Applicability of a conceptual tool in quantifying the effectiveness of Nature-Based Solutions in tropical urban flood mitigation

A case study in Paramaribo, Suriname

MSc Graduation project

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Deltares
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Cover photo made by Perrin Keesmaat at the Van Idsingastraat, Paramaribo

SUMMARY

Paramaribo is facing repetitive flooding, which is expected to worsen due to urbanization and climate change. Nature-Based Solutions (NBS) can help mitigate the effects of flooding by providing green areas for water retention and infiltration. Although NBS have gained popularity in the last decade as an alternative to traditional grey measures, there are still obstacles to its widespread implementation. These include the complexity of stormwater management, the lack of a standardized modelling approach, and uncertainties associated with NBS design.

The Climate Resilient City Tool (CRCTool) is designed to support the design process of NBS. Its key strengths is its accessibility, immediate results, and the use of continuous modelling to determine effectiveness, which sets it apart from other common approaches. The CRCTool offers two performance indicators related to flood mitigation: Storage Discharge Frequency (SDF) curves and runoff reduction factors. The SDF curves demonstrate the amount of water that must be stored in the area for a specific pump capacity, while the runoff reduction factors demonstrate the decrease in the return period of a runoff event.

This thesis aims to assess the applicability of the CRCTool for evaluating the effectiveness of NBS for mitigating tropical urban floods in the city centre of Paramaribo. The tool's applicability depends on various factors, including the underlying assumptions, sensitivity to changes in certain parameters, compliance with hydrological principles in the output, comparison with a hydrodynamic model and the degree of stakeholder engagement.

This research involved testing assumptions related to the formulation of the runoff reduction factors and SDF curves, performing a sensitivity analysis for the most sensitive parameters, and critically assessing the hydrological behaviour of groundwater processes, evapotranspiration, and percolation. In addition, the model outcomes were compared to a hydrodynamic model, developed in D-HYDRO, to determine the importance of spatial effects such as flow routing and elevation. Two problem areas in the study area were also examined in detail using this model. Finally, a stakeholder design workshop is conducted to determine the tool’s applicability as part of the urban planning and design practice.

This thesis found that the assumptions tested were not applicable to Paramaribo, particularly due to the high rainfall volumes experienced. The current formulation of the runoff reduction factor was found to be invalid under such conditions, and assumptions related to controlled runoff and inflow factors were found to be inaccurate. Additionally, the tool's instantaneous modelling of hydrological flows meant that NBS processes like percolation and evapotranspiration stopped almost immediately after the event, and long-term effects were not observed. Lastly, the current implementation of the groundwater component also had minimal effects on the drainage of measures.

Comparison with D-HYDRO revealed the added value of hydrodynamic modelling. The flooding volumes calculated were significantly higher compared to the CRCTool, and the effectiveness of measures in the two problem areas was different due to factors such as flow routing and local elevation. This highlights the need for tailored solutions for each problem area. Despite this, the CRCTool proved valuable for the urban planning and design practice by generating interest, fostering dialogue, and raising awareness for stakeholders.

The current state of the CRCTool restricts its applicability to areas with low rainfall and runoff volumes. The continuous modelling capabilities are limited due to the way hydrological fluxes are implemented. However, minor adjustments can be made to the model to make it more suitable for areas with larger rainfall volumes. This research recommends implementing these adjustments and thoroughly testing the tool's performance. Additionally, to minimize the impact of flow routing and elevation, it is advised to test the tool on smaller areas where the hydrological conditions are more clearly defined.

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LIST OF ABBREVIATIONS

Abbreviation	**Definition**
CRCTool	Climate Resilient City Tool
DEM	Digital Elevation Model
GI	Green Infrastructure
GW	Groundwater
IDF	Intensity Duration Frequency
LID	Low Impact Development
NBS	Nature-based Solutions
RR	Rainfall-runoff
SDF	Storage Duration Frequency
SUDS	Sustainable Urban Drainage System
SWDS	Stormwater Drainage System
UrbanWB	Urban Water Balance Model
Measures	
BC	Bioretention cells
GR	Green roofs
IT	Infiltration trenches
PP	Permeable pavements
RB	Rain barrels
RG	Rain gardens
RP	Retention ponds
VS	Vegetative swales
Land use types	
PR	Paved roof
CP	Closed paved
OP	Open paved
UP	Unpaved
OW	Open water

1 INTRODUCTION

1.1 URBAN PLUVIAL FLOODING

1.1.1 Recent floodings in Paramaribo

After months of heavy rainfall in Suriname between March and June 2022, Paramaribo experienced significant flooding events that impacted the city and its inhabitants. The city's drainage system was overloaded leading to inundation of low-lying areas. The flooding was severe in flood prone areas such as the Jodenbreestraat and Verlengde Keizerstraat, where flood depths reached up to 50 cm (Figure 1-1). The flooding caused significant damage to infrastructure, buildings, and property, and disrupted daily life for residents, who were forced to wade through the water to get around the city. This was not an isolated incident, as similar flooding of the same magnitude had occurred just a year prior, in April and May 2021. It highlights the urgent need for improved urban flood management strategies and infrastructure in Paramaribo.

Figure 1-1 Floodings in May 2021 (left) and June 2022 (right) in the 'Binnenstad' of Paramaribo

1.1.2 Worsening of the flooding problems

Urban pluvial flooding occurs when natural or human-made drainage systems are unable to manage the rate of precipitation. Paramaribo, with its tropical climate, is particularly vulnerable to flooding due to high rainfall intensity and peak flows, as well as its mostly low-lying topography, which makes it difficult to drain excess water. Moreover, maintaining the drainage system is a challenge in tropical climates, especially for developing countries with limited resources, where fast-growing vegetation deteriorates drainage channels more quickly. The problem is exacerbated by the presence of unpaved roads that allow sediment to clog sewer pipes and storm drains. Finally, the city's expansion into flood-prone areas has only worsened the issues.

In Paramaribo and many other regions worldwide, the occurrence and intensity of heavy rainfall events is expected to increase due to climate change (Yang et al., 2021), which is supported by evidence that shows the number of days of heavy precipitation has been increasing already, particularly high-intensity short duration rainfall (Fowler et al., 2021). On top of that, urbanization worsens the problem by increasing the number of impervious surfaces in and around cities, which reduces infiltration rates and increases surface runoff, leading to higher and more frequent peak flows. Existing drainage systems cannot keep up with the effects of climate change and urbanization, increasing the overall flood risk. Replacing these systems is most of the time a costly matter.

1.1.3 Effectiveness of Nature-Based Solutions

To mitigate the increasing flood risk, retention and storage of storm water is viewed as an effective solution. This can be achieved as an addition to the existing drainage system, which means there is no need for a complete replacement. Nature-Based Solutions (NBS) are effective in providing flood retention and storage and can be a cost-effective alternative for flood risk adaptation measures (Jiang et al., 2018).

In this study, NBS refer to flood risk adaptation measures that depend on water, vegetation, and ecosystem services. They involve the strategic use of networks of natural lands, working landscapes, and other open spaces to conserve ecosystem values and functions and provide associated benefits to human populations (Raymond et al., 2017). They can restore the water retention capacity of the landscape by increasing infiltration rates, providing temporal storage, increasing evapotranspiration rates, slowing down the overland flow and lower channel velocities (Collentine & Futter, 2018). This reduces peak runoff, allowing for a smaller design capacity for the drainage system. In addition, they also bring a lot of other co-benefits: increase in air quality, decrease of heat stress, higher urban biodiversity, and an overall better urban amenity (de Graaf & der Brugge, 2010), which makes them a promising option to consider for urban flood mitigation.

