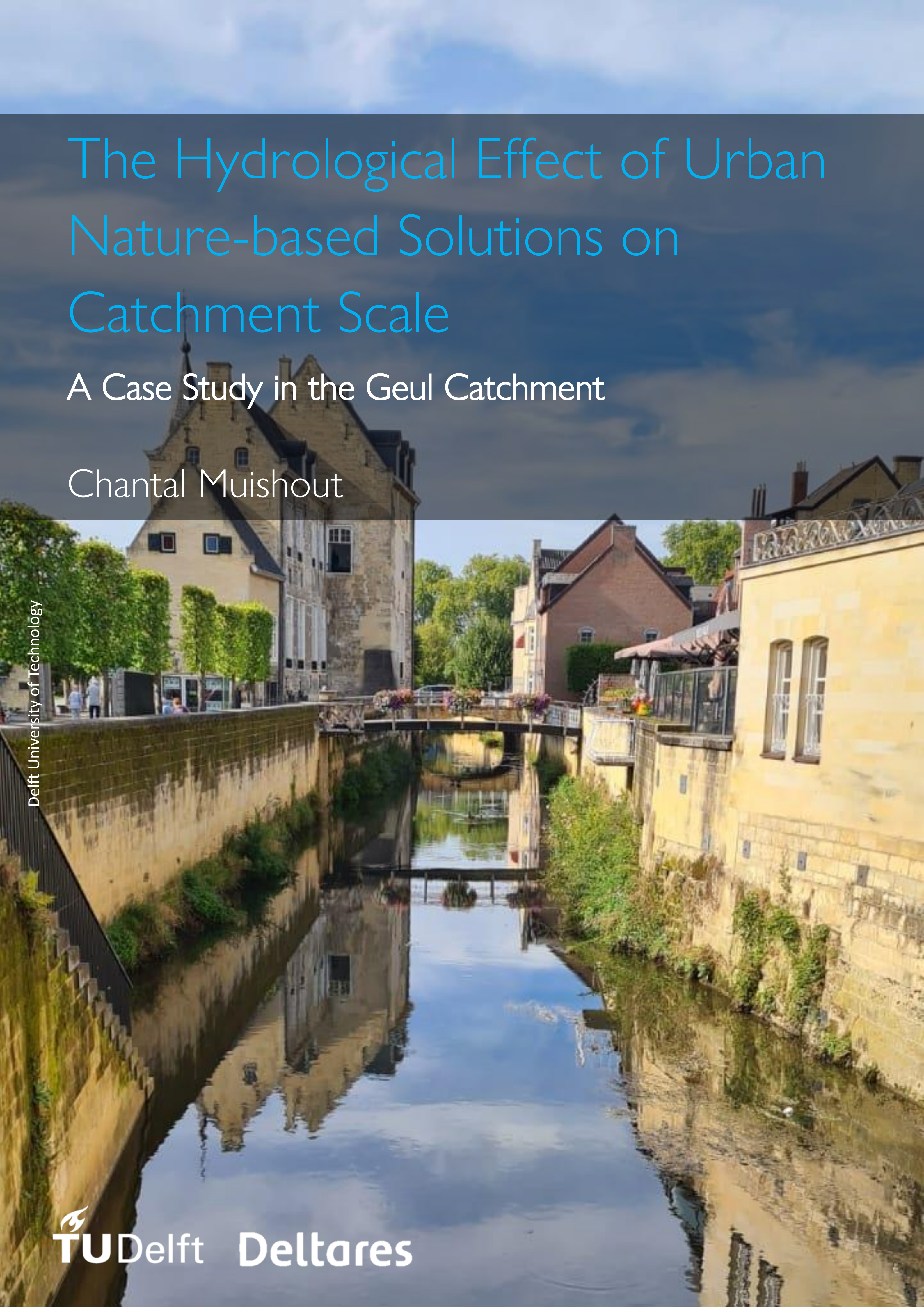
The Hydrological Effect of Urban Nature-based Solutions on Catchment Scale

A Case Study in the Geul Catchment

Chantal Muishout



Delft University of Technology

TU Delft Deltares

The Hydrological Effect of Urban Nature-based Solutions on Catchment Scale

A Case Study in the Geul Catchment

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Cover Image: The Geul passing through Valkenburg, photo taken September 2023

Preface

Dear reader,

Before you lies my master thesis "The Hydrological Effect of Urban Nature-based Solutions on Catchment Scale: A Case Study in the Geul Catchment". It has been written to fulfil the final requirement for the degree of Master of Science in Civil Engineering at the Delft University of Technology. The research and writing were conducted in a period of a little over a year, from August 2022 to October 2023.

This report concludes my eight years (and a bit) of studies here in Delft. Both during my bachelor and master, I have been challenged and pushed towards and over my boundaries. Through the ups and downs, it has been adapting, finding my way, and pushing through the challenges. That being said, the people I have been allowed to meet during my time here, have made it all worthwhile.

This master thesis has been no exception to this. I have learned a lot, bumped my head a few times, but also had a lot of support. Although I am certain that I will forget to mention people that helped me get to this point, there are a few that I would like to thank in particular: Martine, Joost, Remko and Reinder from my thesis committee, for all the constructive feedback and help guiding me through the thesis. Also colleagues and fellow students from Deltares, like Sebastian, Daan and Angela, that wanted to go that extra mile to help me out with my questions and doubts. I would also like to thank Gijs van den Munckhof, Jana Chvalovska and Peter Veldt from waterschap Limburg, gemeente Valkenburg aan de Geul and Stichting Stroming, respectively, for taking the time to think along with me.

Last but certainly not least, I would like to thank the people closest to me: my friends, family, teammates and of course Martijn. Your love, cheering and support have made it possible for me to cross this finish line. I am incredibly grateful that I will have you with me to celebrate this moment.

Chantal E. Muishout
The Hague, October 2023

Abstract

Climate change imposes an increasingly big challenge worldwide regarding floods and droughts. The Netherlands is no exception to this, as it has been increasingly hit by these phenomena in recent years, especially in the south of the country. The July 2021 flood in the Geul catchment intensified discussions on climate resilience. It prompts consideration of transforming the Dutch landscape into a more sponge-like system. Urban areas, identified as both problem areas and potential solutions within the catchment, stand out, since these areas are highly vulnerable and amplify climate change effects. Implementing Urban Nature-Based Solutions (UNBSs) emerges as a promising approach to address these challenges, potentially offering a solution to enhance climate resilience and mitigate the vulnerabilities of urban areas.

This research addressed the challenge of flood protection in the Geul catchment. It focuses on studying the impact of UNbSs and developing a methodology to select, model, and assess their performance in the catchment. This has been done by answering the following questions:

- Which Urban Nature-based Solutions are suitable for the Geul catchment?
- What is the hydrological effect of these Urban Nature-based Solutions locally?
- What is the hydrological effect of Urban Nature-based Solutions at catchment scale?

This research followed a three-step workflow in line with the research questions. Firstly, the study focused on an assessment of neighbourhood types in the catchment and selecting suitable UNbSs for the Geul catchment. Based on this assessment, UNbS measures were chosen for their compatibility with these neighbourhoods. Next, this research analyzed the local effects of the implementation of these measures into the chosen neighbourhoods using the Climate Resilient City Tool. The final step involved an assessment of the hydrological impact of UNbSs on catchment scale. This was achieved by converting the previous results to wflow parameters.

The research succeeded in establishing a workflow for modeling UNbS impact at the catchment scale. It involved selecting UNbSs for three neighborhood types, resulting in the selection and implementation of green roofs, water roofs, permeable pavement, retention ponds, removing pavement to plant green and bioswales.

Locally, the study found that permeable pavement and bioswales were most effective for increasing storage capacity, evapotranspiration, and groundwater recharge. However, the overall order of magnitude for all measures remained consistent across neighbourhoods. Considering the total storage capacity increase, the order of magnitude was found to be between 34- and 39-mm storage equivalent over the total surface area of the neighbourhoods.

On a catchment scale, UNbS implementation resulted in a discharge reduction ranging from 1.71% to 3.10%, with a more pronounced effect upstream. Three neighbourhood scenarios exhibited minimal differences, all below 0.1%, which is considered insignificant. Absolute discharge reduction consistently followed patterns across low and high discharge periods, with more substantial reductions during peak discharges. However, the percentage difference between original and altered discharge was found to be similar across all periods, making this trend less evident.

Based on these results, the research proposed the following five recommendations regarding future research and implementation: 1) improve model transparency and sensitivity analysis, 2) consider practical implementation challenges, 3) refine typology mapping and data, 4) evaluate Nature-based Solutions in diverse landscapes and 5) promote the role of UNbSs in climate resilience.

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1. Introduction

1.1 Background and problem statement

Climate conditions are changing worldwide. This leads to an increase in intensity and frequency of extreme weather events like heavy precipitation, droughts and heat, which in its turn means that floods, heat stress and drought are becoming more common (EcoShape, 2023; IPCC, 2022; Voskamp & Van de Ven, 2015). These effects of climate change are already notable. Since 1980, there have been 4588 flood disasters in 172 countries (Dąbrowska et al., 2023). Subsequently there is also an increase of magnitude, severity, and duration of drought periods worldwide, which are forecasted to be more regular, longer, and more widespread (Dąbrowska et al., 2023; Philip et al., 2020). Also the Netherlands is facing an increasingly big challenge regarding floods and droughts, especially in the south of the country, which has faced major floodings and extreme droughts in recent years (Ministerie van Infrastructuur en Waterstaat, 2022). One example is the drought of 2018, which caused such low groundwater tables that there were increased land subsidence and hundreds of houses in urban areas got damaged, leading to a total economic loss of between 450 and 2080 million euros (Philip et al., 2020). However, maybe most notable was the flood of the Geul catchment in Limburg in 2021. In the catchment, an average precipitation of 128 mm fell in 2 days, which led to casualties in the upstream part of the catchment and caused an initial estimated damage between 100 and 400 million euros and extensive flooding especially in Valkenburg and Meerssen (Klein, 2022).

Due to the recent high water in mid-July 2021, the issue of climate resilient design has gained momentum (Natuurmonumenten & Stroming, 2022). While in the past centuries, the Netherlands has been focussing on draining water to the sea as quickly as possible, the increase in floods and droughts asks for a change of strategy, turning the landscape into a sponge again (Ministerie van Infrastructuur en Waterstaat, 2022; Natuurmonumenten & Stroming, 2022). Especially urban areas are vulnerable to floods and droughts, mainly because most people live in these areas and because these urban areas magnify the effects of climate change (Voskamp & Van de Ven, 2015). Van Heeringen et al. (2022) investigated different measures that could prevent future floodings in Valkenburg, like tunnels and dams, which are locally very efficient but not for the entire catchment and change the old centers experience. Buffering water was the only measure that was found that could be effective catchment wide. Additionally, in an analysis from (Natuurmonumenten & Stroming, 2022), it was found that the impermeable surface of roads and urban areas had a big contribution in the peak discharge of the high-water wave in July 2021. The claim that the soil was saturated causing this high water was found to be false, and instead the infiltration time of the soil that was hindered by impermeability was pointed as the issue. One of their recommendations for the entire catchment is the implementation of buffers and urban green, so-called Nature-based Solutions.

Nature-based Solutions (NBS) are defined by The European Commission as “Solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social, and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes, and seascapes, through locally adapted, resource-efficient and systemic interventions” (European Commission, n.d.) In the urban context, Urban Nature-based Solutions (UNbS) have been regarded as an inclusive umbrella concept of urban ecosystem-based approaches like urban ecosystem services and green–blue infrastructure (Kabisch et al., 2022). A wide range of (UNbS) have been developed and implemented under varying terminologies including low impact development, best management practices, sustainable drainage systems, water sensitive urban design, green infrastructure, blue–green infrastructure and sponge city. Though these terminologies have differences in scopes and contexts as discussed in the works of Fletcher et al (2015) and Ruangpan et al. (2020), they are all based on the same broad principle of mitigating the impact of urban developments through mimicking nature and achieving wider benefits such as flood risk reduction, biodiversity, amenity, and heat island effect reduction. (Fu et al., 2023). Runoff volume reduction, runoff flow reduction and delay of peak time, runoff pollution control, and re-use of stormwater as a natural resource is emphasised with UNbS. According to studies conducted for European cities, flood and drought protection is one of the three main functions of the NBS, and water stored in them during rainfall is used in times of drought (Oral et al., 2020). Solutions based on LID and NBS are developing around the world, their value and limitations are well recognised. Thanks to those measures, water retained during rainfall may be utilized in the periods of drought (Dąbrowska et al., 2023).

Even though the concept of NBSs is well known, NBS incorporation into hydrologic and hydraulic models is not yet well understood and explored in the hydrology community (Guido et al., 2023). Additionally, current studies tend to have in common that they acknowledge that these benefits are difficult to quantify (Reu Junqueira et al., 2023). However, in an extensive state-of-the-art review of Ruangpan et al. (2020), it was found that Nature-based Solutions can contribute to a peak flow reduction in ranges of 2.2% up to 89%, where, for low urbanized, small-scale catchments, results tend to range between 2.2% and 13% (Guido et al., 2023; Ruangpan et al., 2020).

1.2 Research questions

Given the current challenge for the Geul catchment regarding flood protection, as has become clear during the recent floodings of 2021, and the potential but not well studied effect that Urban Nature-based Solutions can have on catchment scale, this research determines a methodology for selecting, modeling, and evaluating the performance of UNbSs and improving the modeling aspects of NBS implementation in the Geul catchment. This will be done by answering the following questions:

- Which Urban Nature-based Solutions are suitable for the Geul catchment?
- What is the hydrological effect of these Urban Nature-based Solutions locally?
- What is the hydrological effect of Urban Nature-based Solutions at catchment scale?

1.3 Scope and methods

The local hydrological effect of Urban Nature-based Solutions can be plentiful, like flood and heat reduction, improvement of water quality, health benefits and more. For this research, the local hydrological effect is defined as the effect on water storage, evapotranspiration, and groundwater recharge relative to the current situation. The hydrological effects at catchment scale of UNbS can also be manifold, like peak flow reduction and attenuation and baseflow increase. For this research, the hydrological effect is the peak flow reduction in the runoff hydrograph.

Currently, the most suitable hydrological model for the Geul catchment to our knowledge is the wflow_sbm model made by Klein (2022). This model is specifically calibrated for a two-year period to accurately capture the flood of July 2021. Wflow, especially the simple bucket model (sbm) version, is well suitable for gravity-based flow simulations in natural flowing rivers. For the model parameters, most are based on model parameters which are derived from point scale (pedo)transfer-functions from literature. An advantage of this is that, in contrary to lumped models like HBV-96 which the waterboard of Limburg uses, parameters are mainly physically based, only constrained by field and laboratory measurements and are well suitable for land cover change modelling.

However, UNbSs are still on a much smaller scale than the model resolution of the model of Klein (2022), which makes it difficult to assess the local hydrological effect of UNbSs and to parametrize on catchment scale. Since general model performance reduces for resolutions higher than the 1x1 km^2 resolution of Kleins model (Aerts et al., 2022), this might not represent the effect of the UNbSs well. To be able to represent UNbSs more accurately, both locally and on the relatively coarse model scale of wflow, the Climate Resilient City Tool (CRCTool) is used. This visual tool, which includes 62 UNbS measures, is a selection tool for ranking measures based on their applicability and an assessment tool to estimate the effectiveness of applied adaptation measures, allowing to investigate the local effect of UNbSs. Next to this, the CRCTool estimates the performance of the measures for e.g. created storage capacity, extra groundwater recharge and evapotranspiration, which are parameters which can be parametrized to wflow parameters. This makes wflow and the CRCTool a suitable combination for the objective of this research.

1.4 Report structure

The structure of this thesis is as follows. Chapter 2 gives more insight in the study area, namely the topography, geohydrology, climate and land-use of the Geul catchment. In Chapter 3, the methods of this research are explained, providing insight into to data and models used. Chapter 4 contains the results of this research. This includes the selection of Urban Nature-based Solutions and an analysis on local and catchment scale effect. A discussion of the findings can be found in Chapter 5 and this thesis is finalized with a conclusion and recommendations in Chapter 6.

2. Study area

Before answering the research questions posed in the previous chapter, it is important to first get a better understanding of the Geul catchment and its characteristics. Therefore, this chapter covers the topography and location of the catchment (2.1), followed by the geo(hydro)logy (2.2) and climate (2.3). Finally, the land use per sub catchment will be presented (2.4).

2.1 Topography and location

The Geul catchment is a transboundary catchment of approximately 340 km^2, covering parts of the Netherlands, Belgium and Germany. An overview of the location of the river and its catchment can be found in Figure 1. Most of its area is located in the Netherlands (52%) and Belgium (42%) with the remaining fraction located within Germany (6%) (Tsiokanos, 2022; van den Munckhof, 2020). The origin of the Geul is in the east of Belgium at the border with Germany, near the town of Lichtenbusch. From here, the river leaves Belgium via Sippenaeken and enters the Netherlands. In the downstream part of the catchment, the river flows past places like Schin op Geul, Valkenburg and Meerssen, before it finally converges with the Meuse downstream of Maastricht near Bunde. Aside from its main stream, the Geul has three main tributaries: the Gulp, Eyserbeek and Selzerbeek, which all converge with the main stream near the cities Gulpen and Partij.

Since the Geul flows underneath the Julianakanaal culvert one kilometer before its convergence with the Meuse, most studies consider the catchment until the start of this culvert instead of until(Natuurmonumenten & Stroming, 2022; Thewissen, 2022)Stroming, 2022; Thewissen, 2022). Also for this study, the Geul catchment is considered from the origin near Lichtenbusch to the Julianakanaal culvert.

