflowing of the doorstep?

To give people advice on the amount of rainwater that should be stored when exposed to a peak shower with T = 25 years, a model has been constructed. The model calculates for every owner of a private parcel their respective amounts of rainwater that should be stored. Before the start of this interview, the interviewee is sent an overview with the results from this analysis. The interviewee is asked to take a look at these results. Now, these results will be discussed.

11 For your specific parcel, the following amount of rainwater should be stored on your private parcel. Do you think it is realistic to demand such a sum of water?

Incidental, during a peak shower, there should be stored: **- ... litres;** **- ... mm (storage demand)** on your parcel in order to become waterproof* *waterproof = to be able to fully catch an extreme precipitation event with T = 25 years on your parcel, and on top of that be able to store/infiltrate rainwater to neutralize extreme precipitation deficits.

12 The following measures can be taken for your specific case. Do you think it is unrealistic to ask these measures?

Type	Contribution to required capacity [%]	Price (€) for contribution
Bioretention swale	43	1,92
Rainwater pond	75	81,68
Infiltration well	17	20,39
Permeable pavement	11	17,20
Open pavement	4	14,93
Infiltration trench	51	122,00
Infiltration crates	29	76,17
Infiltration tubes	3	13,86
Rain barrel	33	117,25
Rain blocks	36	414,53
Extensive green roof	4	11,74
Intensive green roof	6	35,82
Water roof	8	126,00
Detaching rainpipe	4	0,00

13 What would motivate you to make your parcel waterproof?

14 Do you consider the database sources used in this model to be reliable enough?

15 What did you think of the user interface of the model? Could this be used intuitively?

Closure

16 Do you have tips or recommendations that could be of added value to this research?

Thank the interviewee. Tell again what will be done with the data and how this will be processed. Ask whether or the interviewee would like to check the transcript to avoid misconceptions.

Appendix G2 - Expert elicitation

The expert elicitation followed a similar interview structure as posed in Appendix G1, though the substantive questions vary greatly. In an overview, which is listed below, the questions that revolve around the expert elicitation are posed:

Expert elicitation - Municipality of Oisterwijk

- How does the municipality of Oisterwijk respond to the increased stress caused by extreme rainfall and periods of drought? And do you feel that Oisterwijk is ahead / behind or behind compared to other municipalities?
- Are private individuals also moving with this movement or is it limited to the municipality?
- What do you notice about the intrinsic motivation of a private individual to take action? Do these need help from the municipality through subsidies or are local awareness campaigns?
- Would the Municipality of Oisterwijk benefit from such a tool and if so, in what way would you bring this tool to the man?
- What measures are most often selected by private residents as well as the commercial and industrial sector in the region of Oisterwijk?

Expert elicitation - Witteveen+Bos

- I had contact with an employee of the municipality of Oisterwijk and he told me that they worked with a universal requirement of 60 mm. This is the case for many municipalities in Brabant. To get an insight, W+B uses 15 mm in the tool IkBenWaterproof, what do you think of both requirements?
- The model is designed for 2050 with the worst-case climate scenario (WH-upper). What do you think of this and what are your experiences with other models that are focused on the future?
- The model is semi-automated and uses free online databases. If you look at the overview of databases in the Excel sheet, how accurate do you consider these data to be for the outcome of the model?
- The model assumes run-off rainwater if it falls on a sloping surface of more than 1.0 percent. What are your experiences with this and do you think this is a good assumption?
- During the development of the model, it was assumed that on average a street may be flooded twice a year, up to 5 cm above the street surface. This is claimed by Stichting RioNED, what is your personal and professional opinion on this?
- What do you think of the factors (pavement degree, potential precipitation deficit, development, groundwater level, which are used to manipulate the storage requirement?
- This model has been tested on 3 private parcels. Do you consider this enough to see how realistic the model is?

Appendix G3 - Interview summaries

Note:

- These interviews were recorded and transcribed manually
- The transcripts are summarized below, the full transcripts can be accessed on request

Private residents

	D. van den Heuvel	Y. Ypma	J. de Jong
Respondent number	**1/5**	**2/5**	**3/5**
Interviewer	**Jildert de Jong**	**Jildert de Jong**	**Jildert de Jong**
Date	**4-1-2021**	**9-1-2021**	**10-1-2021**
Time	**14:00**	**14:30**	**15:30**
Location	**MS Teams**	**Sneek**	**Harich**

The findings from the interviews with the three residents are described in this section. The similarities, as well as the deviations, are depicted.

Van den Heuvel has a high level of expertise with regard to this research. Both de Jong and Ypma are less familiar with the discussed matter. Nonetheless, the responses are all rather similar from the logical perspective of private residents.

Both De Jong (2021) and Van den Heuvel (2021) have detached their rain pipe, with 6 and 20 m^2 respectively. However, all respondents agree on the fact that they will not take action unless nuisance or damages occur on their estate. When it would be necessary though, all would take action themselves to prevent any damages. Common ground can be found in the fact that measures will be purchased when living in an owner-occupied home.