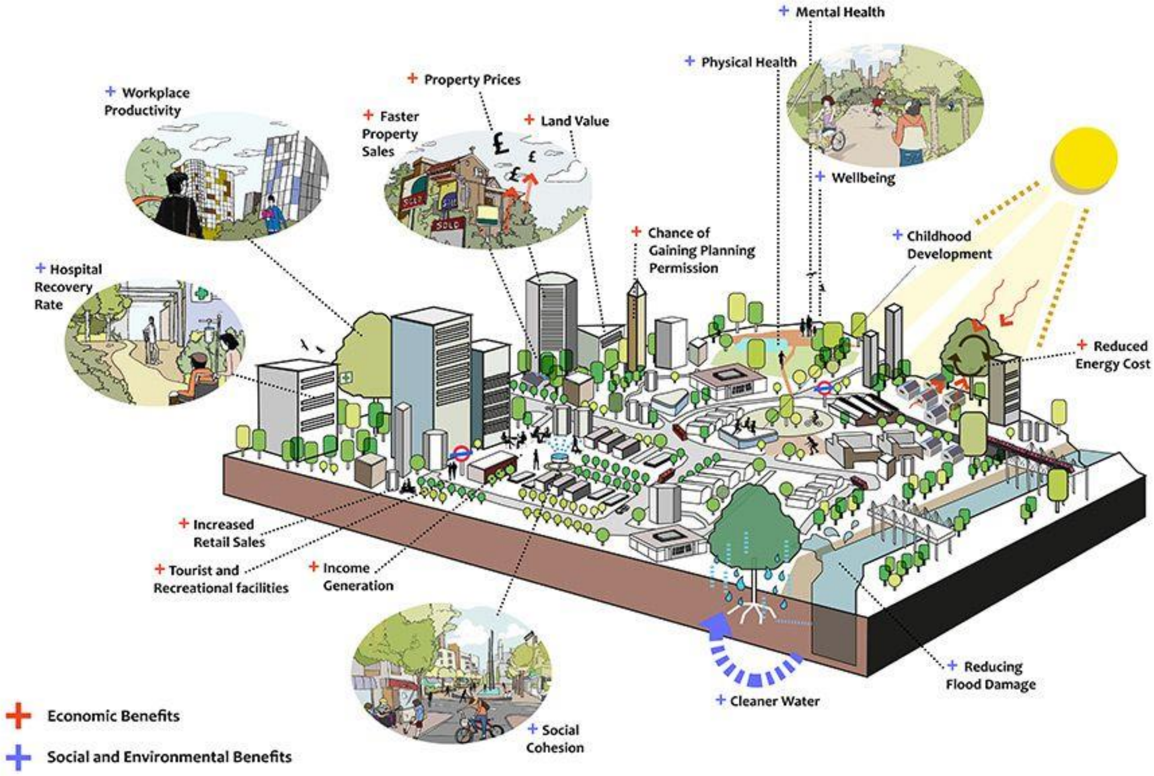


Figure 1-2 Several economic, social and environmental benefits of NBS for cities (Thorpe, 2017)

1.2 CHALLENGES FOR NATURE-BASED SOLUTIONS

1.2.1 New concept in flood mitigation

NBS for urban areas are a relatively new concept that has gained popularity in the last decade. However, due to the complexity of stormwater management and the variations in the design of each NBS, there is limited robust scientific evidence available on their long-term performance (Sahani et al., 2019; Vijayaraghavan et al., 2021). Previous research into the effectiveness of NBS is often simplified and its results are dispersed. To date, there is no standardized method for assessing the effectiveness of NBS at the scale of an entire urban drainage system (Qin et al., 2013).

NBS measures are typically tested on individual storm events, either based on historical events or using "design storms” (Olsen et al., 2015). This approach predetermines the antecedent conditions which can greatly affect NBS measures that rely heavily on infiltration and buffer capacity. Additionally, smaller, or larger storm events are not considered when using a single design storm. NBS are most effective when unsaturated, but during large storm events they may reach their maximum retention capacity or become fully saturated, leading to a drastic decrease in performance. This can lead to an unrealistic representation of the measure if it is only tested for a single design storm.

1.2.2 Quantification of NBS

NBS are not consistently defined, and their characteristics can vary widely depending on location and design. For example, a green roof can have a substrate depth of 6 cm or 15 cm, and the choice of depth depends on factors such as roof type, funding, desired effects, and other design considerations. The purpose of the design is site- or service specific (Farrugia et al., 2013): a green roof may be implemented to reduce heat stress or increase biodiversity, whereas if it is intended to function as a garden, the substrate depth will likely be greater than 10 cm. Additionally, soil and vegetation are subject to many uncertainties, such as heterogeneity, vegetation growth, sediment clogging, seasonality, and maintenance. These uncertainties, along with the variability in terminology and design, make it difficult to generally quantify the effectiveness of NBS.

The previous paragraphs highlight the difficulties in evaluating the effectiveness of NBS for flood mitigation. There is a scarcity of reliable data in the literature on how well NBS can mitigate flooding. This has been acknowledged by several authors, who have emphasized the need for quantification (Ferreira et al., 2020; Zhou, 2014), because of the limited number of studies available. This lack of quantification may be a contributing factor to the infrequent use of NBS in actual flood plans (Brillinger et al., 2020). Without quantification, the uncertainty surrounding NBS remains significant, making it more challenging to select them over traditional "grey" measures. The uncertainties of grey measures have been reduced over time through extensive use, making them a more familiar option. Thus, quantifying the effectiveness of NBS is crucial for policymakers and decision-makers to make informed choices when implementing NBS.

Applying NBS in Paramaribo poses additional challenges due to the tropical climate, which includes heavy rainfall events, fast-growing vegetation, and rapid degradation of infrastructure (Hamel & Tan, 2022). The country also faces financial constraints and limited specialized knowledge, making it difficult to fully utilize investments in the drainage system. Besides, the current state of the drainage system is worrying and will require significant investments to restore. NBS may be a suitable solution as it requires minimal initial investments compared to replacing the existing drainage system. It also simultaneously addresses various other problems. However, maintenance requirements and accessible quantification should be considered for the design.

1.3 CLIMATE RESILIENT CITY TOOL

This study will focus on the Climate Resilient City Tool (CRCTool) from Deltares (Vergroesen & Brolsma, 2020). Its main purpose is to activate stakeholders and produce conceptual designs of NBS in urban areas. It uses a general conceptual approach at neighborhood scale for assessing the effectiveness of NBS for urban flood mitigation, heat reduction and water quality improvements. It aims to raise awareness about NBS and tries to take away uncertainties in the design and implementation process.

This is very important, because NBS must fight for a place in the competitive urban landscape. Uncertainties in their implementation weakens their position. These uncertainties are abundant, because quantifying their effectiveness is comprehensive. NBS have multifaceted functions and variations in design. All these aspects must be quantified and evaluated to be able to make a convincing case for them.

Furthermore, there is a general need for accessible modelling in developing countries like Suriname, due to the often lack of more advanced hydrodynamic models. So the CRCTool can be the first step in taking away some of the uncertainties in the design of NBS and be especially useful for developing countries that lack complex hydrodynamic modelling tools.