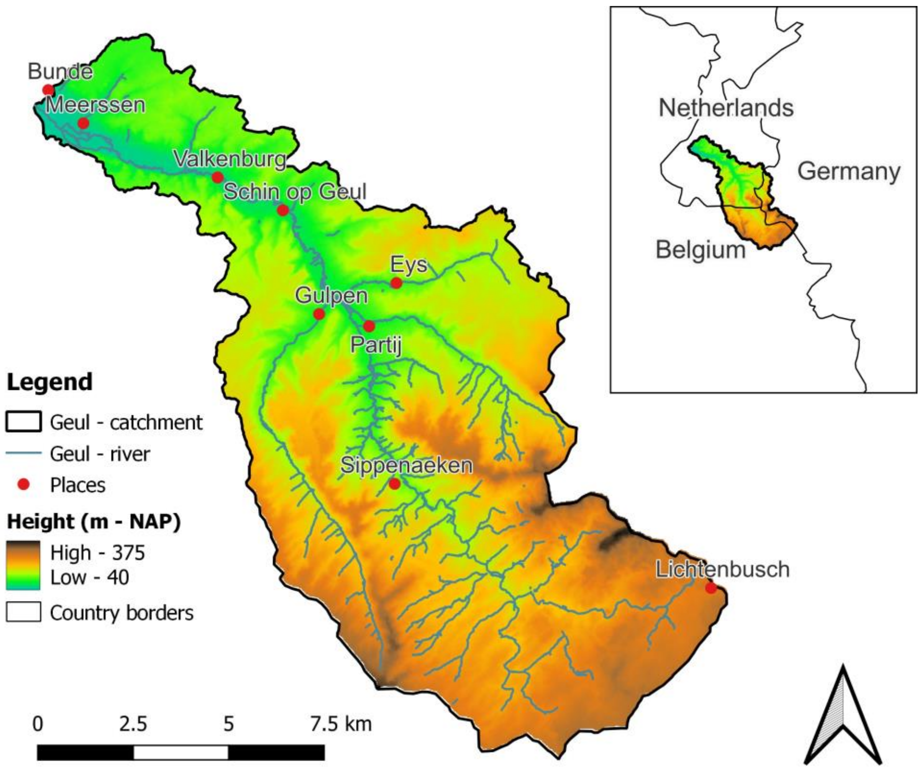

Figure 1: Topographical overview of the Geul catchment and its location relative to the Netherlands, Belgium and Germany

The exact length of the river Geul is difficult to determine due to its meandering nature and has been estimated between 45 km (Natuurmonumenten & Stroming, 2022) and 58 km (Suijkens, 2022). Over the full length of the river, the Geul drops 275 meters, meaning that it has an average gradient of around 0.004 m/m. This makes it a relatively hilly and steep river for Dutch standards. This gradient varies however along the river, from a steeper 0.02 m/m near the source to a flatter 0.0015 m/m at the confluence with the Meuse (van den Munckhof, 2020). The change in gradient for the main stream and the three tributaries is illustrated in Figure 2.

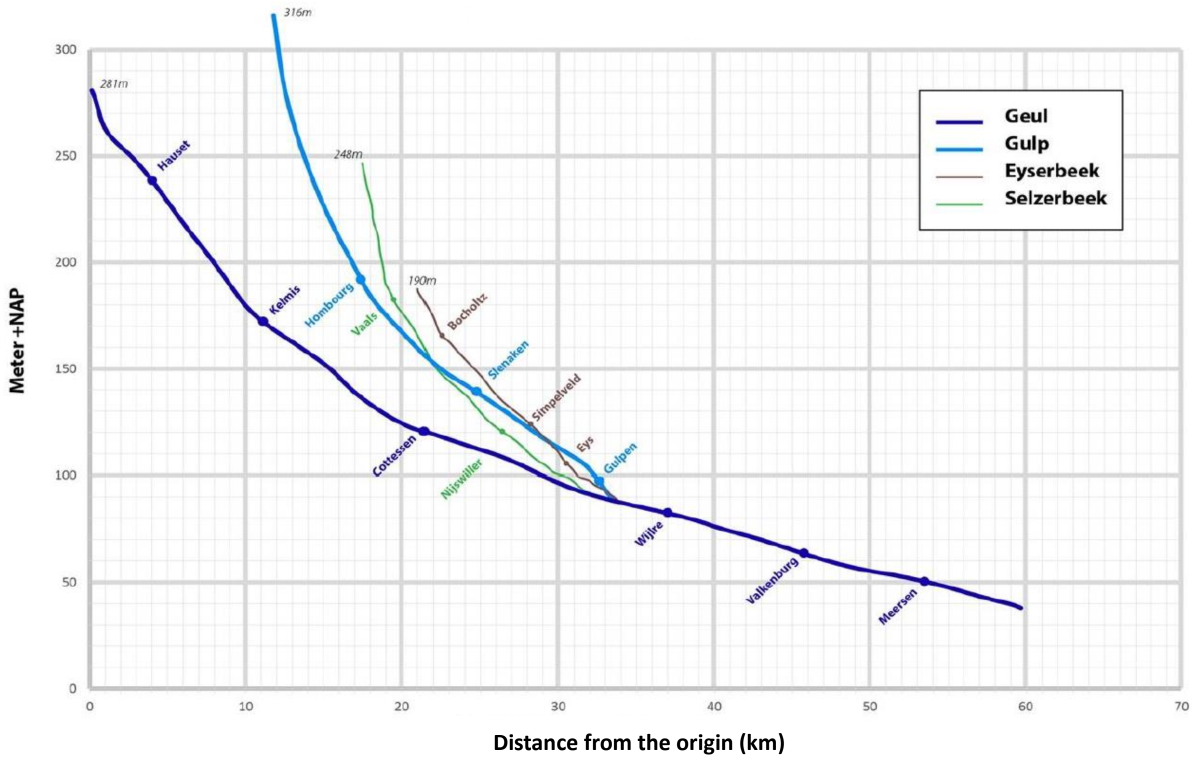

Figure 2: Gradient of the main river and three tributaries of the Geul (source: Natuurmonumenten & Stroming, 2022)

Besides being a relatively steep and hilly river, the Geul is also one of the few rivers in the Netherlands which can meander through the landscape without a stabilized riverbed (Klein, 2022). In the past, to reduce erosion, the river has been straightened and the riverbank protected. This however also led to higher peak discharges. Large floods of the Meuse at the end of the 20th century called for a reduction of these higher discharges and an increase in natural storage capacity. This has led to restoration of meanders, construction of water retention basins and the transformation of areas into inundation areas for during high-water events at the beginning of the century (Tsiokanos, 2022; van den Munckhof, 2020). Currently, the Geul meanders in a specific meander zone with little bank protection, except for short stretches through villages (van den Munckhof, 2020).

2.2 Geo(hydro)logy

Also the geology of the Geul catchment differs greatly from the geology of the rest of the Netherlands. Geologically, the area belongs to the northern extensions of the Ardennes and Eifel mid mountain range and consists of rock deposits from various periods. During the last two ice-ages, loess was deposited with a thickness ranging from 1 m to 15 m (Hendrix & Meinardi, 2004). Still nowadays, the main soil type in the catchment consists of loess (Munckhof, 2020; Klein, 2022; Tsiokanos, 2022). An overview of the complete soil type classification for the catchment based on permeability and geological era can be seen in Figure 3.

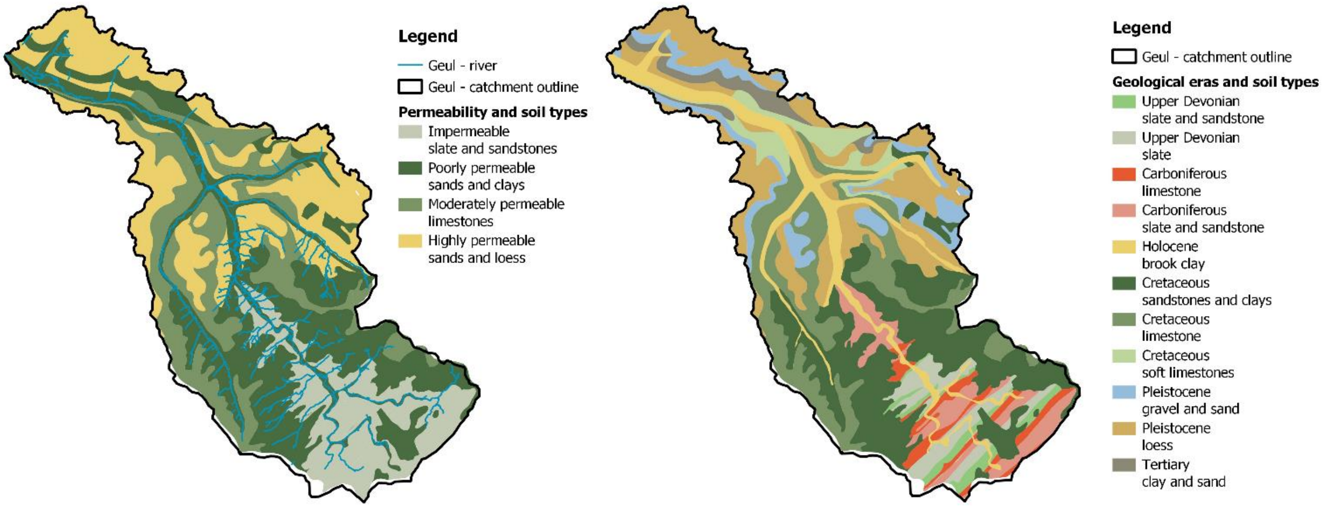

Figure 3: Geological overview of Geul catchment. The figure on the left illustrates the coarse classification of soil types by their permeability (note that this refers to the geological soil types and not the thick soil layers that often lie on top of them). The figure on the right depicts the soil types based on their geological era (adapted from Natuurmonumenten & Stroming, 2022)

There are roughly four types of geological deposits recognizable in the soil (Klein, 2022; Natuurmonumenten & Stroming, 2022):

1. The most upstream part mainly consists of old Paleozoic rocks from the Upper Devonian and Carboniferous, which also extend into the downstream Walloon Geul valley and for a small area into the Dutch Geul valley. These rocks, including slate, sandstone, and hard limestone, are compact with a very poor permeability.
2. Ancient rocks from the Cretaceous are found in the Walloon and Flemish parts of the basin, characterized by varying permeability, including softer limestones, sandstones, and occasional clayey sandstones. In the Netherlands, they are primarily located in the valley flanks, but can also be found on plateaus under younger layers.
3. Younger sandy and clayey deposits are prevalent in the Dutch part of the catchment, especially on the plateaus in the south and downstream of Valkenburg. These deposits from the Pleistocene and Tertiary include layers with loess, with generally good permeability, but deeper loess layers can have a reduced permeability.
4. The most recent deposits are loamy stream deposits in valley plains, deposited by the Geul over the past thousand years. They are widespread in the Dutch part of the catchment, as well as in parts of the Flemish Gulp valley and Walloon Geul valley. These sandy and clayey soils have a poor permeability.

Also the geohydrology is different compared to a typical Dutch catchment in the lowlands. The whole catchment has impermeable carboniferous rocks at its base and three main water bearing aquifers: Aken, Vaals and Gulpen formation. These formations can be described as dual porosity and dual hydraulic conductivity media. The flow through the fractures shows a quick response to precipitation, while the porous flow shows a slow response (Hendrix & Meinardi, 2004). Klein (2022) divides the area into five different geohydrological zones based on the different deposits which the river cuts into at the valley bed and flanks (3 through 6) based on the Dutch Groundwater Model (Schaminée et al., 2009). An overview is provided in Figure 4:

• Typically, zone 3 has a low to medium permeability. Groundwater movement is slow laterally through sand and slow at the entrance of clay layers.

• Zone 4 is characterized by a thick chalk layer cut through by the river. Permeability is highly heterogeneous and ranges from high to low. There are preferential flow paths for groundwater, thus flow is generally quick. Storage capacity of these plateaus is high because of the thickness of the soil.

• Zone 5 has medium to low permeability and groundwater is 30-50 meters below the surface and is recharged with precipitation.

• Zone 6 is low in permeability but has high heterogeneity such that the groundwater movement is low through very high. Storage capacity is limited.

• The Belgian upstream area is characterized by impermeable carboniferous rock and therefore there is little to no storage capacity in plateaus or valleys and limited capacity on hill slopes.

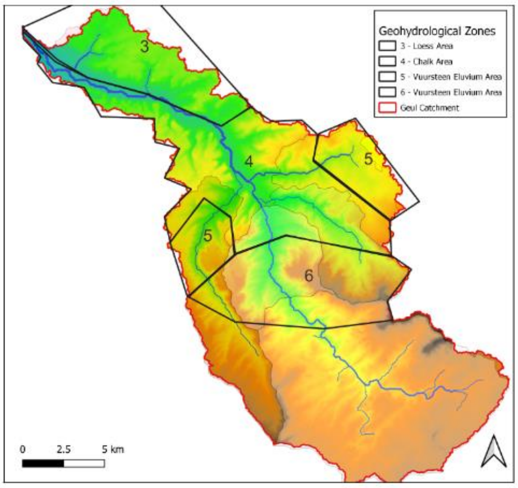

Figure 4: The five different geohydrological zones as indicated by Klein (2022) based on the Dutch Groundwater Model (the fifth time zone being the Belgium upstream area, which is not numbered)

2.3 Climate

According to the Köppen-Geiger classification system, the climate of the Geul catchment is classified as Cfb, or a temperate oceanic climate. This means that its main characteristics are: no differences in precipitation throughout the seasons, the lack of a dry seasons, yearly moderate temperatures, and warm summers (Peel et al., 2007). Additionally, when considering the Budyko curve of the catchment, Klein (2022) and Thewissen (2022) found that the catchment is an energy limited catchment, meaning that the evapotranspiration is limited by energy and not by water.

The Geul has an average precipitation of between 620 to 870 mm per year, with the highest monthly values recorded in August (90 mm/month) and the lowest in April (45 mm/month). The average seasonal cycles of precipitation, potential evaporation and discharge as calculated by Klein (2022) are visualized in Figure 6. While the rainfall intensity is the highest in the summer months, the winter is the usual flood season, when the discharge of the Geul is the highest. The high discharges in winter are caused by any combination of (relatively) high precipitation, wet antecedent conditions, snow melt and low evapotranspiration. The runoff is evenly distributed throughout most of the year due to the groundwater storage provided by the extensive chalk aquifers in the catchment (Min, 2006).

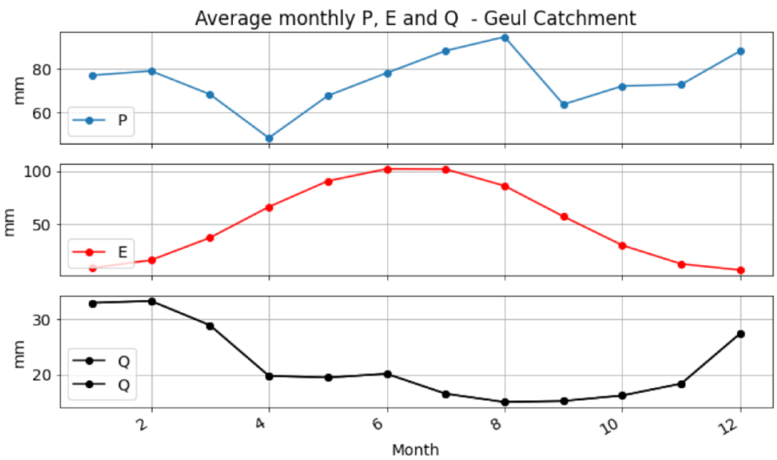

Figure 5 Average monthly precipitation, evaporation and discharges for the Geul (source: Klein (2022))

2.4 Land use per sub catchment

The Geul catchment can be divided into six sub catchments: Meerssen, Hommerich, Gulp, Eyserbeek, Selzerbeek and Sippenaken. For each of these sub catchments, Natuurmonumenten & Stroming (2022) investigated the land use per sub catchment and came with the results as presented in Figures 6 and 7. As can be seen from these Figures, the catchment consists mainly of paved areas, corn fields, other fields, grassland and forest. In general, most sub catchments consist of grassland and forests and between 8-20% paved areas. Esyerbeek is one of the subcatchments that stands out, with its main area dedicated to fields.

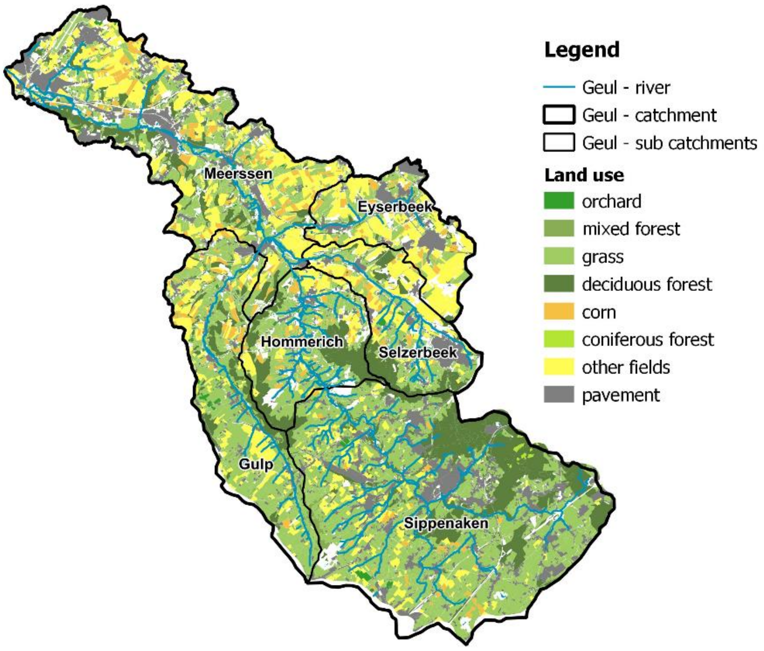

Figure 7 The land use in the Geul catchment, divided into the six sub catchments

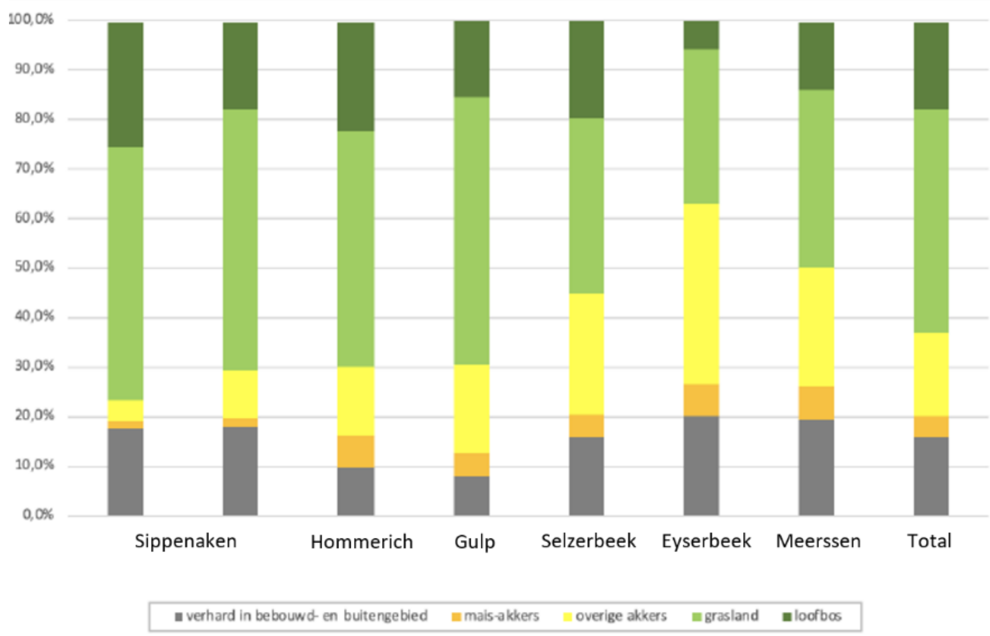

Figure 6 Percentage of land uses per sub catchment and in total

3. Materials and methods

After the introduction and study area overview provided in the previous chapters, this chapter shows the methodology used for this research by means of 4 sections. Section 3.1 provides a general workflow overview of the methodology. This is followed by section 3.2, in which the materials and method for the neighbourhood and UNbS selection is presented. After this, section 3.3 shows the second step in the research, in which the local effect analysis method will be explained. Finally, section 3.4 covers the final research step, which is the analysis of the hydrological effect on catchment scale.