None were subjected to floods on a private parcel level. All have noticed, however, the effect of heat stress, to different extents. De Jong mentions the drought in the summer and the subsidence as a result.

Both Ypma and De Jong consider it unacceptable when the doorsteps overflow. Van den Heuvel mentions that the street adjacent to his parcel floods on average two times per year, which he considers acceptable.

All respondents think the advised storage capacity is realistic. Also, the measures that are suggested are considered sensible options. Though Ypma emphasizes that the storage demand in mm is hard to imagine, especially while the consequences of extreme precipitation have not (yet) been noticed.

For future applications, all participants agree on the fact that automatization of the tool would improve the reliability and user-friendliness. Van den Heuvel mentions that there should be work with what there is, and make the best of this. Though, the false analysis on the flat roof on the parcel indicates that automatization or close contact with the developer would be necessary. Ypma agrees to this and views it as a good initial indication for which measures to take.

Also, the number of litres or millimetres is considered abstract by both De Jong and Ypma. The model output should therefore be directly converted to concrete steps that should be taken.

Aftermath:
The model supports the suggestion that there has not been any flooding, while the use of bui10 as precipitation input in a drop to 4.1, 4.8, and 3.9 mm for De Jong, Ypma, and Van den Heuvel respectively. This gives an insight that the parcels are near water resilient when stressed with a precipitation event with T=10 years.

Expert elicitation - Municipality Oisterwijk

Interviewee	Arjan van der Meijden
Respondent number	4/5
Interviewer	Jildert de Jong
Date	5-1-2021
Time	11:00
Location	MS Teams

Own experiences are the use of a universal 60 mm storage demand for the whole municipality. Van der Meijden explains that this is considered unreasonably high, where often complaints are dropped. Though often after negotiations the storage demand is dropped. The location dependency of the storage demand appeals to Van der Meijden. In the municipality of Oisterwijk, local geographic and hydraulic deviations exist. Own advice for private residents is to simply lower the ground level, and control the flow of rainwater to this area.

Van der Meijden mentions the effectiveness of the first millimetres with regard to catching peak showers. For instance, how many showers are already collected with a 40 mm storage demand? This could possibly form a recommendation for later studies.

Van der Meijden mentions that people are only willing to take action when they are acquainted with the consequences of the problem. Raising awareness is therefore important. Though, while being aware of the problem but not be subjected to the consequences themselves, private residents will not take action. Subsidies could be a solution, however, fraud is rather easy (detaching rain pipe, collection of subsidy, and reinstall the rain pipe to the sewage system).

The storage demand from an exemplary analysis looks realistic. It is way less than the 60 mm that is currently maintained and if this catches a peak shower with T = 25 years, it is considered to be suitable.

In the model, the private residents should be given the freedom to fill in the measures that they want to take.

For future applications, the distinction between superficial and subsurface storage is the next step. Superficial storage not only enables catching peak showers but also heat stress prevention and infiltration options. Another important aspect that could be considered is the emptying of the facilities.

Expert elicitation - Witteveen+Bos

Interviewee	Paul Roeleveld
Respondent number	5/5
Interviewer	Jildert de Jong
Date	13-1-2021
Time	15:00
Location	MS Teams

Roeleveld (2021) works as a consultancy engineering Urban Water Management and Climate Adaptation at Witteveen+Bos. While the concept of storage demand is rather new, Roeleveld mentions that he has some experience with the concept.

To intrinsically motivate private residents to take action, Roeleveld explains that people have to be addressed personally. The residents should be given a guideline on which and how many measures to take. Dutch citizens are acquainted with the issue, though do not know what action can be taken.

Roeleveld has had experiences in Utrecht with the concept. The demand was 45 mm and this should be facilitated near a ring road. Once the initial design was completed, the facility seemed unreasonably large and thus expensive. Roeleveld questions whether this demand - which is filled once in 10 years - is not unreasonably high. Though, the installation costs can be reduced, when replacing a lot of small facilities with a large facility with a similar storage capacity. The municipalities are trying to make the Dutch residents help and finance the step towards urban water resilience.

The factors used in the model look reasonable and no remarks are made. Though, Roeleveld would consider a universal storage demand. Otherwise, the model should include the parcel size. If this is not done, the storage demand will be larger for an old dwelling, in a dense but poor environment, than for a rich, spacious environment. This is considered unreasonable.

Besides the technical calculation, also the socio-economic aspects are important while considering the implementation. The output should be fair and reasonable, otherwise, it will not be accepted.

Another view of Roeleveld towards this model is the use of subsidies. If the model gives a relatively high storage demand, more subsidies are granted to reach the required storage capacity.

To give a better indication of the working of the model and its outcome, it should be tested in different contexts. Make the only variables the type of neighbourhood, or the type of city. If the other variables remain relatively similar, this could result in an interesting analysis.