The CRCTool is a web-based tool that can display the real-time effectiveness of NBS. This requires a model that is both fast and easily accessible. To provide real-time results, it utilizes pre-calculated outcomes from an Urban Water Balance Model (UrbanWB), which is a lumped conceptual model, that assesses the reduction of runoff from NBS. The conceptual approach makes it possible to use long rainfall timeseries as input. In this way all kind of rainfall events are analyzed with different kinds of initial conditions. It also includes important modelling concepts for NBS, like shallow groundwater flow.

The real-time results make it possible to use the tool in design workshops, to show the effects of different types of solutions immediately. It will encourage stakeholder discussions, by clearly showing the effectiveness of different NBS. This will help in making a preliminary design which consists of combinations of NBS. These designs can be made with urban planners, policy makers and decision makers to fit them optimally into the urban landscape, without having to do more complex hydrodynamic modelling.

It is important that the preliminary quantification of the effectiveness of NBS is done accurately. The tool has only been validated for Dutch design cases, which raises questions about the quality of the outputs and the applicability of the tool in quantifying the effectiveness of NBS for flood mitigation. The quality of the outputs determine how the tool can be used in design cases.

The previous studies conducted with the CRCTool have mostly focused on utilizing the tool for conceptual designs and program formulations (McEvoy et al., 2020; van de Ven et al., 2016). These studies have provided valuable insights into the experiences and lessons learned from using the tool, with a particular emphasis on urban planning and stakeholder engagement. Other studies that used the CRCTool as a tool have only utilized it without critically reviewing the outputs (Chen et al., 2021; Costa et al., 2021).

The CRCTool could serve as a basis for further hydrodynamic modeling, where NBS are incorporated into the current drainage system by focusing on their effects on drainage transport and capacity. However, the results may also reveal characteristics of NBS design that are overlooked by hydrodynamic models, making them important to use in conjunction with hydrodynamic models when designing NBS. Lastly, it is also possible that the outputs of the CRCTool are too unreliable for a good preliminary design, or it only works under very specific conditions. This research aims to examine how the CRCTool fits into the design process of NBS.

1.4 PROBLEM STATEMENT

The previous sections show the potential and challenges facing NBS and how the CRCTool tries to make it more accessible to implement NBS. It uses a conceptual modelling approach for determining the effectiveness of various NBS. The quality of such an assessment is not yet quantified extensively.

This study focusses on determining the applicability of the CRCTool in quantifying the effectiveness of NBS for tropical urban flood mitigation. For this the pre-calculated results from the UrbanWB, must be critically assessed. The applicability of the CRCTool will be evaluated in three different ways.

The initial analysis will focus on the tool itself, including testing the modelling assumptions and investigating how the model responds to variations in parameters. This assessment will examine how the model represents various fluxes and processes to ensure accurate outputs. Furthermore, the output will be qualitatively evaluated by comparing it to a hydrodynamic model. This model will include sewer flow, flow routing and elevation by physically representing flow processes. For this research, D-HYDRO, also from Deltares, will be the software used for hydrodynamic modeling. Lastly, the tool will be put into practice to see how it performs in stakeholder engagement, which is described as one of the tool’s main strengths.

The research objective can be addressed in the following main question and sub-questions:

WHAT IS THE APPLICABILITY OF THE CLIMATE RESILIENT CITY TOOL IN QUANTIFYING THE EFFECTIVENESS OF NATURE-BASED SOLUTIONS FOR TROPICAL URBAN FLOOD MITIGATION?

1. ARE ASSUMPTIONS IN THE CRCTOOL SUBSTANTIATED?
2. HOW SENSITIVE ARE OUTPUTS TO CHANGES IN MODEL INPUT PARAMETERS?
3. DOES THE CRCTOOL CORRECTLY REPRESENT IMPORTANT HYDROLOGICAL FLUXES?
4. HOW DO OUTPUTS COMPARE TO OUTPUTS FROM A HYDRODYNAMIC MODEL?
5. HOW DOES THE CRCTOOL PERFORM IN STAKEHOLDER ENGAGEMENT?

1.4.1 Hypotheses

On one hand, it is anticipated that the CRCTool will be useful for the conceptual design stage, providing accurate representation of the effectiveness of NBS and offering additional insights compared to hydrodynamic modeling due to its analysis of long rainfall time series and additional groundwater component. This is supported by the argument that the complexity in hydrodynamic models do not account for the key components of NBS, making it difficult to define model parameters and oversimplifying important reactive processes of NBS (W. Liu et al., 2014). This is partly addressed in the CRCTool.

On the other hand, the assumptions, and simplifications of hydrological processes in the CRCTool can lead to inaccurate or limited determination of the effectiveness of NBS, which means that the tool may only be valid for specific conditions or produces results that are too general.

1.5 READING GUIDE

The thesis starts with a theoretical framework (Ch. 2) that discusses the design considerations and requirements for NBS and provides an overview of various flood modelling approaches for NBS. It also includes a detailed description of the CRCTool and explains how NBS are incorporated into this model. It ends with a concise modelling framework for this study. The methods and material section (Ch. 3) starts with an overview of the study area and a description of the methods used for analysing the area. This is followed by a description of the rainfall and evaporation data and the methods used to prepare this data as input for the CRCTool and D-HYDRO model. Additional data for hydrodynamic modelling is presented next. The report then goes on to describe the model set-up for the CRCTool and D-HYDRO model and the methods used to analyse the model outputs. The results (Ch. 4) are presented in order of the content of the research sub-questions. The general discussion (Ch. 5) answers these sub-questions by interpreting the results and puts the result into perspective. Furthermore, it presents what can be concluded regarding the research limitations. The report sums up the main findings, gives recommendations for model improvements and future research in the conclusion (Ch. 6).

2 THEORETICAL FRAMEWORK

This chapter describes the background information which is used to make a modelling framework. The first section (2.1) describes the urban water system, what the function is of storage and how NBS fit in this system. The second section (2.2) describes NBS in general and which measures are considered in this research. It goes on to describes the design requirements of these measures and experiments that are done that tested their performance. It also describes what defines the effectiveness of NBS for flood mitigation and how it is defined in this study. Section 2.3 describes how NBS are currently implemented in hydrodynamic models and how this has been done in earlier studies to put the CRCTool into context with existing modelling techniques. Section (2.4) gives a detailed description of the CRCTool: describing the conceptual model behind it and its main performance indicators for flood mitigation. The last section (2.5) presents a concise modelling framework for this study based on the presented theory in this chapter.

2.1 URBAN WATER SYSTEM AND RETENTION OPTIONS

2.1.1 Design philosophy of urban drainage systems

Managing urban runoff is a complex task that affects various aspects of city life, including public safety, property rights, environment, and citizens' health and welfare. Impervious surfaces such as streets, sidewalks, buildings, and parking lots prevent rainwater from infiltrating and instead cause it to run off. The urban drainage system, which includes drainage pipes, gutters, ditches, curbs, canals, and pumps, is responsible for preventing flooding by draining this water. In countries with tropical climates like Suriname, heavy rain events are common, making it difficult and expensive to design a drainage system that can handle such large amounts of water. In the past, the main design philosophy for urban drainage systems was to drain the water as fast as possible. This philosophy is switching to a more sustainable approach, where the system tries to restore its original hydrological and ecological functions (Zischg et al., 2019). Hence water is temporarily stored in the city during heavy rain events. This benefits urban ecology, protects against droughts, and reduces flood risk.