3.1 General workflow overview

The overall workflow of this research consists of three consecutive steps, that align with the order of the research questions: the selection of suitable Urban Nature-based Solutions (UNbSs) for the Geul catchment, an analysis of the local effects on urban scale and an analysis of the hydrological effect on catchment scale. This workflow overview can also be seen in Figure 8.

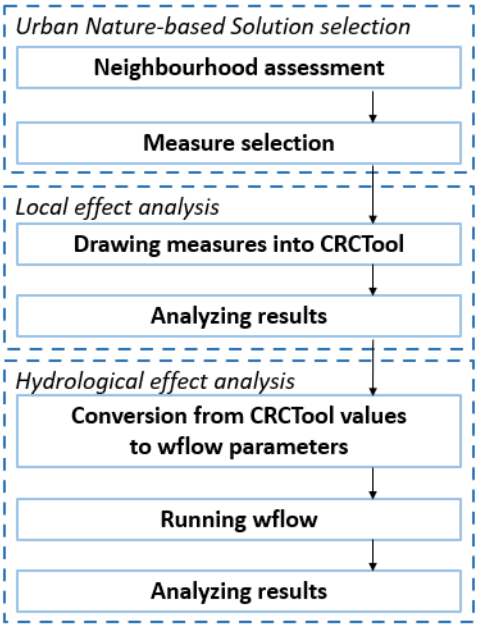

Figure 8: General workflow overview for the methodology of this research

For the UNbS selection, first an assessment will be done on the types of neighbourhoods that exist in the catchment. Based on a selection of neighbourhoods from this assessment, UNbS measures will be chosen based on their suitability for these neighbourhoods.

For the analysis of the local effect of these measures, the selected measures will be drawn into the selected neighbourhoods using the online Climate Resilient City Tool developed by Deltares. The results of this will be analysed.

Finally, for the analysis of the hydrological effect of UNbSs on catchment scale, the results of the previous step will be converted to wflow parameters. After this, the model will be run, and these results will be analysed. A detailed explanation on each step and the exact used tools and data can be found in the next sections.

3.2 Step 1: Urban Nature-based Solution selection

3.2.1 Neighbourhood typology map

The Klimaateffectatlas is a tool which is meant to give a first impression of the impact of climate change on a local scale. It exists of a viewer and five “map stories” (“kaartverhalen”). These map stories give background information regarding the topics of waterlogging, drought, heat, and flooding. Additionally, they provide basic maps with information regarding landscape characteristics, potential natural climate buffers, green and grey areas, and neighbourhood typologies.

In the field that focuses on design of public space, neighbourhood typology is often used in its communications, but for anyone less directly focused on it, these types are not everyday terms and there is sometimes doubt as to which type a neighbourhood belongs to. The neighbourhood typology map assists in this in a clear a simple way which communicates the vulnerability of neighbourhoods to the impact of climate change which can be understood also be non-experts based on just a few characteristics (like construction period, building style, degree of urbanization, type and size of housing, type and amount of greenery and water, the layout of public space and the layout an width of the road profile) with limited amount of actions.

In this research, this neighbourhood typology map is used. The map is a submap of the basic maps bundle which can be downloaded via [Data opvragen - Klimaateffectatlas](). Within the map, 14 types of neighbourhoods are specified, which can be accessed and modified in QGIS. The neighbourhood typology map is based on the work of Kluck et al (2017), which in its turn is based on the classification system of Kleerekoper (2016). An overview of all the neighbourhood types with their characteristics and indicative vulnerability to waterlogging can be found in Appendix A.

3.2.2 QGIS

QGIS is an open-source Geographic Information System (GIS) software application, which allows for the creation, editing, visualization and analysis of geospatial data, such as maps, spatial databases, and layers. In this research, it is used for processing and analysing the data from the neighbourhood typology map.

3.2.3 Selection tool score table

To account for the fact that multiple UNbS can be fitted in the same type of locations, the Selection tool scores table of the CRCTool (in combination with discussion sessions) is used to determine the measure that are most suitable for the selected neighbourhoods. This scores table is the weighting system behind the CRCTool which determines the suitability of UNbSs given a certain location in a catchment and neighbourhood. It scores the effectiveness of measures for a predefined project area based on the assessment of two categories: technical feasibility and site suitability. Based on this score, the measures are ranked by their applicability and expected effectiveness in the project area. The method used for this assessment is an adapted version of the selection assistant of the "Adaptation Support Tool (AST)" developed by Voskamp & Van de Ven (2015), which also assesses effectiveness based on technical feasibility and site suitability. Table 1 shows an overview of the assessment criteria of the CRCTool, Appendix B contains the criteria in more detail with each selectable option.

Table 1 Overview of the assessment criteria of the CRCTool (□ is multiple selection possible, ○ is only single selection)

	Scenario Name	○	Scenario for the calculation of the effectiveness of climate adaptation measures
	Climate Resilience Capacity	□	The most important adaptation objective(s) for the project area
Technical feasibility assessment	Scale level	□	The scale at which adaptation measures will be planned
	Soil type	○	Indication of shallow subsurface material
	Slope	○	Relative position of project area on a slope
Site suitability assessment	Multifunctional land use	○	Combining multiples functions on the same land; Important in densely built areas
	Existing space types	□	Existing land use in the project area
	Sub-surface availability	○	Availability is determined by presence of subsurface infrastructure (e.g. cable and pipe networks)
	Roof characteristic	○	Presence of flat roofs or gently sloping roofs in the project area

The technical feasibility is assessed based on slope of the terrain (and expected groundwater depth and dynamics), soil type, and scale level of implementation. The site suitability is assessed based on existing types of urban space, subsurface availability, multi-functional land use and roof characteristics.

The full table can be found on Selection tool scores table - Climate Resilient City Tool - Deltares Public Wiki.

3.2.4 Method

Neighbourhood assessment

The Klimaateffectatlas neighbourhood typologie map has been downloaded via *Klimaateffectatlas → KAARTVIEWER*. Under *Filter op thema, Wijktypologie* has been selected. After this, the data has been collected via *DATA OPVRAGEN* and was received as a .qgz file on February 14, 2023.

The .qgz file with the basic maps bundle was opened and modified using QGIS Dekstop 3.28.0 in the EPSG coordinate system 28992. From *Basiskaarten, Wijktypologie* has been clipped using the *Clip…* option under *Vector → Geoprocessing Tools* to the pre-existing polygon of the Geul catchment provided by Tsiokanos (2022). From this clipped layer, the attribute table has been exported as an Excel file. Using this Excel file, the total amount of neighbourhoods, percentage per typology of the total amount of neighbourhoods, and percentage per typology of the total surface area of neighbourhoods have been calculated.

Based on these results, three neighbourhoods from different types have been selected to investigate in more detail. Selection is based on frequency of appearance and vulnerability to waterlogging as indicated in Appendix A.

Measure selection

Given the scope of this research and knowing that the area is sloping and with a low groundwater table, measures in the Selection tool scores table must comply with the following criteria:

- Effective against drought and/or flood prevention
- Effective on neighbourhood, street and/or building scale
- Effective on high and sloping areas

The selection that follows from this analysis is discussed and adjusted based on expert judgement, and based on this the final most suitable combination of measures, the final selection is chosen for the following types of locations:

- Roofs
- Roads
- Pavement
- Private properties
- Open water bodies
- Grass areas
- Parking lots

3.3 Step 2: Local effect analysis

3.3.1 CRCTool

The Climate Resilient City Toolbox (CRCTool) ("Klimaat Bestendige Stad Toolbox" in Dutch) is an interactive online selection tool which was developed to explore the effect of Urban Nature-based Solutions on the water resilience in urban areas. Based on the feasibility and suitability assessment of measures, the CRCtool provides the measures in the order of most to least suitable for the project area, after which the measures can be selected and drawn into the area. Before confirming a selected measure, the option is given to change the water storage depth (m) and inflow area (x) of the measure. After this, the tool gives an overview of the estimated effect of the measures on three different categories: climate, costs and water quality. Each category has their own subcategories as shown in Table 2 below. A step-by-step overview for using the CRCTool can be found on Climate Resilient Cities Toolbox (crctool.org). The focus of this research is on the storage capacity, groundwater recharge and evapotranspiration.

Table 2 The estimated effect of the three main categories of the CRCTool: climate, costs and water quality

	Main category		
	Climate	***Cost***	***Water quality***
Sub category	Storage capacity	Construction	Pathogen reduction
	Groundwater recharge	Maintenance	Nutrient reduction
	Evapotranspiration		Adsorbing pollutants
	Heat reduction		
	Cool areas		
	Return time factor		

3.3.2 Method

Drawing measures into the CRCTool

After choosing the neighbourhoods and measures as indicated in the previous section, these measures are drawn into the CRCTool. The project area will be drawn based on the shape of the neighbourhood in the neighbourhood typology map. Although the selection of settings before drawing them does not influence the output, the choices have been included in Appendix C. After this, the chosen measures for the chosen locations are drawn into the CRCTool. For this, the settings for the storage depth and inflow area are kept as their default setting. Drawing of the measures has been done on own insight.

Analyzing results

Once drawing the measures is finished, the storage capacity, groundwater recharge and evapotranspiration will be investigated to see what the local effect is of the measures. This analysis will mainly focus on increased storage capacity over the full neighbourhood area and the relative contribution of each measure.

3.4 Step 3: Hydrological effects

3.4.1 Wflow_sbm

“Wflow.jl (v0.6.1) is an open-source modelling framework for distributed hydrologic modelling, containing multiple distributed hydrologic model concepts, implemented in the programming language Julia” (Van Verseveld et al., n.d., p. 3). Out of the three vertical hydrologic concepts that are available within wflow.jl, “wflow_sbm is the main hydrologic model and represents a family of hydrologic models that have the vertical SBM concept in common” (Van Verseveld et al., n.d., p.4). The wflow_sbm model, as will be used for this research and is shown in Figure 9, uses the kinematic-wave approach for river, overland and lateral subsurface flow.

3.4.2 The wflow_sbm model from Klein (2022)

For this research, the wflow_sbm model of Klein (2022) was used. This model is an adaptation of an existing model for the river Meuse based on a set of different soil, land cover, LAI and hydrography data sets using HydroMT-wflow. The model parameters of the wflow-sbm model are either derived from the gridded input using point-scale (pedo)transfer functions as described by Imhoff et al. (2020) or used with a uniform value. A full overview of the wflow model parameters can be found in Table B.4 of the Appendix in the report of Klein (2022).

Kleins model is used since it is currently the best performing model for predicting the hydrological behaviour of the Geul that allows for land use changes. Klein (2022) reports that the current setup of the hydrological model used by waterboard Limburg, which is a semi-distributed HBV-96 model, has difficulties reproducing the distinct characteristics of the sub catchments and does not allow to evaluate the effect of land-use changes, while their model does allow for this.

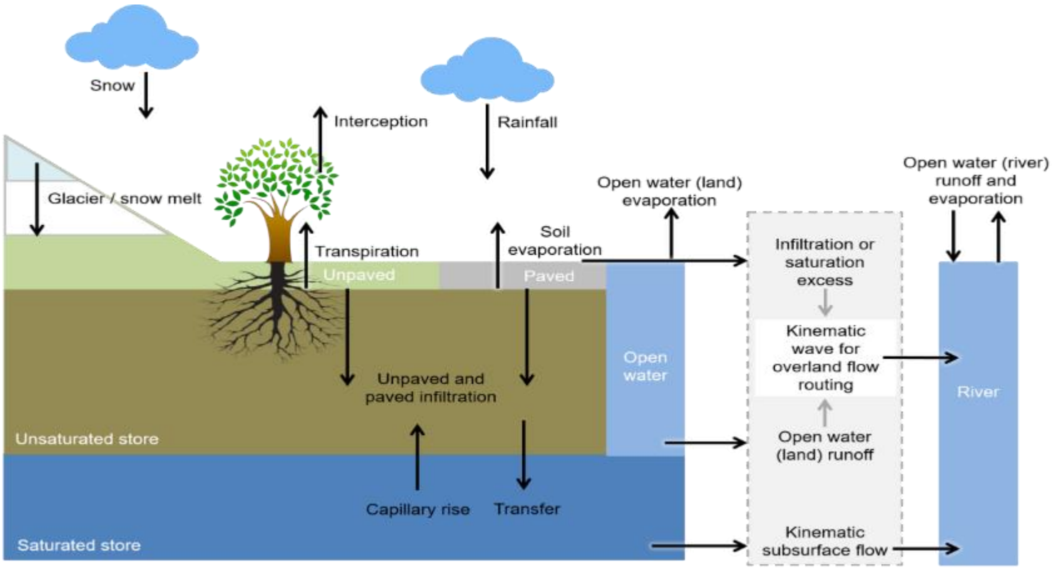

Figure 9: Overview of the different processes and fluxes in the wflow sbm model (source: Van Verseveld et al., n.d.)

3.4.3 Method

Wflow model setup

For the wflow model, the model of Klein (2022) is adjusted and run. The input and output for the model are depicted in Figure 10 below:

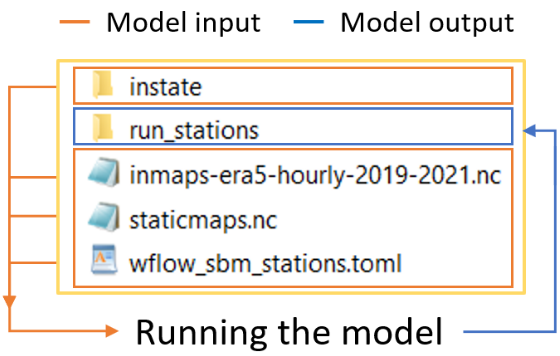

Figure 10 Setup for running the wflow model, with input and output

Instate folder: This folder contains the instate.nc file with the model input initial conditions, which is used to hotstart the model. Using this file instead of starting with default initial conditions avoids a long spin up procedure. The instate.nc file was provided by Klein (2022).

Inmaps-era5-hourly-2019-2021.nc: This file contains the hourly forcing data consisting of precipitation, potential evapotranspiration and temperature. ERA5 is the fifth generation ECMWF (European Centre for Medium-Range Weather Forecasts) reanalysis for global climate and weather. The original 0.25° x 0.25° (about 31 km^2) hourly data set has been up scaled by Klein (2022) to match the 1 km^2 grid size of the model. The full name of the used data set is ERA5 hourly data on pressure levels from 1979 to present (Hersbach et al., 2018).

Staticmaps.nc: This file contains the static input data for the model, like the Digital Elevation Model, rivers, and the land use map and related parameters. The Land Use Land Cover (LULC) map that is used for this model is the Corine Land Cover Map 2018, which has a 300 m^2 resolution. Parameter changes have been applied to pixels that are classified as “Artificial surface”. The Corine Land Cover Map 2018 for the Geul with corresponding land cover classification can be found in Appendix D.

The staticmaps.nc contains, aside from the above mentioned input data, vertical parameters which represent physical properties of the model which can be modified. A complete list of these parameters vertical concepts can be found on [Parameters vertical concepts · Wflow.jl (deltares.github.io)](). The parameters that will be modified for the implementation of UNbS properties is depicted in Table 3 below, including a description of these parameters, the unit, and default value if applicable.

Table 3 Modified vertical parameters in the wflow model, with their description, unit and default value if applicable

parameter	description	unit	default
swood	storage woody part of vegetation	mm	-
infiltcappath	infiltration capacity of the compacted areas	mm Δt^{-1}	10.0 mm day^{-1}
infiltcapsoil	soil infiltration capacity	mm Δt^{-1}	100.0 mm day^{-1}
soilthickness	soil thickness	mm	2000.0
et_reftopot	multiplication factor to correct reference evaporation	-	1.0
pathfrac	fraction of compacted area	-	0.01

Wflow_sbm_stations.toml: This Tom's Obvious Minimal Language (TOML) file is used to run the model, containing all information regarding which input data to use and where to store the output data.

Run_stations: This is the folder where the output of the model run will be stored.

Conversion from CRCTool values to wflow parameters

To make a link between the output of the CRCTool and the model parameters of wflow, the conversion as shown in Figure 11 is applied. As mentioned in the previous section, the parameter values are changed for Swood, SoilThickness, et_reftopot, InfiltCapPath, InfiltCapSoil and PathFrac. Their original default values can be found in Appendix E.