2.1.2 Incorporating storage in urban drainage design: a framework

Retention is the practice of temporarily storing floodwater in a responsible manner, minimizing hindrance and damage. Floods can occur due to limitations in drainage capacity, transportation capacity of the drainage system, or disconnection from it. To address this, retention storage should be incorporated into the design of a drainage system for different levels of rainfall intensity. For frequently recurring events, there should be no hindrance. For infrequent and intense events, water can be temporarily stored on streets, causing hindrance but preventing damage to buildings. Streets can in this way function as storage for the urban drainage system during extreme events, and thus can be incorporated into the design. The storage solutions thus can be ‘layered’, meaning that each storage ‘layer’ activates after the previous one is filled.

In this research a framework is proposed that consist of four types of storage layers (Figure 2-1). The first layer of storage is interception storage, where water is trapped on roofs, puddles, and green fields. The second layer of storage takes effect after the interception storage and before rainwater reaches the drainage system. The third layer of storage is the drainage system itself, storing water in pipes and channels, as well as in storage chambers at the pump for example. The fourth layer of storage is storage of flood water after the drainage system exceeded its capacity, which means storing floods in a controlled way without causing too much hinderance. This is done in infrastructure without a primary storage function like the streets or in specifically designated emergency flooding areas. Designing an urban drainage system means considering all the layers of storage and determining which storage type is appropriate for different types of events.

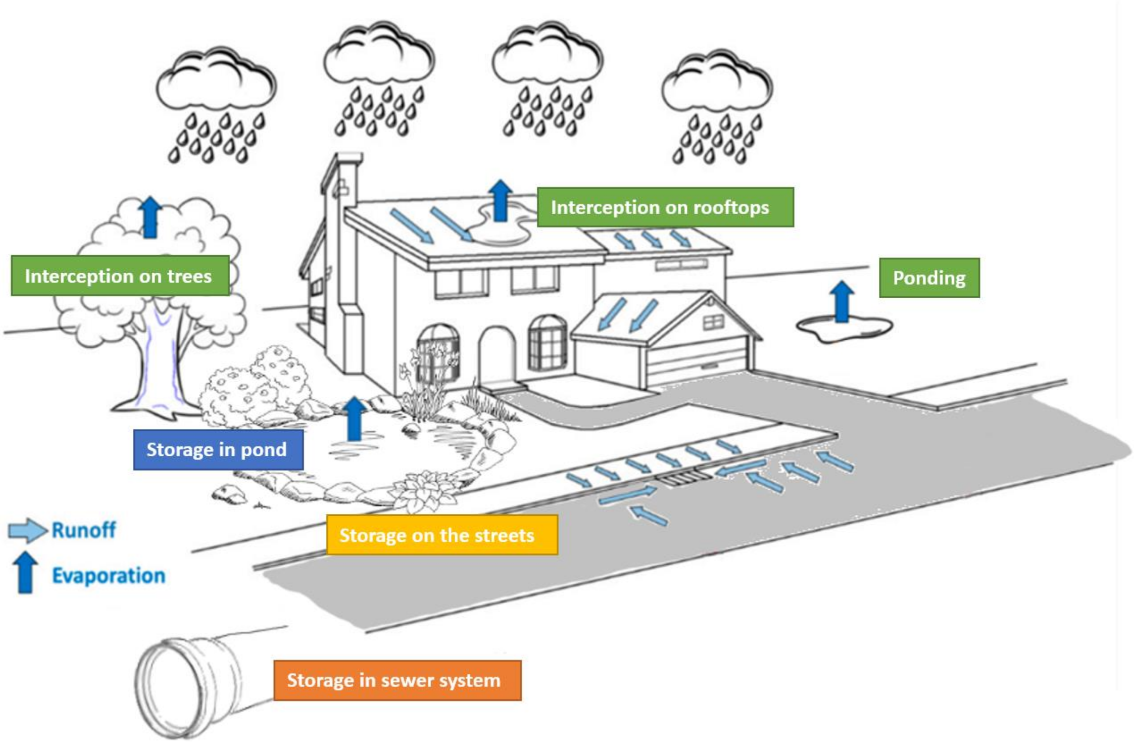


Figure 2-1 Schematisation of storage options in urban setting: 1st (green), 2nd (blue), 3rd (orange) and 4th (yellow) layer (Rammal & Berthier, 2020)

2.1.3 Incorporating NBS in design

This study will incorporate NBS in the form of second-layer storage, intercepting rainwater before it reaches the urban drainage system and thus reducing peak flows. NBS can also be designed as fourth-layer storage, storing stormwater when the capacity of the drainage system is exceeded, and flooding occurs. The main difference is that second-order storage will always store stormwater, where fourth-order storage only functions for extreme events. This means that fourth-layer storage can be designed to serve a different purpose but can be flooded in a controlled manner during emergency situations. Despite the focus on second-layer storage it remains important to consider all storage layers in the design of NBS since they interact with each other.

2.2 NATURE-BASED SOLUTIONS (NBS)

In this research, NBS refer to green infrastructure that mitigates flooding by retaining and infiltrating stormwater in urban areas. Different terminologies have been used in literature, but they all share the same design philosophies (Caparrós-Martínez et al., 2020). These terminologies vary by region, with sustainable urban drainage systems (SUDS) being commonly used in Europe, Low-Impact Developments (LIDs) in the United States and Canada, Green Infrastructure (GI) or Blue-Green Infrastructure (BGI) in other places, where the latter includes water bodies. In China, the relatively new term "Sponge Cities" has been introduced since 2014 as part of a government policy to make cities drought and flood resilient through the implementation of green infrastructure. While there may be minor differences between these terms, they can generally be considered the same and will be referred to as NBS in the context of this research.

2.2.1 Types of NBS for urban areas

There are various types of NBS that can be used to mitigate the effects of pluvial flooding in urban areas. These solutions can be broadly categorized into small-scale and large-scale options. Large-scale NBS, such as wetlands or parks designed as water retention areas, typically require significant urban interventions and careful planning of new urban areas or implementation outside city boundaries. Small-scale NBS, on the other hand, can be integrated into existing city designs and require relatively small interventions in current infrastructure.

Another way to categorize NBS is based on their main functions: infiltration or retention (Eckart et al., 2017). Infiltration-based NBS assist in the restoration of baseflows by recharging groundwater and subsurface flows, but their performance can vary greatly depending on site conditions. Retention-based NBS, such as retention basins, green roofs, and rain tanks, primarily store stormwater during storm peaks and then drain it constantly afterwards, resulting in peak runoff reduction. Drainage can be either natural or human controlled.

In this research, NBS that are applicable on neighborhood scale and do not require large interventions in existing infrastructure were chosen, and their performance was validated using reliable data from field experiments. These measures are listed in Table 2-1 and explained in more detail in section 2.2.2.

Table 2-1 Types of small-scale NBS used in this study (Huang et al., 2020; Kabisch et al., 2017)

Measure	Main function	Definition
Bioretention cells	Infiltration Retention	excavated area with vegetation grown in an engineered soil mixture placed above a gravel bed, designed to hold, and filter stormwater
Green roofs	Retention	roof that is partially or fully covered by vegetation, a small soil layer and a waterproof membrane. They can have additional storage
Infiltration trenches	Infiltration	linear ditches that collect rainwater from adjacent surfaces. Their highly permeable soils allow the water to quickly seep into the ground
Permeable pavements	Infiltration Retention	surfaces that are made of either a porous material or nonporous blocks mixed with vegetation that enables stormwater to flow through it
Rain tanks	Retention	containers above or below the surface that collect roof runoff. The water can be used during dry periods
Rain gardens	Infiltration Retention	like a bioretention cell, however often designed without a gravel bad and for larger areas
Retention/detention basins	Retention	an artificial pond that has either permanent (retention) or temporal (detention) standing water
Vegetative swales	Infiltration Retention	channels or depressed areas with sloping sides covered with grass and other vegetation. They slow down and store runoff

2.2.2 Design requirements of NBS

In this subsection, the NBS introduced in the previous paragraph are discussed in more detail and design considerations and parameters are examined. The main guideline used in this research for NBS design is the CIRIA SUDS Manual (Woods Ballard et al., 2015), which is intended for use in the UK and is considered the most comprehensive among the alternatives (Venvik & Boogaard, 2020). Parameter values provided in this chapter will primarily come from this manual, unless stated otherwise. Since there is no design manual for tropical climates, the parameters will have to be critically evaluated for the potential impact of the tropical climate on their performance. The parameters are organized in the table below.

Table 2-2 Overview of important parameters for NBS from literature

Type	Inflow area (-)	Interception storage (cm)	Measure depth (cm)	Storage depth (cm)	Infiltration design req (mm/h)	Infiltration experiments (mm/h)	Drainage time (hrs)	under-drain
BC	5 – 15	15-30 cm	gw dep.	15 – 30	100 – 300	25 – 1600	24-48	Optional
GR	0 – 1	1 cm	5 - 30	2.5 – 15	-	-	-	No
IT	5 – 20	15-30 cm	gw dep.	soil dep.	50 – 120	-	24	Optional
PP	0 – 5	10 cm	gw dep.	15 – 30	250 – 2500	30 – 1250	24	Optional
RG	10 – 20	15-30 cm	gw dep.	15 – 30	Soil type	-	-	Optional
RP	10 – 20	0 cm	60 – 120	50	-	-	-	Weir
VS	5 - 10	15-50 cm	gw dep.	40 – 60	50- 500	30 – 1200	24	Optional

Bioretention cells & rain gardens

The first NBS discussed in this research are bioretention cells and rain gardens. These are excavated areas in the landscape that are designed to reduce and treat stormwater runoff on-site. The main components of these NBS include vegetation at the top, followed by an engineered substrate layer, a drainage layer, and an optional underdrain. Rain gardens can be designed without a drainage layer.

In literature, the difference between a bioretention cell and a rain garden is not well-defined, and the terms are often used interchangeably. In this research, we differentiate them based on their size and area of application. Rain gardens are larger areas that can be designed as parks with variations in elevation, while bioretention cells are smaller and are engineered with a drainage layer to drain a larger area such as a parking lot.

The design of a bioretention cell is based on the type of soil, site conditions, and land use. According to the CIRIA SUDS Manual, bioretention cells should drain a maximum area of 0.8 ha, and the surface area of the system should be 2-4% of the overall site area to prevent clogging. To provide enough storage for infiltration between storm events, the depth should be around 15-30 cm, which will also enhance evaporation and limit the duration water is standing on the surface. It is recommended that this time is within 24-48 hours of a design storm occurring. The engineered substrate layer should have a permeability between 100-300 mm/h, and to account for clogging, the design should be based on 50% of the initial measured hydraulic conductivity. The available storage in the system is the product of the volume of the system and the porosity of the substrate/drainage layer. The porosity of the drainage layer is normally at least 30%, while the substrate layer has lower porosities. An exceedance flow route is needed for larger storm events than the system is designed for, which can be achieved by installing an overflow pipe, weir, or overflow structure above the design water storage level.

The systems can be incorporated in residential and non-residential areas and can be implemented on private property to collect runoff of the property itself or in public areas such as parking spaces, roundabouts, and pedestrian zones. In other words, they are widely applicable.

Figure 2-2 Schematisation of Rain Garden (left) and Bioretention Cell (right) (Ellis R, 2018)

Green roofs

A green roof is a roof that is partially or fully covered with vegetation, which grows in a small soil layer on top of a filter layer, drainage layer, root barrier, and a waterproof membrane. The drainage layer can also act as an additional storage layer.

There are two types of green roofs: intensive and extensive, which differ in the size of the growing medium. For extensive green roofs, the growing medium is between 25-150 mm (80-150 mm is recommended) while for intensive green roofs, it is larger than 150 mm (Alfredo et al., 2010). Extensive green roofs can be implemented on existing roofs, while intensive roofs must be specifically designed. Intensive green roofs allow for a greater biodiversity and more freedom in vegetation options, but they are also more accessible and require frequent maintenance.

This research focuses on measures that are applicable in existing neighborhoods, so it will focus on extensive green roofs. The vegetation on extensive green roofs is often sedum plants, which have very shallow roots, are lightweight, can withstand droughts, and are easy to maintain. The soil layer is around 100 mm and is able to store around 10-20 mm. The storage layer is often limited to 150 mm due to the weight that can be carried by the original roof construction (Buntsma et al., 2019). A case study in the tropics investigated design considerations and vegetation dynamics on green roofs (Grullón – Penkova et al., 2020) and found that sedum plants performed well in tropical climates, even with minimal maintenance. As sedum roofs are most abundant and have been proven to be applicable in tropical climates, they will be the type of green roof applied in this research.

Figure 2-3 Schematisation and example of a Green Roof (O' Donoghue J, 2016)

Infiltration trenches

Infiltration trenches are shallow excavations filled with granular material that are designed to capture sheet flow or piped inflow from roads, roofs, or parking places. The granular material provides storage, and the water can infiltrate into the soil around it. The permeability of the substrate is between 0.4 and 0.5. These systems may also use an underdrain to drain excess water. An infiltration trench is essentially a storage box that loses its water through exfiltration and should empty in a reasonable time after a storm event. According to the CIRIA Design manual and Chahar et al. (2012), an infiltration trench should be half empty within 24 hours. The depth of the trench can be up to several meters but is generally limited by the groundwater level (Ebrahimian et al., 2021). Emerson et al. (2010) did experiments in the hydraulic evolution of an infiltration trench in the US and found that the empty time decreased from 1 day to 8 days over a period of three years.

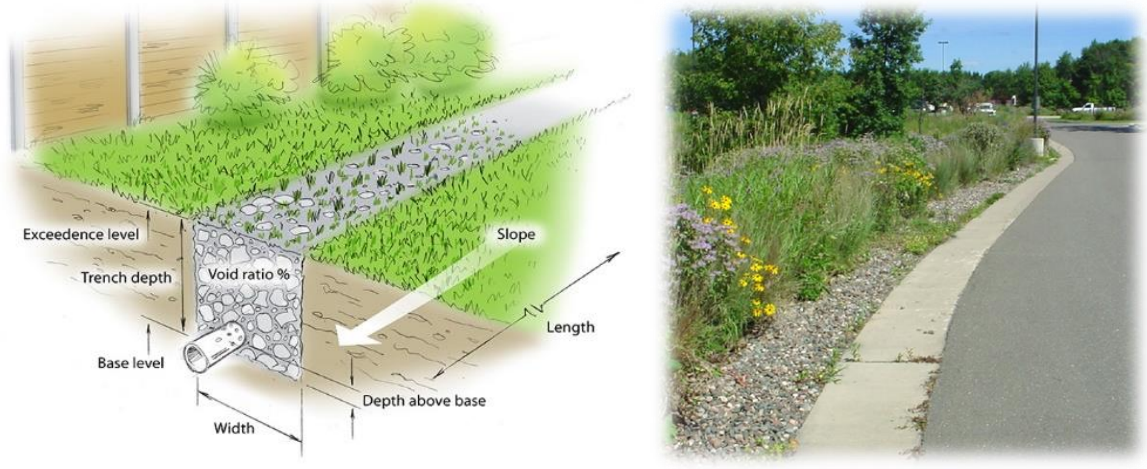


Figure 2-4 Schematisation and example of Infiltration Trench (Ellis R, 2018)

Permeable pavements

Permeable pavements are surfaces designed to allow stormwater to flow through them, which can be made of either porous materials or non-porous blocks with an open structure. Some popular examples include permeable pavers, grass pavers, permeable concrete, and permeable asphalt (Figure 2-5). These pavements are typically placed on top of a storage layer, which is usually made of gravel. An underdrain may be used to drain excess water, depending on the hydraulic conductivity of the native soil. If the soil conductivity is lower than 0.06 mm/h, an underdrain is recommended.