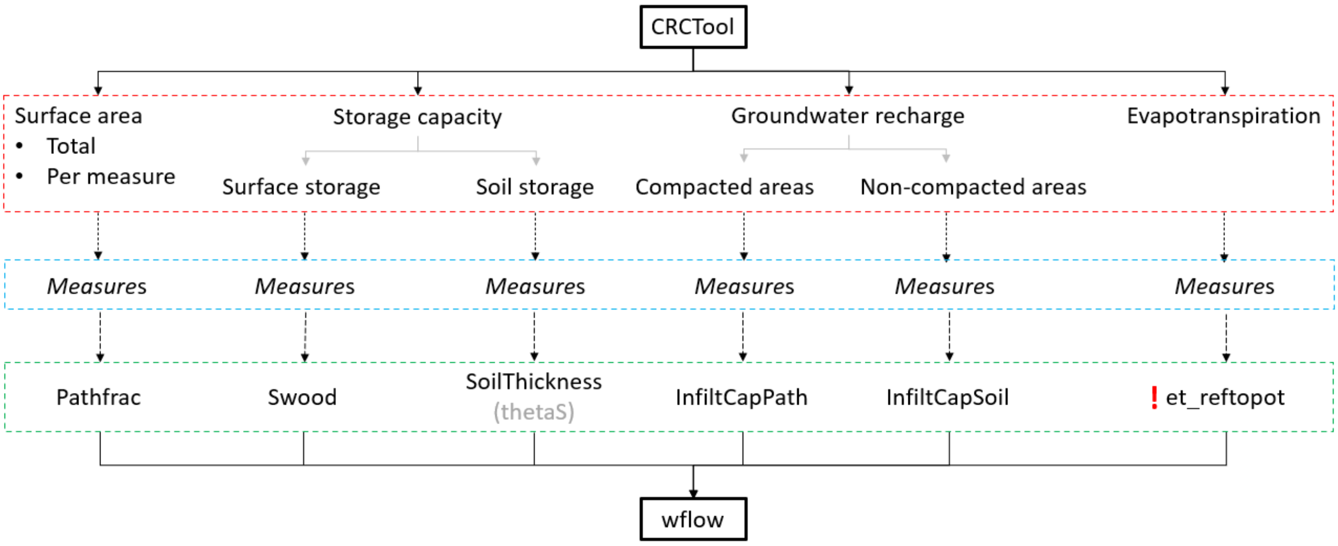

Figure 11 Conversion of CRCTool output to wflow model parameters

This conversion of the wflow parameters Swood, InfiltCapPath, InfiltCapSoil, SoilThickness, et_reftopot and PathFrac in the urban pixels to the new values $_{u,new}$ will be done using the following formulas:

$$Swood_{u,new} = Swood_u + \frac{S_s}{A_t} * 1000 \qquad \text{(mm)}$$

$$InfiltCapPath_{u,new} = InfiltCapPath_u + \frac{I_{gw,c}}{365} \qquad \text{(mm/day)}$$

$$InfiltCapSoil_{u,new} = InfiltCapSoil_u + \frac{I_{gw,nc}}{365} \qquad \text{(mm/day)}$$

$$SoilThickness_{u,new} = SoilThickness_u + \frac{S_s}{A_t * thetaS} \qquad \text{(m)}$$

$$et_{reftopot_{u,new}} = et_{reftopot_u} * \ et\_reftopot_e \qquad \text{(-)}$$

$$PathFrac_{u,new} = PathFrac_u * (1 - \frac{A_{path}}{A_t}) \qquad \text{(-)}$$

where $Swood_u$, $InfiltCapPath_u$, $InfiltCapSoil_u$, $SoilThickness_u$, $et\_reftopot_u$ and $PathFrac_u$ are the original wflow parameter values in the urban pixels, S_s the total additional surface storage, A_t the total area of the neighbourhood, $I_{gw,c}$ the total additional groundwater infiltration for the compacted areas, $I_{gw,nc}$ the total additional groundwater infiltration for the noncompacted areas, thetaS the original urban porosity in the wflow model and A_{path} the area of measures that reduce the paved area. The estimated $et\_reftopot_e$ is set to 1.2 for all urban areas in the new scenarios. This was chosen since the values from the CRCTool in the order of magnitude of a few mm/year evapotranspiration increase are estimated to be insignificantly low and cannot directly be converted to the unitless parameter Etreftopot. The staticmaps.nc file will be modified by adding et_reftopot as an explicit variable that can be changed in Python.

Analysing results

For the analysis of the model output, the output data will be analysed in Python. This analysis will mainly focus on absolute and percentage discharge changes relative the the original situation. Next to this, the change in wflow parameters will briefly be discussed.

4. Results

The previous chapter provided the methodology of this research to answer the three research questions posed in the introduction. In this chapter, the results are presented. Section 4.1 dives into the results regarding the neighbourhood and UNbS selection. After this, section 4.2 considers the effect of the UNbSs on local scale. Finally, section 4.3 presents the results regarding the effect of the UNbSs on catchment scale.

4.1 Urban Nature-based Solution selection

Based on the neighbourhood typology map of the Klimaateffectatlas, 7 (out of 16 predefined) types of neighbourhoods were identified in the Dutch part of the Geul catchment: working-class neighbourhood, garden town low-rise, post-war neighbourhood, residential neighbourhood, vinex, villa and industrial (in Dutch, respectively: “volkswijk”, “tuinstad laagbouw”, “naoorlogse woonwijk”, “bloemkoolwijk”, “vinex”, “villa” and “bedrijven”). An overview of the location of these neighbourhoods in the catchment can be found in Figure 12.

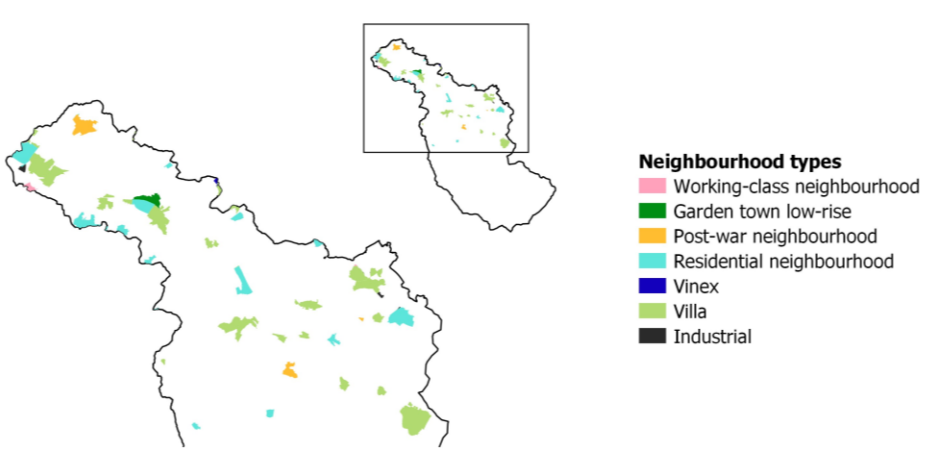

Figure 12 Overview of the different neighbourhood types in the Dutch part of the Geul catchment

There are 55 neighbourhoods indicated in total in the Dutch part of the catchment. How they are distributed in number and surface area, as well as their indicative vulnerability to waterlogging, is depicted in Table 4 below:

Table 4 Number of neighbourhoods per type, their percentage distribution regarding number and surface area, and their indicative vulnerability to waterlogging

	Type	Neighbourhoods (-)	Percentage of total number of neighbourhoods (%)	Percentage of total surface area of neighbourhoods (%)	Indicative vulnerability to waterlogging
	Villa	27	49.1	50.7	💧
	Residential neighbourhood	17	30.9	38.5	💧
	Industrial	3	5.5	0.8	💧
	Post-war neighbourhood	3	5.5	5.8	💧💧
	Vinex	2	3.6	0.3	💧
	Working-class neighbourhood	2	3.6	1.8	💧💧
	Garden town low-rise	1	1.8	2.2	💧💧

Most neighbourhoods are classified as villa and residential neighbourhood, both in the number of neighbourhoods (together 80%) and the total surface area that they cover (together 89.2%). The other 5 types of neighbourhoods account for 20% and 10.8%, respectively. Given the low total number of neighbourhoods, it is not possible to identify how exactly the different types are distributed over the area, although villa and residential neighbourhood seem to be evenly distributed. Additionally, there are no neighbourhood types with a high indicative vulnerability to waterlogging. Most neighbourhood area (90.3%) indicated with a low vulnerability to waterlogging. Post-war neighbourhood, working-class neighbourhood and garden town low rise are the 3 types of neighbourhoods with a medium vulnerability indication.

Based on occurrence and vulnerability, the following 3 neighbourhoods have been selected for further investigation: Broekhem and Stoepert in Valkenburg, and Rothem. The location of these neighbourhoods is indicated in Figure 15. Stoepert (garden town low-rise) and Rothem (working-class neighbourhood) are chosen based on their relatively high vulnerability to waterlogging. Broekhem (residential neighbourhood) is chosen based on the high occurrence of the type of neighbourhood.

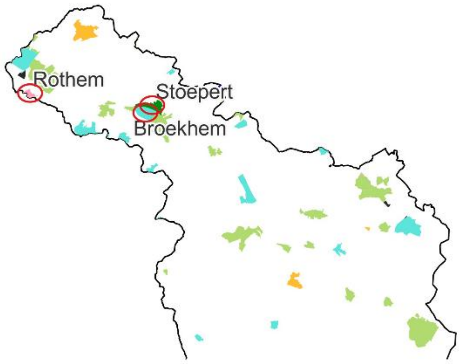

Figure 13 Selected neighbourhoods

Given the scope of this research and knowing that the area is sloping and with a low groundwater table, measures have to comply with the following criteria:

- Effective against drought and/or flood prevention
- Effective on neighbourhood, street and/or building scale
- Effective on high and sloping areas

This initially eliminates 13 out of 37 available options in the Selection tool score table, leaving 24 measures as depicted in Appendix F.

After assessing the 3 neighbourhoods selected in the previous section (Broekhem, Stoepert and Rothem) and expert discussions for potential areas suitable for UNBS, the water roof measure was reassessed. Combined with the suitable area, the combinations of measures and corresponding locations have finally been chosen as depicted in Table 5 below:

Table 5 Final selection of 6 measures for 7 different types of locations

Location	Measure
Roofs	Green roof / water roof
Roads / pavement / parking lots	Permeable pavement
Private properties	Removing pavement to plant green
Open surface water	Retention pond
Grass areas	Bioswale

4.2 Local effect analysis

Figures 14, 15 and 16 show the layout after drawing the measures into the CRCTool for Broekhem, Stoepert and Rothem, respectively. For the full-page sized figures, the reader is referred to Appendix G. As can be seen from these figures, the retention pond measure has only been applied in Broekhem.

Figure 14: Urban Nature-based Solution layout for Broekhem

Figure 15: Urban Nature-based Solution layout for Stoepert

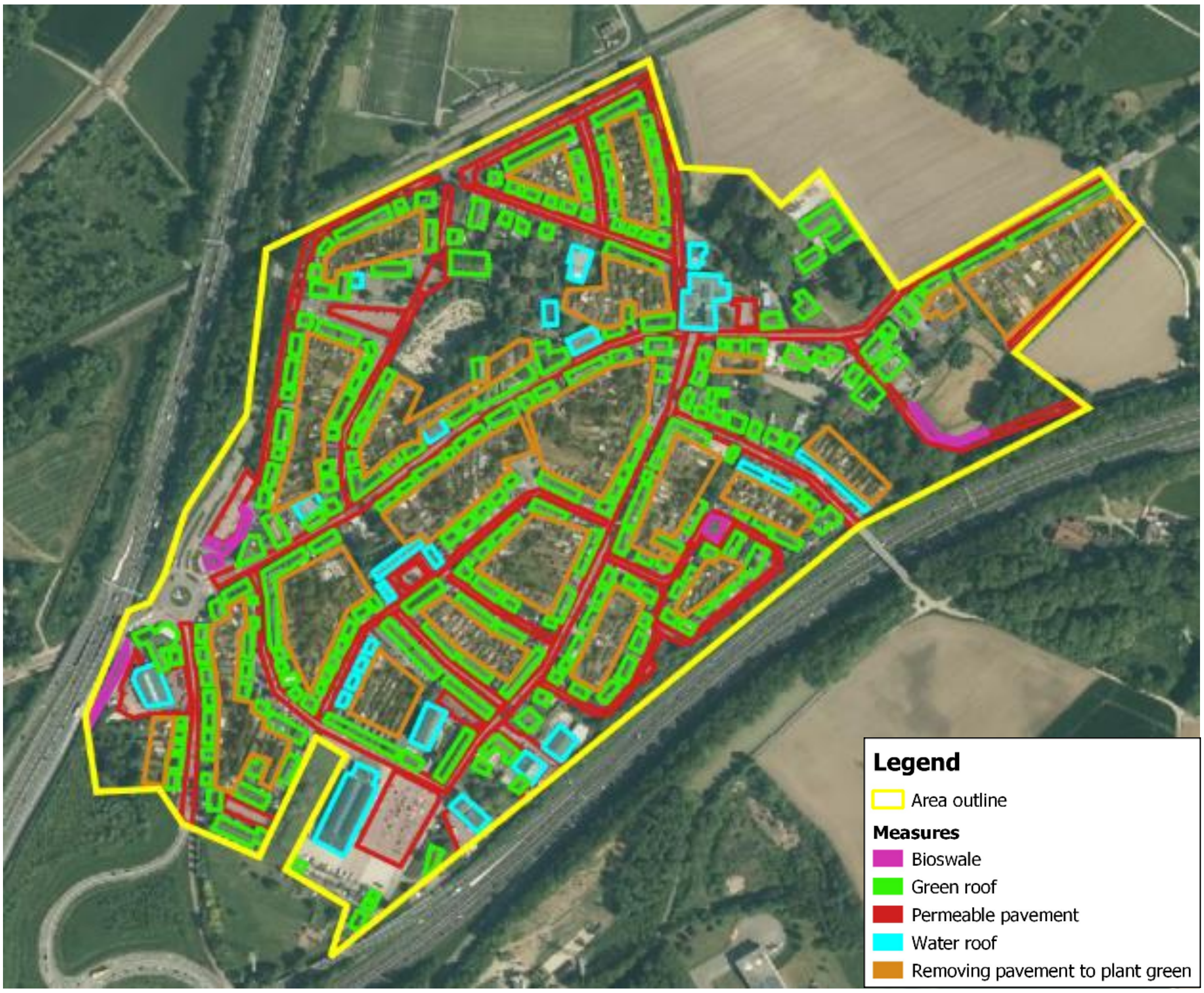

Figure 16: Urban Nature-based Solution layout for Rothem

For the analysis of the impact of the UNbS measures in the CRCTool, Table 6 presents the absolute contribution of the UNbS measures for each neighbourhood regarding storage capacity, groundwater recharge and evapotranspiration.

Table 6 Additional storage capacity, groundwater recharge and evapotranspiration contribution of each of the UNbS measures for the different neighbourhoods

	Storage capacity (m^3)			Groundwater recharge (mm/year)			Evapotranspiration (mm/year)		
Measure	Broekhem	Stoepert	Rothem	Broekhem	Stoepert	Rothem	Broekhem	Stoepert	Rothem
Bioswales	3152	2433	593	30	24	8	0	0	0
Green roofs	616	546	521	0	0	0	6	6	11
Permeable pavement	6521	7981	4633	4	5	6	15	20	18
Water roofs	1059	3576	1153	0	0	0	1	4	3
Retention pond	2304	-	-	3	-	-	0	-	-
Remove pavement to plant green	5644	2962	6047	10	6	22	13	8	24
Total	19296	17498	12947	47	35	36	35	38	56

Of all three neighbourhoods, Broekhem has the highest increase in storage capacity and groundwater recharge, while Rothem has the highest evapotranspiration increase. For all three neighbourhoods, most storage capacity and evapotranspiration is gained through implementation of permeable pavement, while most groundwater recharge is gained through bioswales.

Accounting for the difference in surface area per neighbourhood (with Broekhem being around 0.50 km^2, Stoepert 0.44 km^2 and Rothem 0.39 km^2) allows to analyse the relative contribution of each measure. Splitting up the storage capacity into surface storage (for green roofs, water roofs and retention ponds) and soil storage (bioswales, permeable pavement and remove pavement to plant green) and dividing this by the surface area of each neighbourhood gives the result as presented in Table 7 and Figure 17. For all three neighbourhoods, the soil storage is around 30 mm equivalent and the surface storage between 4- and 9-mm equivalent. Considering the total storage capacity, all three neighbourhoods show the same order of magnitude of between 34- and 39-mm storage equivalent over the total surface area of the neighbourhood.

Table 7: The total storage equivalent for each neighbourhood

Neighbourhood	Storage (m^3)	Surface area neighbourhood (m^2)	Storage equivalent (mm)
Broekhem	19296	495185	39
Stoepert	17498	438482	40
Rothem	12947	386114	34

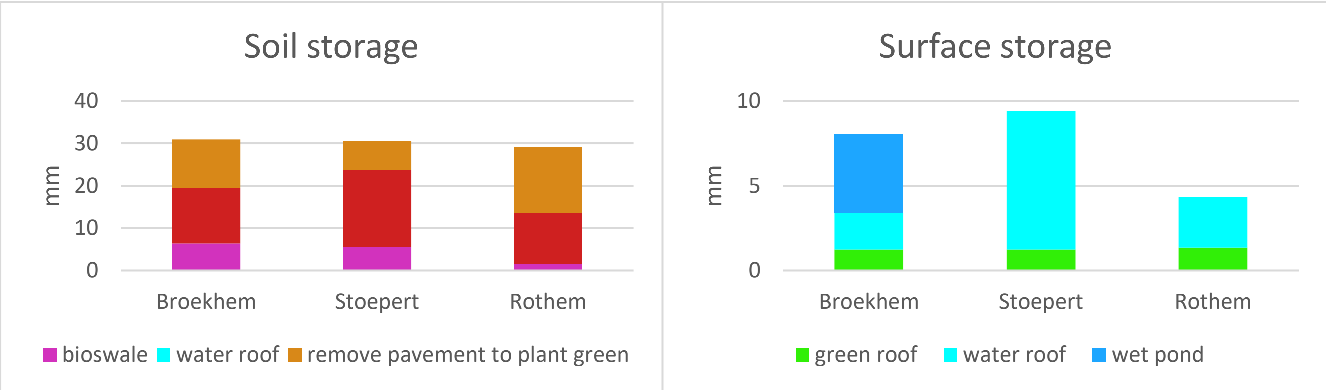

Figure 17: Storage (mm) per measure over the total neighbourhood surface area per neighbourhood

Table 8 and Figures 18, 19 and 20 show this relative contribution of each of the measures per neighbourhood. Green roofs in general have the least impact regarding storage capacity with 3 to 4%, while permeable pavement and removing pavement to plant green make up for 63 to 83% of the extra storage capacity in the neighbourhoods. Where Broekhem and Stoepert gain most recharge through bioswales with respectively 60 and 69% of the total groundwater recharge increase, Rothem gains most recharge through removing pavement to plant green with 61%. Similarly as for the storage capacity, the evapotranspiration gains most by permeable pavement (between 32 and 53%) and removing pavement to plant green (between 21 and 44%).

Table 8: Relative surface area covered by each measure per neighbourhood

Measure	Percentage of total surface area (%)		
	Broekhem	Stoepert	Rothem
Bioswale	1.8	1.4	0.3
Green roof	12.4	11.0	10.5
Permeable pavement	13.2	16.1	9.4
Water roof	2.1	7.2	2.3
Wet pond	1.6	-	-
Remove pavement to plant green	15.2	8.0	16.3
Total	46.3	43.7	38.8

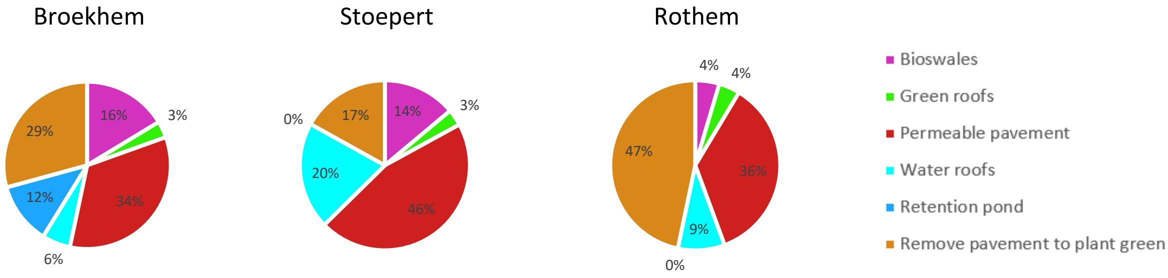

Figure 18: Relative storage capacity per measure per neighbourhood

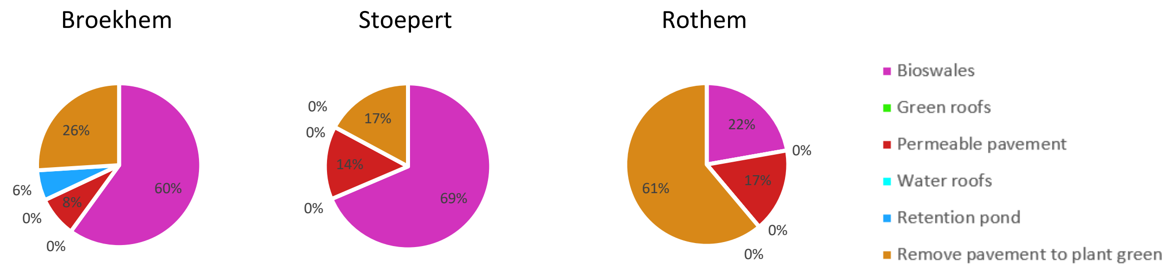

Figure 19: Relative groundwater recharge per measure per neighbourhood

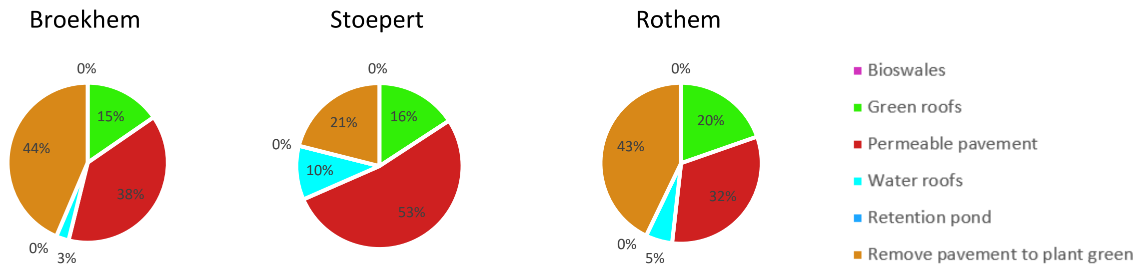

Figure 20: Relative evapotranspiration per measure per neighbourhood

Although both in absolute sense and relatively over the total area of the neighbourhood Broekhem has most surface area dedicated to UNbS measures, the amount of measures are in the same order of magnitude for all neighbourhoods. Also, since Stoepert is partially industrial terrain with many flat roofs, this neighbourhood lends itself more for water roofs but has less private property which can be used for the measure “Remove pavement to plant green”. Finally, fewer opportunities were found to implement bioswales in Rothem. Overall, although there are differences between the different neighbourhoods and measures, the order of magnitude for each of them is the same considering their surface area differences.

4.3 Hydrological effect analysis

After changing the wflow parameters according to the calculations as were presented in the methodology chapter, Swood changes from a maximum of 0.5 mm to a maximum in the range of 4.60 to 9.65 mm, depending on the neighbourhood. Similarly, PathFrac reduces from a maximum of 0.998 to a range of 0.726 to 0.670. The other four parameters change minimally, especially in the case of parameters InfiltCapPath and InfiltCapSoil. The tables with the full overview of all parameters and their changes can be found in Appendix H.

This analysis focusses on the impact of the implemented Urban Nature-based Solutions on catchment scale for the three different neighbourhoods or scenarios in the location of the three different gauging station locations as indicated in Figure 21. The absolute discharge differences compared to original situation can be seen in the hydrograph of Figure 22 and 23, in which Figure 22 highlights peak discharge periods and Figure 23 highlights low discharge periods. These Figures show a consistent trend in the discharge data over the full timeseries, as the difference in m3/s is predominantly negative, indicating a general reduction in discharge. Qualitatively, the magnitude of this reduction aligns closely with the peaks of the hydrograph of the original situation, which can be found in Appendix I. Periods with higher discharges experience more absolute reductions and lower discharge periods experience comparatively smaller reductions.

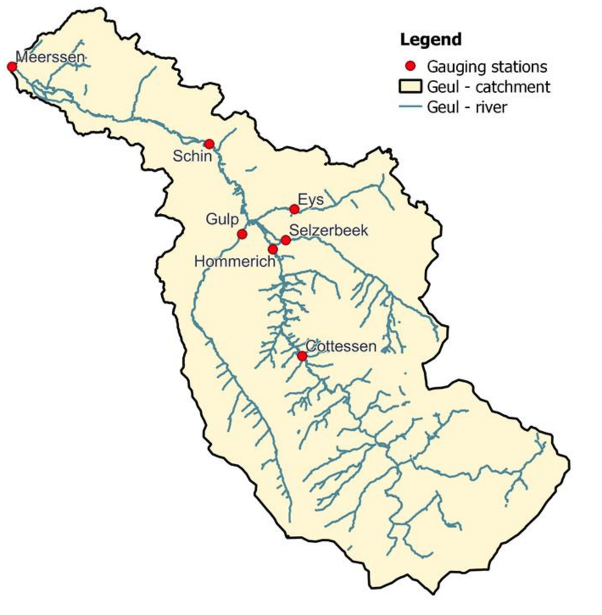

Figure 21 The location of the seven gauging stations

Table 9 shows the absolute average values of the difference in discharge for all neighbourhoods together in terms of minimum, maximum, mean, median, and standard deviation. Average values are chosen since the differences between the values of the three different neighbourhoods are minimal. The different values for every neighbourhood separately can be found in Appendix J. As the average values show, the minimum values can vary from -4.87 to -0.15 m3/s relative to the original state, but the maximum, mean, median, and standard deviation values across all measurement stations are clustered around 0 and 0.1.

Table 9 Absolute average values of the difference in discharge for all neighbourhoods

	Location	Min	Max	Mean	Median	Standard deviation
Difference with original discharge [m3/s]	Meerssen	-4.87	0.00	-0.07	-0.04	0.12
	Schin op Geul	-4.02	0.00	-0.06	-0.04	0.11
	Eys	-0.74	0.03	0.00	0.00	0.01
	Gulp	-0.15	0.11	-0.01	0.00	0.01
	Selzerbeek	-0.19	0.06	0.00	0.00	0.01
	Hommerich	-3.62	0.02	-0.04	-0.03	0.10
	Cottessen	-3.73	0.00	-0.04	-0.03	0.09

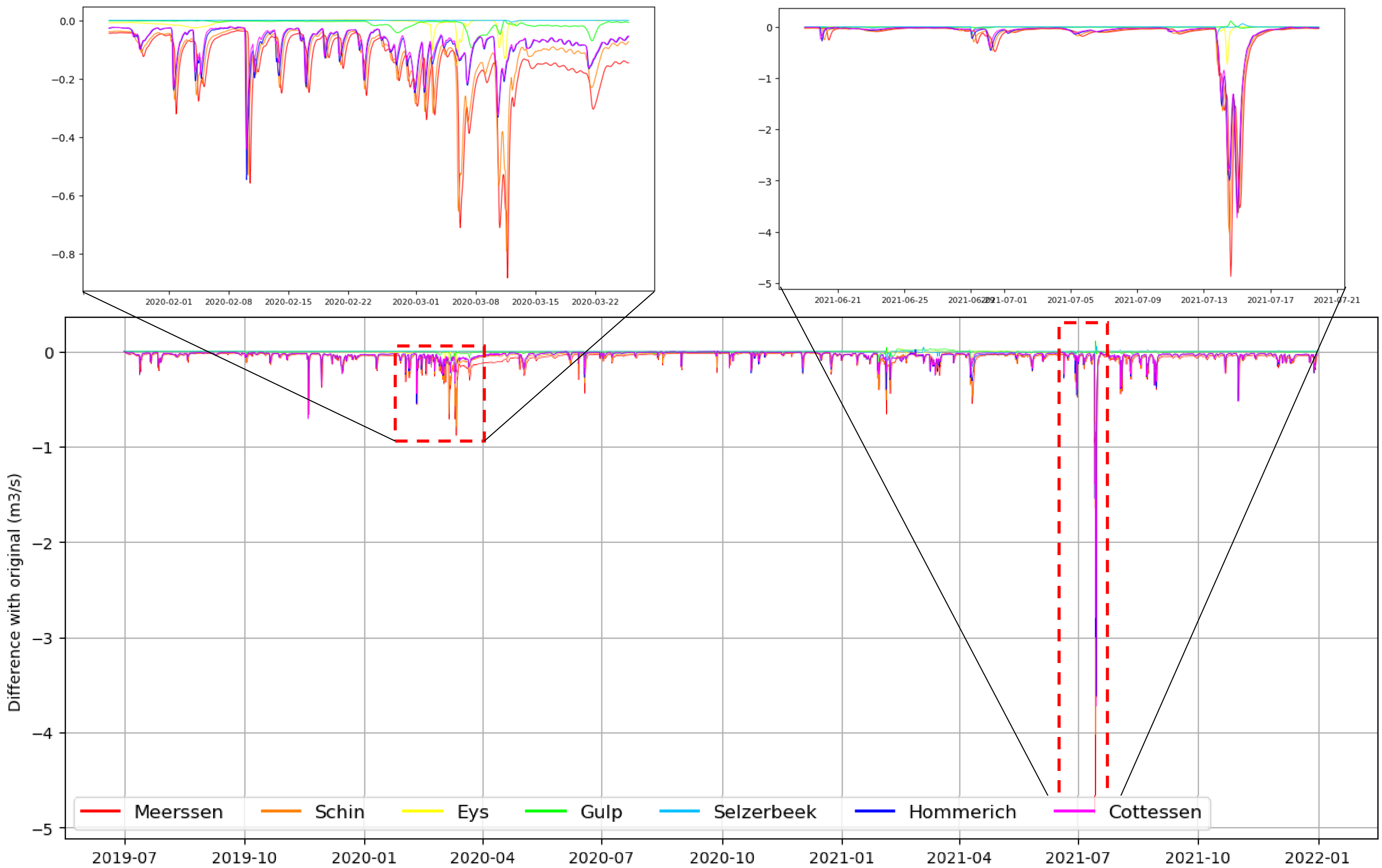

Figure 22: Absolute difference between the original discharge and average discharge of the three scenarios for the seven gauging stations in the period of July 2019 – January 2022. The zoomed-in graphs show peak discharges for periods of January 25, 2020 – March 25, 2020 and June 19, 2021 – July 19, 2020.

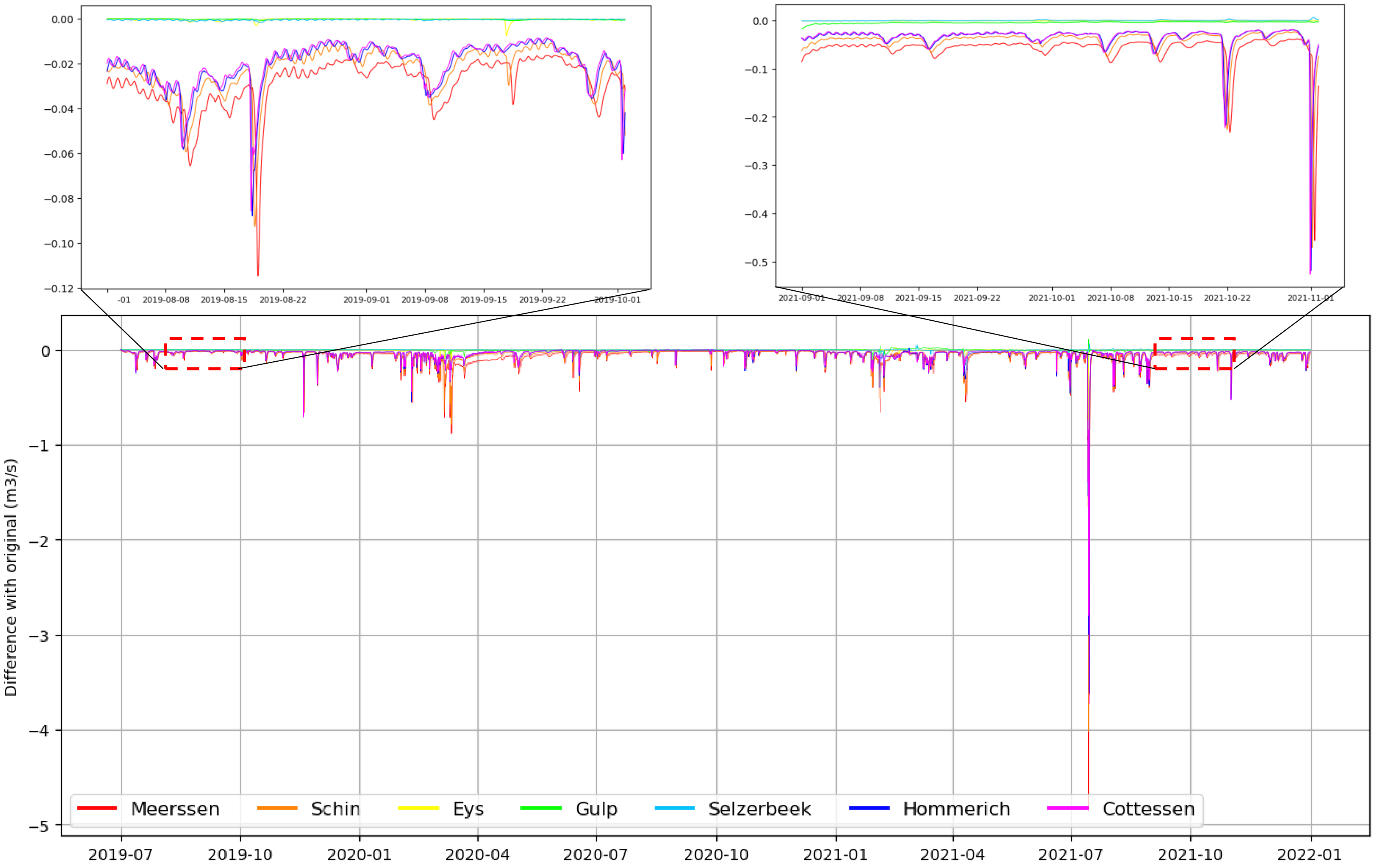

Figure 23: Absolute difference between the original discharge and average discharge of the three scenarios for the seven gauging stations in the period of July 2019 – January 2022. The zoomed-in graphs show low discharges for periods of August 1, 2019 – October 1, 2019 and September 1, 2021 – November 1, 2021.

However, examining the percentage difference between the original and altered flows reveals a less clear trend as is shown in Figure 24. Despite notable absolute negative differences in flow, the percentage differences fail to distinctly distinguish between high and low discharge periods.

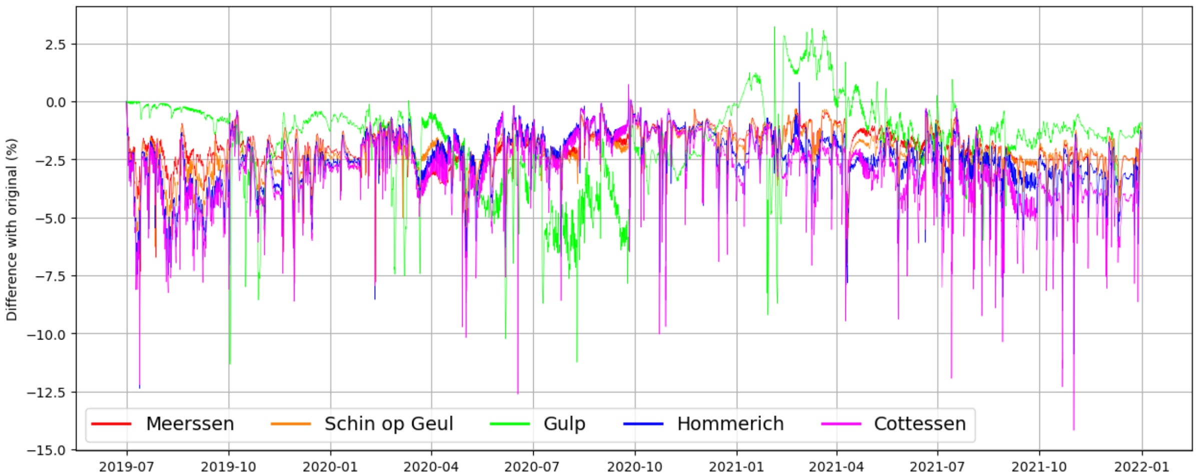

Figure 24 Percentage difference between the original discharge and average discharge of the three scenarios for five gauging stations in the period of July 2019 – January 2022.

In terms of percentage differences, except for Eys and Selzerbeek, a similar pattern emerges. Table 10 has a similar format as Table 9. However, it shows the difference in percentage compared to the original situation. Upstream measurement points tend to exhibit larger percentage differences than downstream points, likely due to lower discharges being more susceptible to errors and model adjustments. On average, the discharge decreases within a range of 1.71% to 3.10%. Ultimately, the three scenarios (Broekhem, Stoepert, and Rothem) show minimal differences relative to each other, all falling below 0.1%, which is a negligible difference in practical terms.