To ensure effective performance, the surface infiltration rate of permeable pavements should be significantly higher than the design rainfall intensity. The design manual recommends a minimum rate of 2500 mm/h for new pavements. However, this value may decrease to 250 mm/h over the pavement's design life due to clogging with clogging rates of around 74 mm/h per year for Dutch conditions (Veldkamp et al., 2021). To prevent clogging, permeable pavements should be limited to drain two times their surface area (Kellagher, 2013).

The storage capacity of the storage layer is based on the porosity of the material, which should have a minimum value of 30%. If the system experiences an exceedance flow, it can be transported by gullies or the sewer system. These systems should be slightly above the pavement's elevation to provide extra storage.

The choice of pavement material depends on expected traffic loads and visual appearance requirements. While permeable pavements can be used on most sites, they should be avoided in areas with high silt loads.

Figure 2-5 Permeable pavement concept and different pavement types: 1: permeable pavers, 2: grass pavers, 3: permeable concrete, 4: permeable asphalt (Ellis R, 2018)

Rain tanks

Rain tanks are a form of rainwater harvesting that collect roof runoff, mostly at a household scale. However, they can also be used to collect runoff from a whole street or small neighborhood, with larger rain tanks placed underground. The collected water can be used during dry periods for irrigation and gardening, and their outflow is determined by the needs and behavior of the owner(s). Rain tanks sizes are based on standard sizes from Rotoplastics Trinidad LTD., which is a common supplier of rain tanks in Suriname.

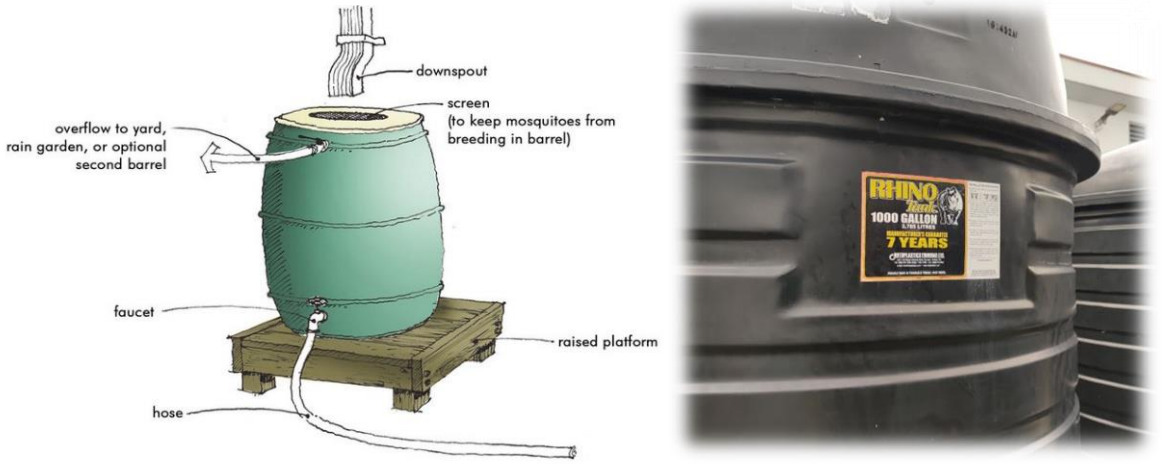


Figure 2-6 Conceptualisation of a Rain tank and a rain tank from Rotoplastics Trinidad LTD. (Zimney M, 2018)

Retention/detention basins

Retention and detention basins are designed to provide additional storage and remove pollutants from stormwater. The main difference between the two is that retention basins have a constant body of water, while detention basins temporarily hold water.

For retention basins, it is ideal to design them with a standard water level between 0.6-1.0 meters, as this depth allows for oxygen to reach the bottom, promoting biodegradation of oils by natural organisms without the risk of algal blooms or drying out. In urban environments, the maximum water depth should be around 1.5 meters for safety reasons (Aravinda et al., 2015). Detention basins are similarly constricted by the maximum water depth of 1.5 meters for safety reasons. However, the groundwater level may be the limiting factor in determining the depth of a detention basin. The maximum depth of temporary storage above the permanent pool should be limited to 0.5 meters, meaning a retention basin has a maximum storage of 0.5 meters. Stormwater can leave the system through an outlet drain.

Figure 2-7 Concept of retention (left) and example of detention basin (right) (Woods Ballard et al., 2015)

Vegetative swales

Vegetative swales are channels or depressed areas with sloping sides covered with grass and other vegetation. They slow down and store stormwater runoff, allowing more time for evapotranspiration and infiltration. They are generally used to replace or enhance traditional curbs and gutters for transportation of stormwater. An underdrain can be applied if the infiltration capacity of the native soil is insufficient.

Swales should generally be designed with a bottom width of 0.5–2.0m, which allow for shallow flows without creating erosion. The longitudinal slope should be between 0.5-6%, for larger slopes check dams should be incorporated. Side slopes should be maximum 1 in 3 and preferred 1 in 4. The general maximum swale depth is between 400-600mm. Deeper depths increase land take requirements, water depths and lead to costlier excavations. The infiltration rate depends on the infiltration capacity of the soil and the longitudinal slope. Slopes should be smaller than 1.5% for infiltration to have a significant contribution. The infiltration capacity can be enhanced by combining the system with an infiltration trench. For a swale system the same requirement of half emptying in 24 hours does apply. The total storage capacity is the volume of the swale system and the porosity of the soil layer.

Swales are mainly suited for managing runoff from roads, but also from car parks and other impermeable surfaces. They require significant land take due to their shallow side slope, which make them less suited for dense urban areas. In these areas shallow swales with steep side slopes could be an option. Flow velocities for extreme events should be kept below 1 m/s. They can be designed as an open channel design with a Manning coefficient of 0.35.