Table 10 Percentage average values of the difference in discharge for all neighbourhoods

	Location	Min	Max	Mean	Median	Standard deviation
Difference with original discharge [%]	Meerssen	-8.78	-0.04	-2.00	-1.97	0.85
	Schin op Geul	-9.49	-0.04	-2.17	-2.11	0.95
	Eys	**-46.33**	**92.18**	**-2.02**	**-0.68**	**6.24**
	Gulp	-11.33	3.22	-1.72	-1.37	1.87
	Selzerbeek	**-100.00**	**1.25e+24**	**5.78e+19**	**-1.13**	**8.46e+21**
	Hommerich	-12.37	0.82	-2.52	-2.41	1.26
	Cottessen	-14.18	0.73	-3.01	-2.81	1.51

As already mentioned above, the results of the Eys and Selzerbeek are an exception and stand out. Eys exhibits a substantial difference in minimum and maximum values, likely attributed to consistently low flow, which renders it sensitive to measurement errors and model adjustments. Selzerbeek has a peculiar moment where the original discharge is nearly zero, significantly skewing the statistics, indicating a need for corrections before making meaningful interpretations about this tributary's hydrograph.

5. Discussion

The results in the previous chapter indicate that the implementation of Urban Nature-based Solutions in the Geul catchment can locally increase the storage capacity and, on catchment scale, reduce discharges. Before any final conclusions can be drawn regarding these results, some discussion points will be addressed. Section 5.1 covers the interpretation of the results, discussing whether they meet expectations and explaining any unexpected results. Section 5.2 follows by acknowledging the limitations of this research.

5.1 Interpretations

5.1.1 Relevance of neighbourhood classification

There are 7 different types of neighbourhoods, of which three were selected to further investigate. Locally, we see some differences in the types of measures that can be applied and their relative contributions to the storage capacity, groundwater recharge and evapotranspiration, but the impact of all three neighbourhoods are relatively in the same order of magnitude. At catchment level, these differences are not even longer significant relative to each other. This means that, to assess the effect of UNbS on catchment scale, selecting one neighbourhood and extrapolating the local results for this neighbourhood for the entire catchment gives reliable results of their implementation on large scale.

5.1.2 CRCTool output

The storage capacity data obtained from the CRCTool reveals an expected order of magnitude. As Van Der Steen (2022) stated, natural solutions were found to have an adaptive capacity of roughly 20 mm equivalent upstream of Valkenburg and 24 mm equivalent in Valkenburg itself, which is in the same order of magnitude as the 34 to 40 mm found in this research.

However, both groundwater recharge and evapotranspiration values appear to be exceptionally low, measured in millimeters per year (mm/year). The lack of clarity regarding how these values are calculated, hinders the ability to assess the underlying reasons for the observed order of magnitude.

Moreover, it is important to acknowledge that some measures within the CRCTool show no contributions to groundwater recharge and evapotranspiration, due to certain model assumptions. Notably, green roofs and water roofs are not integrated into the soil component of the CRCTool, resulting in their exclusion from groundwater recharge calculations. Similarly, bioswales, designed to replace areas already covered by grass, are assumed not to contribute to the total evapotranspiration. However, in practical scenarios, these assumptions underestimate the actual contributions of green roofs, water roofs, and bioswales. For instance, enabling a linkage between green roofs and the soil could enhance groundwater recharge. Furthermore, bioswales tend to retain water more effectively than regular grass areas, preserving the grass in better condition and potentially resulting in increased evapotranspiration. It is also worth noting that wet ponds, which are assumed to raise the water level in existing bodies of water, are assumed to not add to evapotranspiration. This assumption appears to be justifiable, given the energy-limited nature of the climate within the catchment and since in most cases, the region already features an ample supply of water relative to evaporation rates.

5.1.3 Storage solutions

An additional observation is that, across all three neighbourhoods, the soil storage, with an approximate depth of 30 mm equivalent, is considerably larger than the surface storage, which ranges between 4 and 9 mm equivalent. This can be attributed to two main factors. Firstly, the soil storage measures encompass roughly twice the area in each neighbourhood, constituting 30.2% of the total area for Broekhem, 25.2% for Stoepert, and 26% for Rothem, as opposed to the surface storage, which accounts for 16.1%, 18.5%, and 12.8%, respectively. Additionally, these soil storage measures possess a greater storage depth and inflow area allocation in the CRCTool, ultimately resulting in a higher storage equivalent.

5.1.4 Wflow output

The unexpected constant reduction in baseflow observed in the hydrographs contradicts the anticipated behavior of Urban Nature-based Solutions, which are designed to attenuate and smooth peak discharges while boosting base flows.

It is plausible that the heightened storage capacity might be underestimating baseflow during dry periods. Klein (2022) emphasizes that soil storage capacity is not always correctly reflected in wflow. Investigating the influence of changes in Swood, influencing surface storage, and SoilThickness, influencing soil storage, could provide valuable insights into this phenomenon. Another potential explanation lies in the impact of the model parameter Etreftopot, which elevates evapotranspiration rates. It's possible that the model has become overly sensitive to excessive evapotranspiration, causing water to evaporate before reaching the stream. An assessment of the sensitivity of this parameter is necessary to gain a better understanding of its role in the observed reductions in baseflow. Similarly, the increase in groundwater infiltration, facilitated by the wflow parameters InfiltCapPath and InfiltCapSoil, could be contributing to this.

The unexpected constant reduction in baseflow can therefore be a model artefact, for which a parameter sensitivity analysis should be needed to understand how this can be improved.

5.2 Limitations

5.2.1 Manual implementation of UNbS measures

Given that the primary goal of this research was to assess the maximum potential of Urban Nature-based Solutions, the solution space, which was manually generated, may have been more optimistic than practically can be realized, leading to unrealistic implementation of UNbS.

During a visit to one of the neighbourhoods, Broekhem, this point was underscored by a specific example depicted in Figure 25. In this illustration, we correctly identified both parking lots, but a closer examination revealed a discrepancy. The leftmost parking lot could benefit from improvements through the implementation of permeable pavement. However, the rightmost parking lot was already constructed with gravel and bare soil underneath, rendering it unsuitable for further enhancement through permeable pavement. Similarly, in a discussion with a policy officer for water and sewerage in the municipality of Valkenburg, it was mentioned that the open waterbody designated as a retention pond in this research is situated within the boundaries of the Valkenier amusement park. Plans have been approved for constructing additional buildings on this land (personal communication, September 26, 2023), rendering this specific solution impractical. Instead, there may be potential for green roofs and water roofs to gain ground in this context.

These examples serve to emphasize the necessity of obtaining additional information beyond what remote investigation can provide to create a more realistic representation of solution spaces. This may involve tapping into more extensive data sets, conducting on-site visits to the study area, or engaging in conversations with local policy makers.

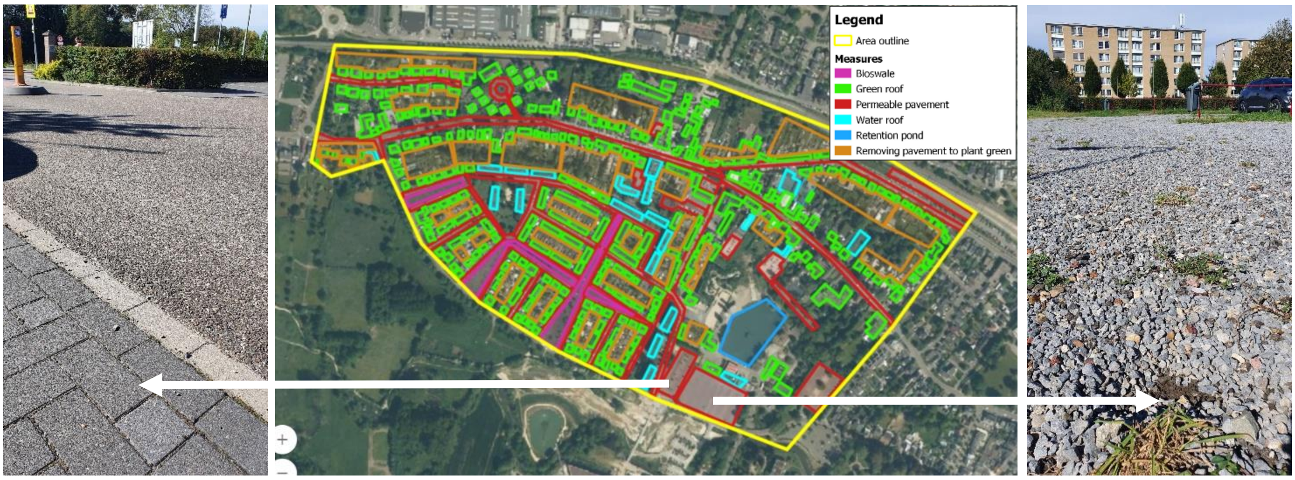

Figure 25 Two parking lots in Broekhem, where the left parking lot is fully paved and the right parking lot covered in gravel

5.2.2 Practical implementation

Aside from these practicalities, implementation of the UNbS measures depends on more than their technical feasibility and site suitability. However, no combination of measures can achieve the 2050 adaptation goal set by the Netherlands (Van Der Steen, 2022). Next to this, cooperation quality was found to likely not be sufficient between many actors to implement very intrusive adaptation measures. These issues should be tackled to optimize the implementation and effect of Urban Nature-based Solutions.

5.2.3 Neighbourhood typology map

The neighbourhood typology map used to selected representative neighbourhoods has its constraints. The typology interpretation occurs at the postcode 6 level, where homogeneity is assumed. However, in the Geul catchment, such homogeneity is often lacking. The cities and villages in the area of the Geul are often indicated at postcode 6 level due to their small size. However, their layout is often more diverse, accommodating more types of neighbourhood classifications on smaller scale. Unlike larger cities like Amsterdam and Deventer, where the GIS-based determination works well, neighbourhood sub-assignment isn't feasible at this level. While the methodology performs well in assigning typologies for many neighbourhoods, some types, such as villa types, cauliflower neighbourhoods, and post-war housing estates, require refinement.

5.2.4 Crctool

Some areas for improvement include the lack of transparency in the CRCTool regarding how processes are calculated and what reasonable ranges for measure are. The precise scripts and calculations used in the online tool are neither easily accessible nor easily understood. Also (Keesmaat, 2023), focusing on the UrbanWB model, documents that there are a lot of uncertainties surrounding Nature-based Solutions and that variation in the parameters could potentially have a significant impact on the effectiveness of the measures. A further look into the way the online CRCTool is modelled and the assumptions behind it is therefore advisable.

5.2.5 Wflow model

Klein (2022) suggests that a finer resolution of 0.000833°, rather than the current 0.00833°, might be necessary for studying land-use effects. However, in the Geul catchment, it's not necessary for improving the model, especially when there are no land use changes (Klein, 2022). In general, resolutions smaller than 1 km x 1 km do not enhance wflow models (Aerts et al., 2022). Still, increasing the resolution could better represent urban areas and potentially include roads as preferential flow paths, which are not in the current model.

Not all sub-catchments were equally well calibrated in Klein's model, with four out of five having an NSE lower than 0.5 due to the emphasis on overall performance. Moreover, the application scale of (pedo)transfer functions is uncertain (van Verseveld et al., n.d.), and parameter calibration is needed for non-physically based parameters like KsatHorFrac (Aerts et al., 2022). No sensitivity analysis for wflow parameters, including KsatHorFrac, has been performed in this research, which is recommended for a better understanding of parameter settings. Klein (2022) calibrated KsatHorFrac in a six-month period in 2020, but it overestimated flows in 2021, indicating the need for recalibration.

5.2.6 Scope

The study suggests that Urban Nature-based Solutions alone may not effectively prevent major flood events and might not be suitable for implementation. To grasp their true impact, it's crucial to expand our perspective beyond urban areas and consider Nature-based Solutions and their application in various landscapes. While urban nature-based solutions address urban issues, the full potential of Nature-based Solutions extends to rural, suburban, and natural environments.

In contemplating the impact of climate change on a catchment, it becomes increasingly clear that the relevance and effectiveness of Urban Nature-based Solutions (UNbS) may grow in significance. Climate change is altering weather patterns, intensifying extreme events, and raising the stakes for sustainable resource management. As temperatures rise, so does the likelihood of more frequent and severe droughts, as well as increased precipitation in some regions, leading to flooding and water management challenges. UNbS, with their capacity to mitigate flooding, regulate stormwater, and enhance groundwater recharge, become indispensable in such scenarios. These solutions not only reduce the burden on conventional infrastructure but also help in preserving water resources.

Moreover, as climate change accelerates, the role of UNbS in urban cooling and mitigating the urban heat island effect gains prominence. They offer shade, improve air quality, and make urban environments more livable during heatwaves, thus safeguarding public health. Considering these dynamics, it's evident that UNbS will become even more relevant in the context of climate change adaptation and mitigation. Their multifaceted benefits encompass climate resilience, resource conservation, and overall urban well-being, making them a critical component of our sustainable future. In a world increasingly shaped by climate change, the value of nature-based solutions cannot be overstated.

6. Conclusion and recommendations

Given the current challenge regarding climate change induced floods for the Geul catchment and the hydrological negative effect urban areas impose, Urban Nature-based Solutions (UNbSs) might provide a solution. This research aimed to determine a methodology for selecting, modeling, and evaluating the performance of UNbSs and improve the modeling aspects of UNbS implementation in the Geul catchment.

This research succeeded in developing a methodological workflow that allows to parameterize the hydrological effect of UNbSs and model this effect on catchment scale. This was achieved by a combined approach of analysis and modelling. The selection of suitable UNbSs was performed through a neighbourhood assessment and a selection of measures on several datasets and discussions. The local hydrological effect and on catchment scale were analysed through the output of drawn UNbS measures in the online Climate Resilient City Tool (CRCTool) and the modelled output of a hydrological wflow_sbm model, respectively. To conclude, the research questions are answered as follows:

1. *Which Urban Nature-based Solutions are suitable for the Geul catchment?*
   Three different types of neighbourhoods were selected to investigate the most suitable UNbSs for the Geul catchment: a residential neighbourhood (Broekhem), garden town low-rise (Stoepert) and working-class neighbourhood (Rothem). Based on the analysis of these three neighbourhoods, the following six measures were deemed most suitable and were implemented: green roof, water roof, permeable pavement, removing pavement to plant green, retention pond and bioswale.

2. *What is the hydrological effect of these Urban Nature-based Solutions locally?*
   Locally, for all three neighbourhoods, most storage capacity and evapotranspiration is gained through implementation of permeable pavement, while most groundwater recharge is gained through bioswales. However, although there are differences between the different neighbourhoods and measures, the overall order of magnitude for each of them is the same considering their surface area differences. Considering the total storage capacity increase, all three neighbourhoods show the same order of magnitude of between 34- and 39-mm storage equivalent over the total surface area of the neighbourhood.

3. *What is the hydrological effect of Urban Nature-based Solutions at catchment scale?*
   On a catchment scale, the average discharge exhibits a reduction ranging from 1.71% to 3.10% as a consequence of the implementation of the UNbSs. This percentage varies according to the specific locations within the catchment, with a more pronounced effect observed upstream than downstream. In the context of the implementation, the three distinct neighbourhood scenarios (Broekhem, Stoepert and Rothem) show minimal differences relative to one another, all of which fall below 0.1%. This negligible difference holds no practical significance. Furthermore, the absolute decrease in discharge follows a consistent pattern across low and high discharge periods, with larger reductions observed during peak periods and vice versa. However, this trend becomes less apparent when examining the percentage difference between the original and altered discharge, as it demonstrates a similar proportional decrease across all periods.

Based on the research, the following recommendations are done:

- **Improve model transparency and sensitivity analysis:** Enhance the transparency of the CRCTool, conduct sensitivity analyses for various wflow parameters, and refine the model assumptions to gain a better understanding of its calculations and improve accuracy.
- **Consider practical implementation challenges:** Recognize that the implementation of UNbSs depends not only on technical feasibility but also on practical considerations, including cooperation among stakeholders and adherence to adaptation goals.
- **Refine typology mapping and data:** Refine the neighborhood typology mapping process, accounting for local heterogeneity and variations, and use more extensive data sets or on-site visits to create realistic representations of solution spaces.
- **Evaluate NbSs in diverse landscapes:** Recognize that the effectiveness of NbSs extends beyond urban areas and should be evaluated in various landscapes, including rural, suburban, and natural environments, to address broader climate change challenges.
- **Promote the role of UNbSs in climate resilience:** Emphasize the significance of UNbS in climate adaptation and mitigation, particularly in the context of climate change-induced challenges such as droughts, extreme events, flooding, and urban heat island effects, and promote their multifaceted benefits for urban well-being and sustainability.

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Appendix A: Neighbourhood types

DOMINANT NEIGHBOURHOOD TYPOLOGY (Dutch / English)	BUILDING PERIOD	CHARACTERISTICS	INDICATIVE VULNERABILITY WATERLOGGING
Historische binnenstad / Historic center	Before 1900	lots of pavement, 3-5 storeys, monumental greenery	💧💧💧
Stedelijk bouwblok / Urban block	Before 1940	no front garden or green belt, 4-8 storeys	💧💧💧
Vooroorlogs bouwblok / Pre-war block	1900-1940	not always front garden, 3-4 storeys, wider streets than stedelijk bouwblok and sometimes green belt	💧💧💧
Tuindorp / Garden village	1910-1940	spacious front and back gardens, 2-3 storeys, lots of longitudinal parking, 1930s building style, limited municipal greenery, often no street trees	💧💧💧
Volkswijk / Working-class neighbourhood	1910-1940	no front garden, little communal green space, 2-3 storeys, single-family houses	💧💧
Tuinstad laagbouw / Garden town low-rise	1945-1960	open blocks with lots of greenery, 2-3 storeys, single-family houses	💧💧
Tuinstad hoogbouw / Garden town high-rise	1945-1970	open blocks with lots of greenery, 4-6 storeys, apartment blocks, storage on ground floor	💧💧
Naoorlogse woonwijk / Post-war neighbourhood	1945-1990	front and back gardens, 2-3 layers, single-family houses in a row, semi-detached or detached	💧💧
Bloemkoolwijk / Residential niehgbourhood	1970-1990	single-family houses with front and back gardens, winding street patterns, courtyards, wide green space around the neighbourhood	💧
Hoogbouw / High-rise	1945-heden	more than 10 storeys, buildings in grid	💧💧
Sub-urbane uitbreiding – Vinex / Sub-urban expension - Vinex	1990-heden	single-family houses in a row, semi-detached, detached, flats	💧
Vernieuwd / Renewed	1990-heden	renovation of existing buildings, often high densities	💧
Villa / Villa	Of all times	lots of space between houses, detached houses	💧
Bedrijven / Industrial	Of all times	Activity	💧

Table A1: Overview of all the neighbourhood types within the neighbourhood typology map with their characteristics and indicative vulnerability to waterlogging

Appendix B: CRCTool assessment criteria

□ is for settings for which multiple options can be selected, ○ is for single choice settings

English version

Scenario Name ○

- Low NL – Business Park
- Low NL – Closed urban building block
- Low NL – Community neighbourhood
- Low NL – Garden town
- Low NL – Historic city center
- Low NL – Garden town high-rise
- Low NL – Post-war garden city low-rise
- Low NL – Residential housing
- Low NL – Sub urban expansion (Vinex)
- High NL – Business Park
- High NL – Closed urban building block
- High NL – Community neighbourhood
- High NL – Garden town
- High NL – Historic city center
- High NL – Garden town high-rise
- High NL – Post-war garden city low-rise
- High NL – Residential housing
- High NL – Sub urban expansion (Vinex)

Climate Resilience Capacity □

- Heatstress
- Drought
- Pluvial flood
- Water safety

Multifunctional landuse ○

- Not important
- Important
- Very important

Scale level □

- City
- Neighbourhood
- Street
- Building

Existing space types □

- Grey – Paved surfaces
- Green intensive use
- Undeveloped land, green space without recreation
- Green areas and urban farming
- Green/grey – Sports and playground
- Red – Buildings
- Blue - Water

Sub-surface availability ○

- Very low
- Low

Dutch version

Wijktype ○

- Laag NL - Bedrijventerrein
- Laag NL - Hoogbouw centrum
- Laag NL – Bloemkoolwijk
- Laag NL – Tuinstad
- Laag NL – Historische binnenstad
- Laag NL – Tuinsteden hoogbouw
- Laag NL – Tuinsteden na 1940 laagbouw
- Laag NL – Volkswijk
- Laag NL – Vinex wijken
- Hoog NL – Business Park
- Hoog NL - Hoogbouw centrum
- Hoog NL – Bloemkoolwijk
- Hoog NL – Tuinstad
- Hoog NL – Historische binnenstad
- Hoog NL – Tuinstad hoogbouw
- Hoog NL – Tuinsteden na 1940 laagbouw
- Hoog NL – Volkswijk
- Hoog NL – Vinex wijken

Klimaat adaptatiedoel □

- Hittestress
- Droogte
- Wateroverlast
- Waterveiligheid

Belangrijkheid multi-functioneel landgebruik ○

- Beperkt belangrijk
- Belangrijk
- Zeer belangrijk

Schaalniveau □

- Stad
- Buurt
- Straat
- Gebouw

Bestaande ruimtetypes □

- Grijs – Bestraat oppervlak
- Groen intensief gebruik
- Braakliggend terrain en groen zonder recreatie
- Groen en stadslandbouw
- Groen/grijs – Sportterrein en speeltuin
- Rood – Gebouwen
- Blauw - Water

Ondergrondse beschikbaarheid ○

- Zeer lag
- Laag

- Medium
- High

Roof characteristic ○

- Flat roofs
- Roofs slope less than 35 deg
- Roofs slope more than 35 deg

Soil type ○

- Sand
- Peat
- Clay
- Bed rock

Slope ○

- Sloping area
- Flat area on high ground
- Flat area on low ground

- Matig
- Hoog

Daktype ○

- Platte daken
- Daken met helling kleiner dan 35 graden
- Daken met helling groter dan 35 graden

Grondtype ○

- Zand
- Veen
- Klei
- Gesteente

Positie in landschap ○

- Hellende gebied
- Hooggeleden vlak gebied
- Laaggelegen vlak gebied

Appendix C: CRCTool selected settings

Option	Choice	Reason
Scenario Name	*Low NL – Business Park*	A random scenario will be chosen
Climate Resilience Capacity	Drought + Pluvial flood	Since the focus of this research is on drought and pluvial flood, these two objectives will be selected
Scale level	City + Neighbourhood + Street + Building	The goal is to assess the full potential of Nature-based Solutions, so all scale levels are taken into consideration and thus selected
Soil type	*Depending on findings*	The soil type will be selected based on what was found in research step 2 to be the main type of soil in the DINOloket analysis for each city.
Slope	Sloping area / Flat area on high ground	The Geul catchment is sloped with low groundwater levels. However, “flat area on high ground” has the assumption of low groundwater in it and sloping area not, a combination of sloping area with low groundwater levels would have been better to choose. Both sloping area and flat area on high ground are selected to investigate their effect.
Multifunctional landuse	Not important	The multifunctionality of the measures are for this research not important and are therefore selected as not important
Existing space types	*Depending on findings*	Due to a lack of time, there hasn’t been a separate analysis on the existing space types, aside from a rough scan through Google Maps. To make sure that measures are not excluded based on existing space types, all space types are selected
Sub-surface availability	High	The subsurface availability is needed for measures that need space in the ground. This subsurface availability has not been checked beforehand, so for now the availability has been set on High to make sure that no measures are excluded based on this.
Roof characteristic	*Flat roofs*	There are both flat and tilting roofs in the cities, so the setting will be put on flat roofs and roofs slope less than 35 degrees but all types of roofs are considered

Appendix D: Corine Land Cover Map and classes

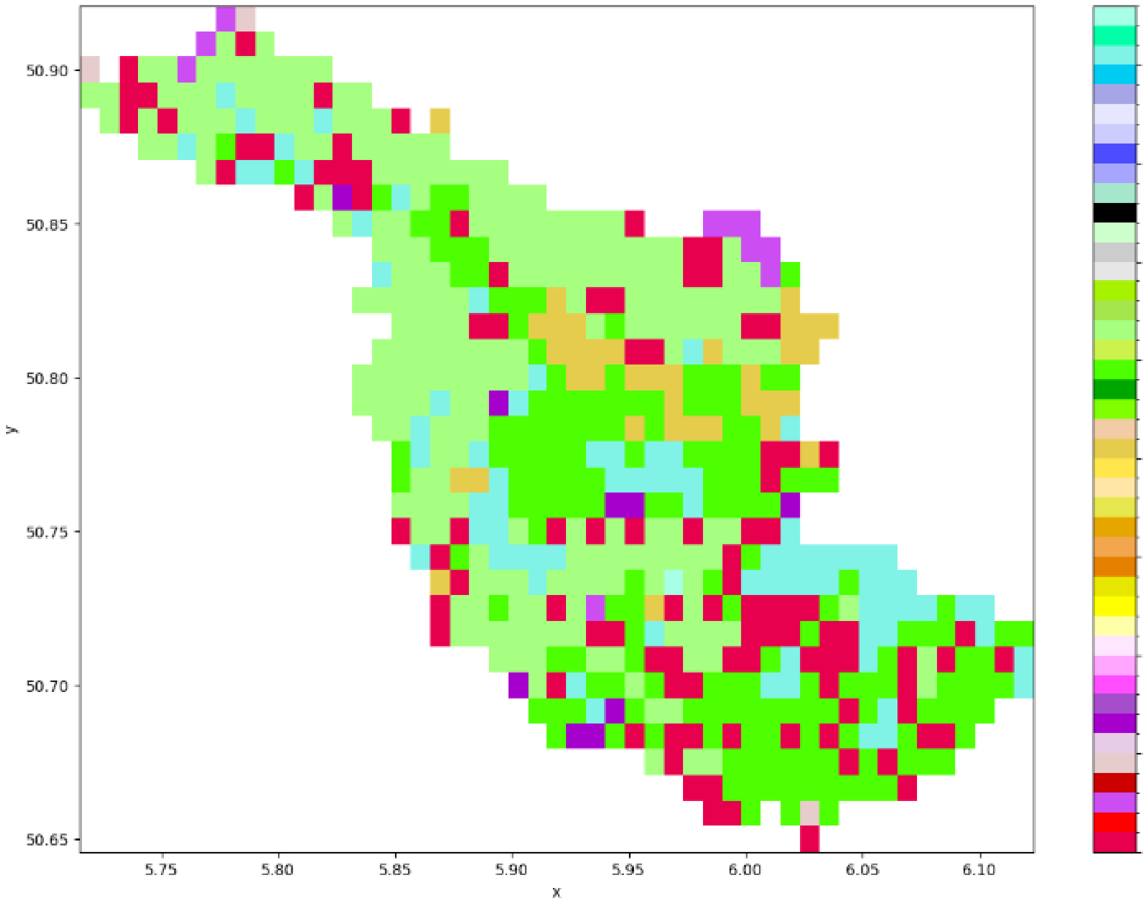
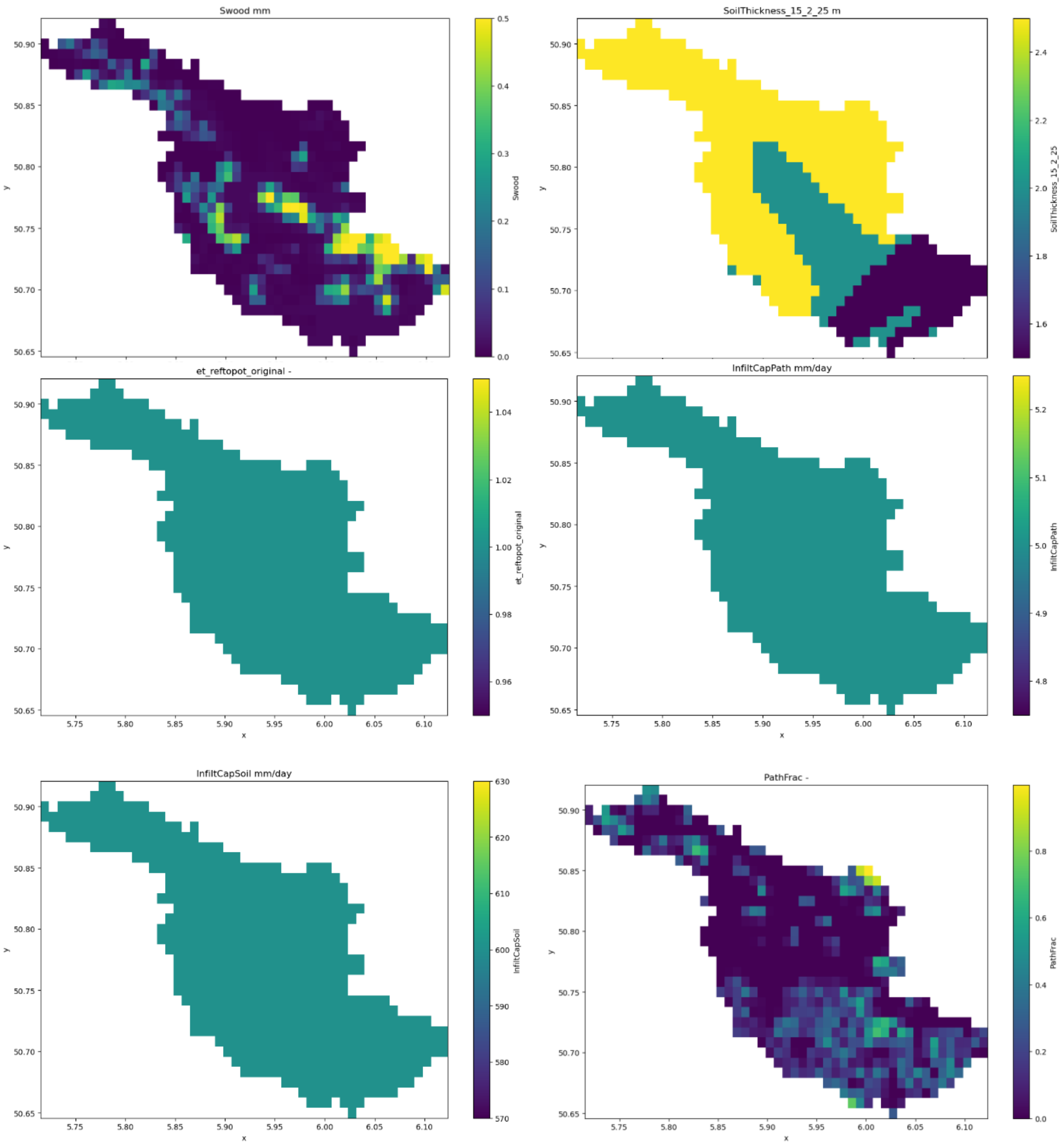


Figure D1: Corine land cover classes (source: European Environment Agency, 2011)

Appendix E: Wflow parameter default values

	Original value range		
	Average	Minimum	Maximum
Swood	0.07	0	0.5
SoilThickness	2.21	1.5	2.5
InfiltCapPath	5	5	5
InfiltCapSoil	600	600	600
PathFrac	0.122	0	0.998
Et_reftopot	1	1	1

Table E1: Original wflow parameter values



Appendix F: Selection tool score table

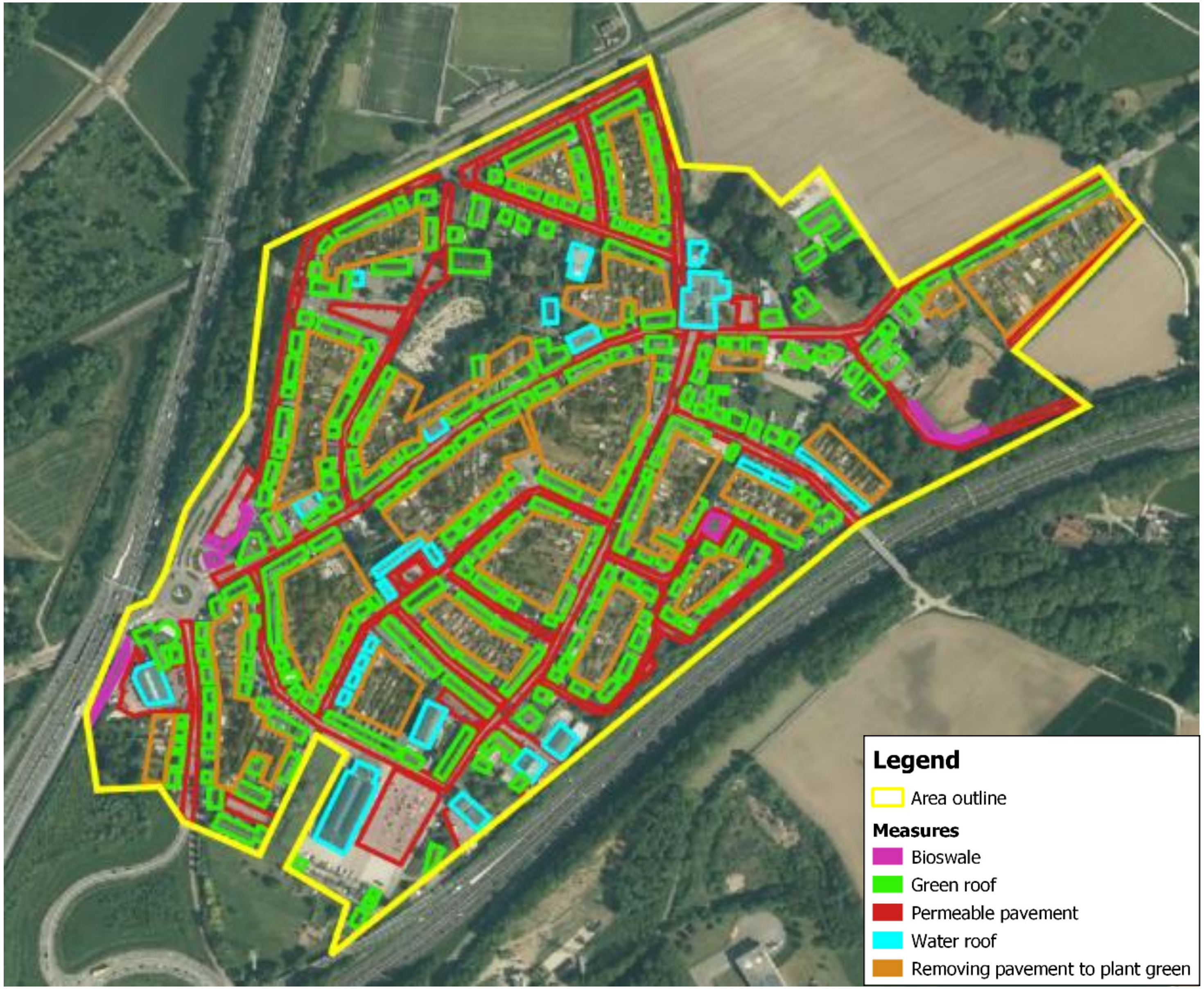
name	city	neighborhood	street	building	soil Sand	soil Peat	soil Clay	soil Bed Rock	sloping Area	flatArea High Ground	flatArea Low Ground	red Space	grey Space	green Space Private Gardens	green Space No Recreation	greenSpace Recreation Urban Farming	greyGreen Space Sports Playground	blue Space	enables Multifunctional LandUse	high Slope Roofs	low Slope Roofs	flat Roofs	sub Surface VeryLow	sub Surface Low	sub Surface Medium	sub Surface High	cooling	heat Prevention	heat Coping	drought Prevention	drought Coping	flood Prevention	flood Coping	water Safety Prevention	water Safety Coping
Urban wetland	10	4	0	0	10	10	10	4	0	10	10	0	0	0	0	7	0	10	2	0	0	0	0	0	0	1	5	1	1	0	1	1	1	0	0
Urban forest	10	10	4	0	10	10	10	10	10	10	10	0	7	0	6	3	8	0	4	0	0	0	0	0	0	1	5	1	1	0	0	1	1	0	0
Create extra surface water (m^2)	10	10	4	0	4	10	10	4	4	10	10	0	1	1	10	8	0	10	2	0	0	0	0	1	0	0	2	1	1	0	1	1	1	0	0
Levees	10	10	2	0	10	10	10	10	4	4	10	0	4	0	10	10	4	10	3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1
Super levee	10	4	0	0	10	10	10	10	4	4	10	4	4	0	10	10	4	10	4	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1
Deep groundwater infiltration	10	10	4	0	10	10	10	0	4	10	10	0	5	0	10	8	8	0	5	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0
Adding trees to streetscape	4	10	10	4	10	10	10	10	10	10	10	0	10	0	7	0	9	0	4	0	0	0	0	0	0	1	3	1	1	0	0	1	0	0	0
Cool building materials (high albedo)	4	10	10	10	10	10	10	10	10	10	10	8	6	0	0	0	0	0	4	0	0	0	0	0	0	0	3	1	1	0	0	0	0	0	0
Drought resistant species	4	10	10	10	10	4	4	10	10	10	10	0	0	10	10	10	0	0	1	0	0	0	0	1	0	0	0	0	0	1	1	0	0	0	0
Quay	4	10	4	0	10	10	10	10	4	4	10	0	10	0	10	10	4	10	3	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1
Storage by creating extra freeboard	4	10	4	0	10	10	10	10	4	10	10	0	0	0	10	0	0	0	3	0	0	0	1	0	0	0	0	0	0	1	1	1	0	0	0
Hollow roads	4	10	10	4	10	10	10	10	10	10	10	0	10	0	0	0	0	0	4	0	0	0	1	0	0	0	0	0	0	0	0	1	1	0	0
Bioswale (with drainage)	0	10	10	0	10	4	4	4	10	10	4	0	4	0	10	8	8	0	1	0	0	0	0	0	0	1	3	1	1	1	0	1	1	0	0
Infiltration fields and strips with surface storage	0	10	4	0	10	4	4	0	4	10	4	0	0	0	10	6	4	0	3	0	0	0	1	0	0	0	2	1	1	1	0	1	1	0	0
Green roofs (extensive)	0	0	4	10	10	10	10	10	10	10	10	10	0	0	0	0	0	0	5	0	1	1	0	0	0	0	2	1	1	0	0	1	0	0	0
Water roof	0	0	0	10	10	10	10	10	10	10	10	10	0	0	0	0	0	0	4	0	0	1	0	0	0	0	3	1	1	0	0	0	0	0	0
Green roofs with drainage delay	0	0	4	10	10	10	10	10	10	10	10	10	0	0	0	0	0	0	5	0	1	1	0	0	0	0	2	1	1	0	0	1	0	0	0
Rainwater detention pond (wet pond)	0	10	4	2	10	10	10	10	0	10	10	0	0	2	10	8	0	10	1	0	0	0	0	0	0	1	5	1	1	0	1	1	1	0	0
Creating shadow	0	2	10	10	10	10	10	10	10	10	10	10	10	10	4	0	4	0	4	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0
Permeable pavement systems (infiltration)	0	4	10	10	10	4	4	0	10	10	4	0	10	10	0	4	6	0	5	0	0	0	1	0	0	0	0	0	1	1	0	1	0	0	0
Permeable pavement (storage)	0	4	10	10	10	4	4	0	10	10	4	0	10	10	0	4	6	0	5	0	0	0	1	0	0	0	0	0	1	1	0	1	0	0	0
Remove pavement to plant green	0	4	10	10	10	4	4	0	10	10	4	0	10	10	0	4	6	0	5	0	0	0	1	0	0	0	0	0	1	1	0	1	0	0	0
Fountains, waterfalls, water facades	0	4	10	10	10	10	10	10	10	10	10	0	10	8	6	9	9	7	2	0	0	0	1	0	0	0	3	0	1	0	0	0	0	0	0
Green facades	0	0	0	10	10	10	10	10	10	10	10	10	0	0	0	0	0	0	5	0	0	0	1	0	0	0	3	0	1	0	0	0	0	0	0
Ditches	0	4	10	0	10	4	4	4	10	10	4	0	6	4	10	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	1	1	0	0
Drainage/Infiltration/Transport (DIT) drains	0	4	10	4	10	4	4	0	0	10	4	0	10	3	6	4	10	0	5	0	0	0	1	0	0	0	0	0	0	1	0	1	0	0	0