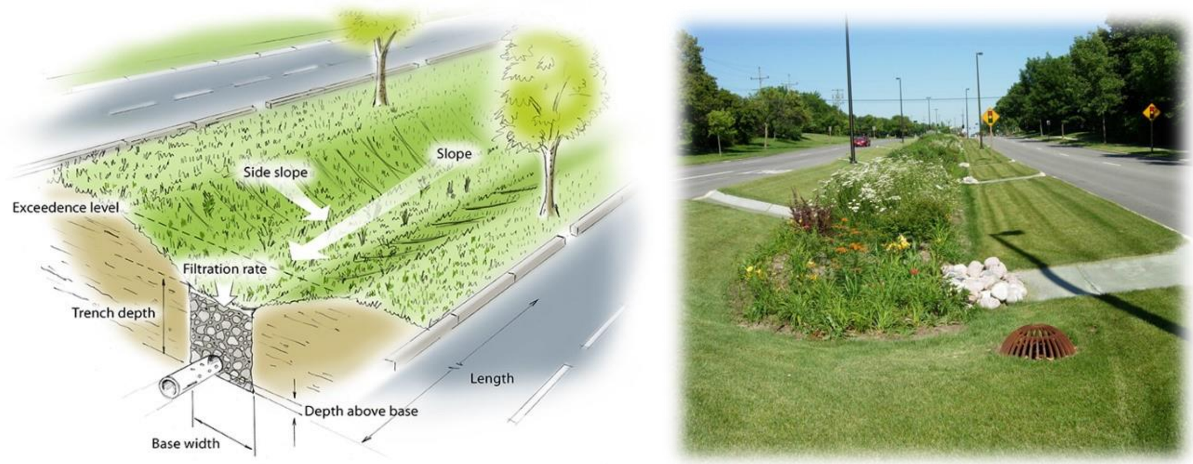


Figure 2-8 Vegetative swale concept and example (Ellis R, 2018)

2.2.3 Experimental data on NBS

In this subsection various experiments are discussed that test the infiltration capacity of NBS under different conditions. These experiments provide insights into the effects of antecedent conditions and help to establish more realistic infiltration capacities. First the effect of soil saturation on infiltration rates are described., then the findings in the experiments are translated to realistic input parameters for the models.

The effectiveness of certain types of NBS depends on the infiltration capacity of the soil. NBS can be designed for a specific infiltration capacity, however, various factors can impact this capacity. Using the design capacity in models can lead to an overestimation of effectiveness. The effect of soil saturation on the infiltration rates can be determined by experiments.

Experiments have been conducted on bioretention cells (Gravenberch, 2022; Venvik & Boogaard, 2020), permeable pavements (Alsubih et al., 2017; F. Boogaard et al., 2014; F. Boogaard & Lucke, 2019; Gravenberch, 2022; Kamali et al., 2017), and vegetative swales (F. C. Boogaard, 2022; Gravenberch, 2022) using full-scale infiltration tests (FSIT). Some experiments were run multiple times to evaluate the effects of soil saturation. FSIT inundates a much larger area of pavement/soil during testing compared to the more standard infiltrometer tests (F. Boogaard & Lucke, 2019). This way any spatial variations in infiltration capacity were effectively averaged out, which will produce more reliable infiltration data.

FSIT tests are performed in the Netherlands, with exception of one test in Bergen, Norway. The main results of the test are included in Table 2-3**.** A more detailed overview of the tests is found in Appendix A6. It is found that infiltration rates vary wildly between measures. The reduction of the infiltration capacity is very similar and falls between 40 & 50%. This is the reduction measured after repeating the test a few times, which simulates how the measure performs if several events follow each other up. Furthermore it must be noted that most measures are tested on sandy soils, which often have a high natural infiltration capacity.

Table 2-3 Parameters of NBS derived from experiments

	infiltration	**reduction**	**soil type**	**initial cond.**	**Location**
Bioretention cell	23 - 62 mm/h	42 – 43%	sand	natural	Tilburg
	177 - 1898 mm/h	-	'spongy'	100% sat.	Eindhoven
	23 – 43 mm/h	-	clay	70% sat.	Eindhoven
	318 – 1260 mm/h	41%	sand	60% sat.	Eindhoven
	510 – 1600 mm/h	-	loam	30% sat.	Bergen (NO)
Permeable pavement	29 – 503 mm/h	39%	all	dry & wet	16 cities (NL)
	270 – 1240 mm/h	-	-	natural	Delft
	43 – 155 mm/h	41 - 47%	sand	natural	Tilburg
	162 mm/h	-	clay	natural	Eindhoven
Vegetative swale	38 – 285 mm/h	50%	-	dry & wet	Dalfsen
	28 – 42 mm/h	-	sand	natural	Tilburg

The values from the experiments are used to define infiltration capacities for the measures in Paramaribo. The situation in Paramaribo is very different from the situation in the experiments. It is assumed that the infiltration capacity in Paramaribo will be on the low end of the spectrum. This assumption is based on the abundance of clay soils in Paramaribo and the overall lower quality of maintenance for infrastructure. So, experiments that are done on 'compacted' soils and the lower end of the range is taken as a benchmark. Furthermore, the design criteria in different design manuals are considered. This resulted in the following infiltration capacities for the measures:

Table 2-4 Infiltration rates for different types of NBS (VS = Vegetative swale, GR = Green roof, RG = Rain Garden, IT = Infiltration Trench, RP = Retention Pond, RB = Rain Barrel, BC = Bioretention Cell, PP = Permeable pavement)

VS	**GR**	**RG**	**IT**	**RP**	**RB**	**BC**	**PP**
25 mm/h	200 mm/h	25 mm/h	50 mm/h	-	-	50 mm/h	100 mm/h

2.2.4 Definition of the effectiveness of NBS

The effectiveness of NBS to mitigate flooding is determined by their ability to lower flood risk in a specific area. Flood risk is the combination of the likelihood and impact of flooding. In urban environments, where there is a high concentration of people and valuable assets, the socio-economic risk of flooding becomes particularly relevant as the potential risks can be significant (Colletine & Futter, 2018). Socio-economic risks refer to the economic and social effects of flooding, including building and infrastructure damage, health effects, and loss of life. This makes a flood risk assessment very complex (Figure 2-9)**.** This section provides an overview of the impact of flooding and how it relates to key hydrological characteristics such as inundation depth, flow velocities, and flow duration. This will substantiate the method for determining the potential of NBS.

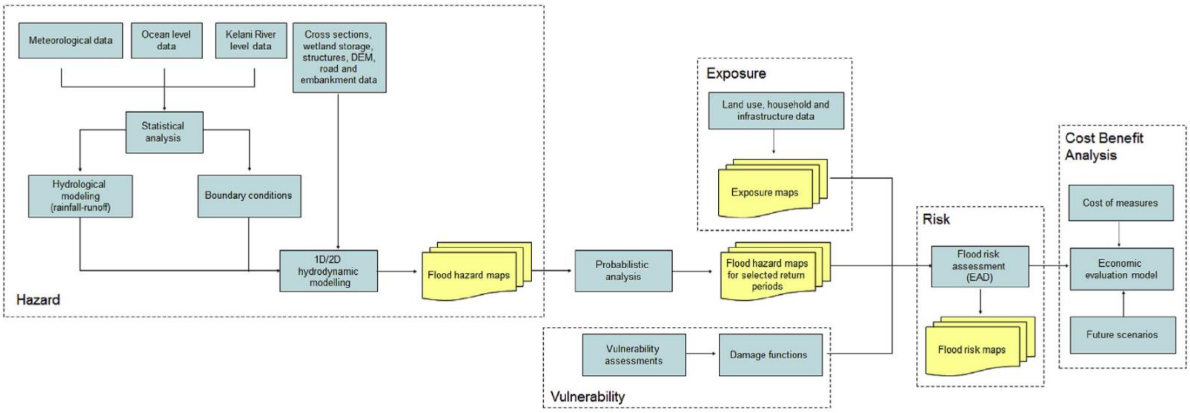


Figure 2-9 Overview of the risk calculation process (Wagenaar et al., 2019).