Infiltration boxes	0	4	10	10	10	4	4	0	4	10	4	5	10	10	6	6	6	0	4	0	0	0	0	1	0	0	0	0	0	1	0	1	0	0	0
Gravel layers	0	2	10	10	10	4	4	0	4	10	10	0	0	10	10	4	4	0	3	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1
Smart irrigation measures	0	0	0	10	10	4	4	10	10	10	10	10	0	0	0	0	0	0	4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Lowering of terrace	0	0	4	10	10	4	4	0	4	10	10	0	0	10	0	0	0	0	4	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0
Lowering part of garden	0	0	0	10	10	4	4	0	4	10	10	0	0	10	0	0	0	0	4	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0
Building as levee	0	4	10	10	10	10	10	10	4	4	10	10	0	0	0	0	0	10	4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1
Temporary levee	0	10	10	0	10	10	10	10	4	4	10	0	10	10	10	10	4	10	5	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1
Rain barrel	0	0	0	10	10	10	10	10	10	10	10	10	10	10	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0	0
Water square	0	10	4	0	10	4	10	4	0	10	10	0	10	0	0	0	10	0	4	0	0	0	0	1	0	0	0	0	0	0	0	1	1	0	0
Storage tank or underground water storage	0	10	10	4	10	10	10	10	4	10	10	0	8	0	8	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
Small quays	0	10	10	0	10	10	10	10	4	4	10	0	10	0	10	10	4	10	3	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0

Table F1: Selection tool score table, where the requirements for 1) effective against drought and/or flood prevention, 2) effective on neighbourhood, street and/or building scale and 3) effective on high and sloping areas (light green columns) have initially eliminated 13 out of 37 measures (grey rows)

Appendix G: UNbS measures drawn into the CRCTool


Legend
Area outline
Measures
Bioswale
Green roof
Permeable pavement
Water roof
Removing pavement to plant green


Legend
Area outline
Measures
Bioswale
Green roof
Permeable pavement
Water roof
Removing pavement to plant green

Appendix H: Wflow parameter changes

	Original			Changed: Broekhem		
	Average	Minimum	Maximum	Average	Minimum	Maximum
Swood	0.07	0	0.5	1.62	0	8.29
SoilThickness	2.21	1.5	2.5	2.22	1.5	2.6
InfiltCapPath	5	5	5	5.00	5	5.00
InfiltCapSoil	600	600	600	600.0	600	600.0
PathFrac	0.122	0	0.998	0.103	0	0.715
Et_reftopot	1	1	1	1.04	1	1.2

	Changed: Stoepert			Changed: Rothem		
	Average	Minimum	Maximum	Average	Minimum	Maximum
Swood	1.88	0	9.65	0.91	0	4.60
SoilThickness	2.22	1.5	2.6	2.22	1.5	2.57
InfiltCapPath	5.00	5	5.00	5.00	5	5.00
InfiltCapSoil	600.0	600	600.0	600.0	600	600.0
PathFrac	0.103	0	0.726	0.100	0	0.670
Et_reftopot	1.04	1	1.2	1.04	1	1.2

Table H1: wflow parameter changes for the three neighbourhood scenarios

Appendix I: Original discharges

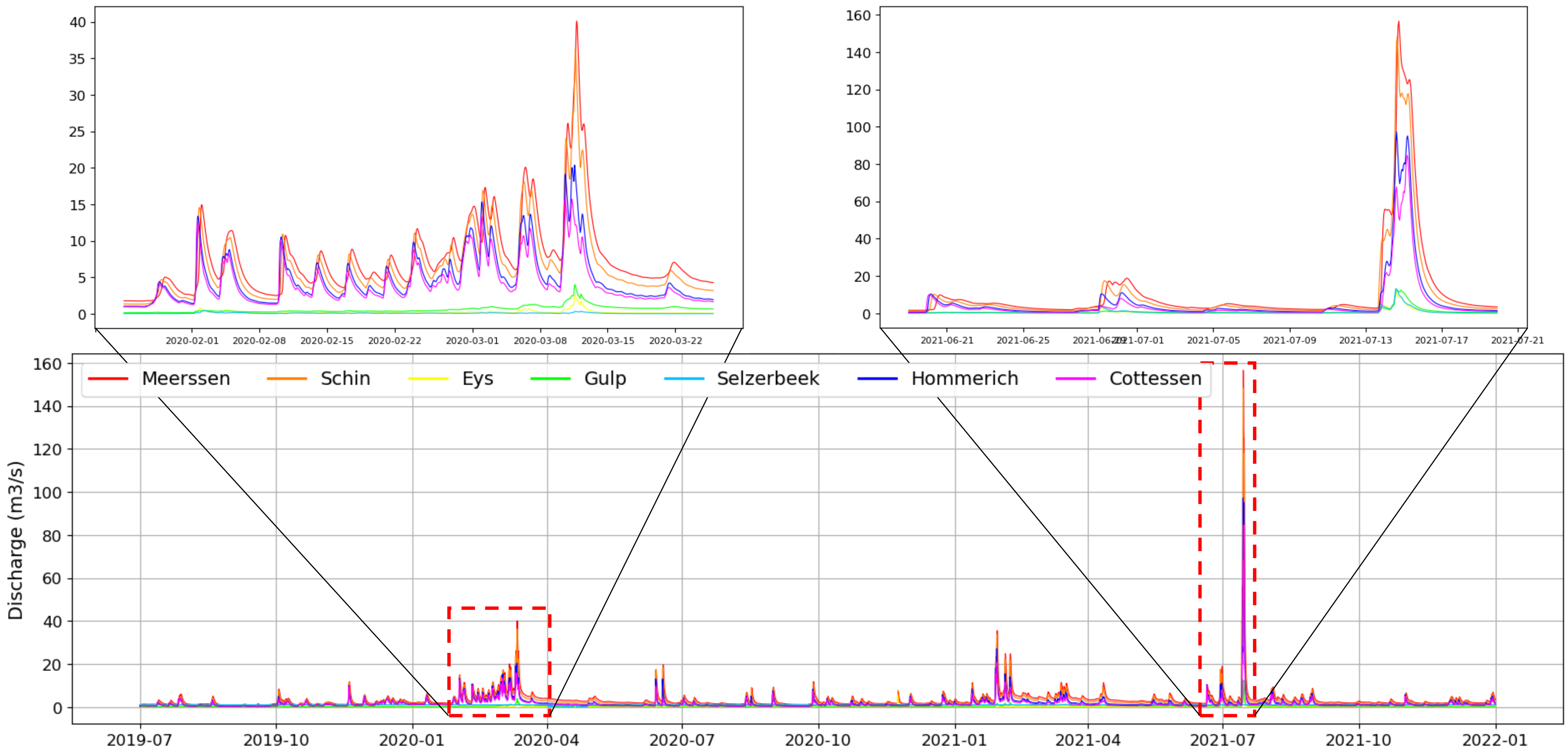


Figure I1: Original discharge for the seven gauging stations in the period of July 2019 – January 2022. The zoomed-in graphs show peak discharges for periods of January 25, 2020 – March 25, 2020 and June 19, 2021 – July 19, 2020.

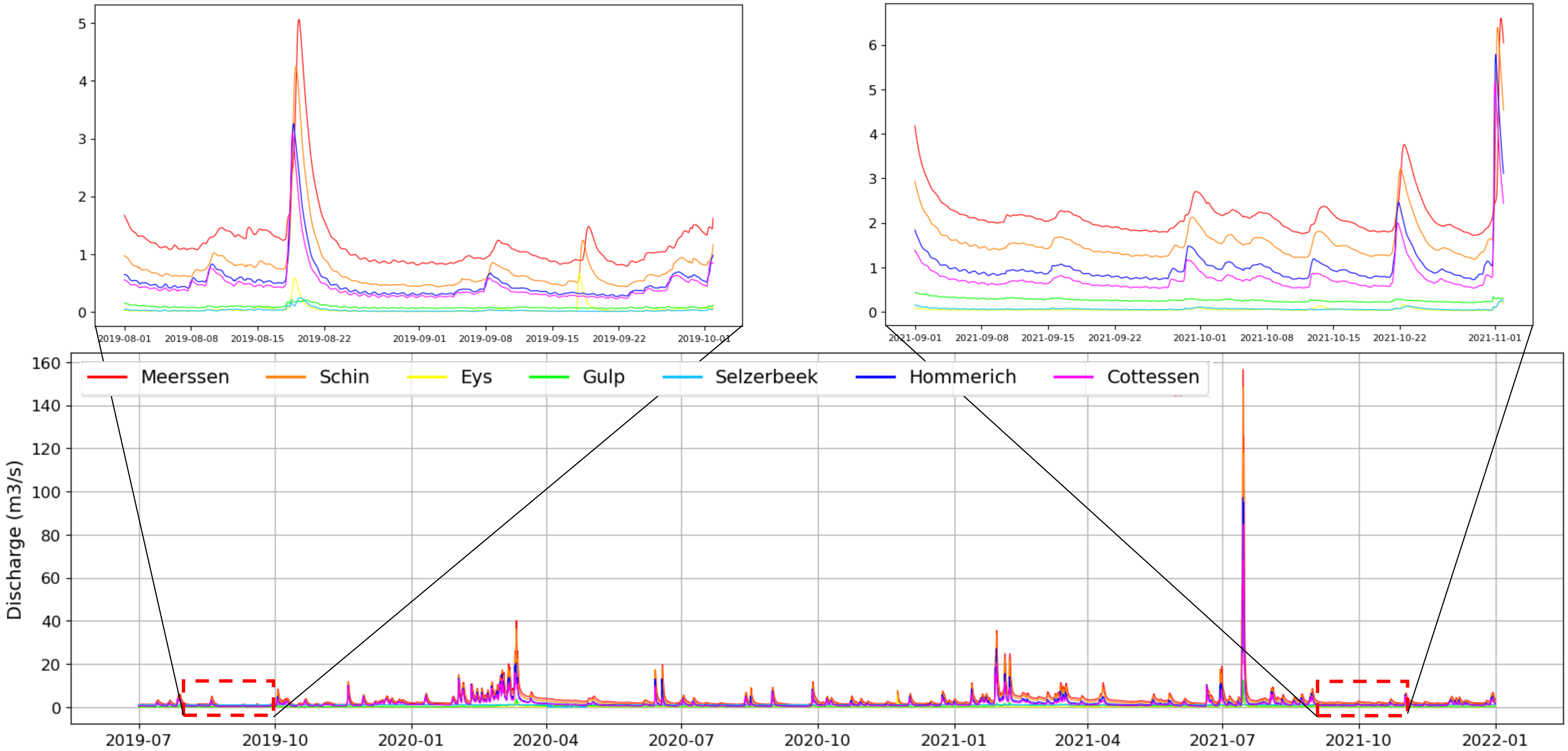


Figure I2: Original discharge for the seven gauging stations in the period of July 2019 – January 2022. The zoomed-in graphs show low discharges for periods of August 1, 2019 – October 1, 2019 and September 1, 2021 – November 1, 2021.

Appendix J: Neighbourhood scenario differences

Broekhem	Location	Min	Max	Mean	Median	Standard deviation
Difference with original discharge [m3/s]	Meerssen	-4.86	0.00	-0.07	-0.04	0.12
	Schin op Geul	-4.02	0.00	-0.06	-0.04	0.11
	Eys	**-0.74**	**0.03**	**0.00**	**0.00**	**0.01**
	Gulp	-0.15	0.12	-0.01	0.00	0.01
	Selzerbeek	**-0.19**	**0.06**	**0.00**	**0.00**	**0.01**
	Hommerich	-3.62	0.02	-0.04	-0.03	0.10
	Cottessen	-3.73	0.01	-0.04	-0.03	0.09

Stoepert	Location	Min	Max	Mean	Median	Standard deviation
Difference with original discharge [m3/s]	Meerssen	-4.86	0.00	-0.07	-0.04	0.12
	Schin op Geul	-4.02	0.00	-0.06	-0.04	0.11
	Eys	**-0.74**	**0.03**	**0.00**	**0.00**	**0.01**
	Gulp	-0.15	0.11	-0.01	0.00	0.01
	Selzerbeek	**-0.19**	**0.06**	**0.00**	**0.00**	**0.01**
	Hommerich	-3.62	0.02	-0.04	-0.03	0.10
	Cottessen	-3.73	0.0	-0.04	-0.03	0.09

Rothem	Location	Min	Max	Mean	Median	Standard deviation
Difference with original discharge [m3/s]	Meerssen	-4.88	0.00	-0.07	-0.04	0.12
	Schin op Geul	-4.03	0.00	-0.05	-0.04	0.11
	Eys	**-0.73**	**0.03**	**0.00**	**0.00**	**0.01**
	Gulp	-0.15	0.10	-0.01	0.00	0.01
	Selzerbeek	**-0.19**	**0.06**	**0.00**	**0.00**	**0.01**
	Hommerich	-3.62	0.02	-0.04	-0.03	0.09
	Cottessen	-3.73	0.0	-0.04	-0.03	0.09

Broekhem	Location	Min	Max	Mean	Median	Standard deviation
Difference with original discharge [%]	Meerssen	-8.77	-0.04	-2.01	-1.98	0.85
	Schin op Geul	-9.53	-0.04	-2.18	-2.11	0.95
	Eys	**-46.31**	**91.89**	**-2.03**	**-0.68**	**6.27**
	Gulp	-11.44	3.22	-1.73	-1.38	1.89
	Selzerbeek	**-100.00**	**1.25e+24**	**5.78e+19**	**-1.15**	**8.46e+21**
	Hommerich	-12.40	0.83	-2.53	-2.42	1.26
	Cottessen	-14.16	0.77	-3.01	-2.82	1.51

Stoepert	Location	Min	Max	Mean	Median	Standard deviation
Difference with original discharge [%]	Meerssen	-8.78	-0.04	-2.01	-1.97	0.85
	Schin op Geul	-9.51	-0.04	-2.18	-2.11	0.95
	Eys	**-46.30**	**92.39**	**-2.02**	**-0.68**	**6.26**
	Gulp	-11.37	3.21	-1.72	-1.38	1.88
	Selzerbeek	**-100.00**	**1.25e+24**	**5.78e+19**	**-1.13**	**8.46e+21**
	Hommerich	-12.38	0.82	-2.52	-2.41	1.26
	Cottessen	-14.17	0.75	-3.01	-2.81	1.51

Rothem	Location	Min	Max	Mean	Median	Standard deviation
Difference with original discharge [%]	Meerssen	-8.79	-0.04	-1.99	-1.96	0.84
	Schin op Geul	-9.44	-0.04	-2.16	-2.10	0.94
	Eys	**-46.37**	**92.25**	**-2.00**	**-0.67**	**6.19**
	Gulp	-11.10	3.22	-1.71	-1.36	1.85
	Selzerbeek	**-100.00**	**1.25e+24**	**5.78e+19**	**-1.11**	**8.46e+21**
	Hommerich	-12.32	0.82	-2.51	-2.40	1.25
	Cottessen	-14.21	0.68	-3.00	-2.79	1.50