Estimating flood damage is a complex process that is often approached using simple methods due to limitations in available data and knowledge of damage mechanics (Merz et al., 2010). Flooding can originate from various sources, such as the sea, rivers, or heavy rainfall, referred to as coastal, fluvial, and pluvial flooding, respectively. NBS focuses on infiltrating and storing rainwater, and thus primarily mitigates pluvial flooding. However, most flood risk assessments are based on fluvial and coastal flooding. There is a lack of adequate pluvial damage models, which is a significant bottleneck in estimating damage and calculating costs in pluvial flood risk assessments (Van Ootegem et al., 2015). Pluvial flooding differs from coastal and fluvial flooding, in that it has higher rates of occurrence, shallower inundation depths, and larger flood extents (Tanaka et al., 2020). This means that impact may depend on different predictors.

Several studies have investigated the factors that influence flood damage using multivariate models. Van Ootegem et al. (2015) incorporates the effects of non-hazard indicators such as building characteristics, behavioural indicators, and socio-economic variables in addition to flood depth and duration. It concludes that flood depth remains the most important predictor, but notes that risk awareness can significantly lower damages. Merz et al. (2013) uses a tree-based data-mining approach that includes factors such as water depth, floor space, return period, contamination, inundation duration, and precautionary measures. They find that the most influential factors are water depth, flood duration, and contamination, which aligns with traditional approaches to flood damage estimation. Kreibich et al. (2009) focuses on flow velocities and concludes that they should not be included in flood damage modelling.

The studies reviewed above demonstrate that flood depth is the most critical factor in determining flood damage. This aligns with previous research and the traditional approach of using stage-damage functions for flood damage estimation in coastal and fluvial flooding. Based on these findings, this study will consider flood depth as the primary parameter for determining flood mitigation strategies.

2.3 MODELLING NBS WITH HYDRODYNAMIC MODELS

It is important for this research to identify which flood modeling methods compete with the CRCTool for evaluating its applicability. Selecting the appropriate model for a certain application can be challenging, given the many different modeling techniques available. The intended application largely determines the level of detail required in the modeling process. Factors such as the time required for computation, the availability and processing of required input data, and the availability of resources such as hardware, technical skills, and software, should all be considered.

A distinction can be made between hydrodynamic models and simplified conceptual models when it comes to modeling pluvial flooding. Hydrodynamic models are mathematical models that attempt to replicate fluid motion by solving equations that are formulated according to the laws of physics. This includes solving the Saint-Venant equation and derivations of the Navier-Stokes equations. Hydrodynamic models for urban pluvial flood modeling can range from simple to complex, such as 1D sewer, 1D overland, 2D overland, and coupling sewer-overland (1D–1D and 1D–2D) (Bulti & Abebe, 2020). Simplified conceptual models, on the other hand, do not simulate physical processes but are based on simplified hydraulic concepts. Each modelling method is described in more detail in Appendix A1.

In the following sections, the 1D-2D modelling approach is used to describe hydrodynamic modelling. This approach is widely used for evaluating the effectiveness of NBS (Appendix A2) and enables a more accurate comparison with the CRCTool. The 1D-2D modelling approach is particularly useful as it incorporates processes that are not accounted for in the CRCTool, providing valuable insights into the impact of these processes.

This section will first describe the fundamental components of hydrodynamic modelling. Thereafter the implementation of NBS within these models is depicted, followed by a summary of the key findings from earlier studies is provided.

2.3.1 Hydrodynamic modelling components

In this subsection the main components of hydrodynamic modelling are described. This highlight available choices in hydrodynamic modelling and which choices are made in previous research. The components are divided into rainfall, rainfall-runoff, and inundation.

Rainfall

The first part of hydrodynamic modelling is the definition of the rainfall input. Rainfall falls on the surface and either directly infiltrates, causes ponding, or is released as runoff. Rainfall can be modelled either continuously or as a single event. The first method uses entire rainfall time series, which can be either replicated from historic time series or simulated by, i.e., stochastic weather generators (Simões et al., 2015).

Modelling a single event is mostly done by using design storms, which is a hypothetical storm for a specific return period and duration. These can be based on Intensity Duration Frequency (IDF) curves and are often location specific. A popular example of a design storm that is frequently used in flood modelling is the Chicago design storm (Figure 2-10) (Huang et al., 2020). Multiple design storms with different return periods can be modelled to find a relation between increasing storm intensity and flooding extent.

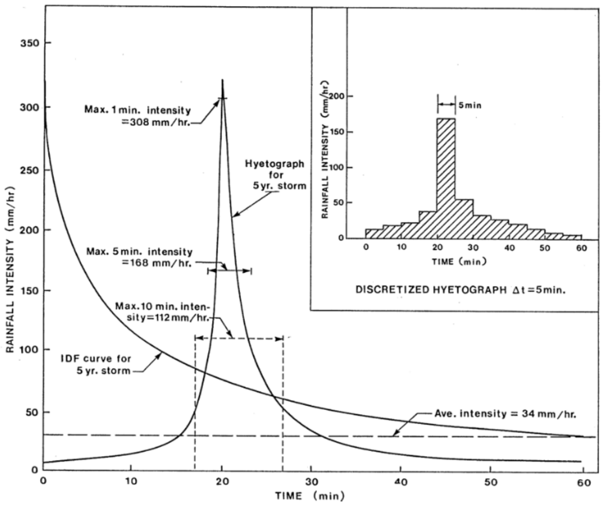


Figure 2-10 Example of a design hyetograph of a rainfall event (Chicago design storm) (Olsen et al., 2015)

Rainfall-runoff

Estimating the runoff from a rainfall event can be done with different methods. A simple empirical method that is used in different research (Eckart et al., 2017; Ferreira et al., 2020; Lallemant et al., 2021; Wagenaar et al., 2019) is the use of the Soil Conservation Service (SCS) Curve Number (CN). The SCS-CN method predicts runoff from an expression for a rainfall-runoff curve that varies according to a single parameter called the curve number (CN). The curve number is based on empirical evidence.

Another method for estimating the rate of infiltration into the soil from rainfall is the Green-Ampt method, used in (Burszta-Adamiak & Mrowiec, 2013; Liu et al., 2014; Ebrahimian et al., 2021; Watkin et al., 2019). This method assumes that the soil is initially dry, and that infiltration occurs through a single, continuous wetting front. The model considers the hydraulic properties of the soil, such as the soil moisture content, the hydraulic conductivity and the intensity and duration of the rainfall.

A third method is Horton’s method, used in (Jamali et al., 2018; Ferreira et al., 2020; Freni et al., 2010; Kong et al., 2017; Cui et al., 2019; Costa et al., 2021; Zeng et al., 2019) . This method assumes that the infiltration rate is proportional to the difference between the initial infiltration capacity and the cumulative infiltration. This means that as the soil becomes more saturated with water, the rate of infiltration decreases over time. Horton's method can be expressed as an exponential function, with the infiltration rate decreasing exponentially over time. The model has two parameters: the initial infiltration capacity and a decay coefficient that determines the rate at which the infiltration rate decreases over time.

Inundation

The third part of hydrodynamic modelling is the modelling of water flows. In 2D models these flows are simulated on a grid by solving the 2D shallow water equations for each grid cell, which represent mass and momentum conservation in a plane and can be obtained by depth-averaging the Navier-Stokes equations (Teng et al., 2017). There are two main approaches: Directly or indirectly simulating of rainfall on the grid.

Directly simulating rainfall is rainfall directly simulated on the grid where flows are generated from each grid cell. This considers ponding; however, it is computationally heavier and relies on an accurate and detailed grid. The other option is to simulate flooding from the 1D sewer system. In this case rainfall is coupled to the 1D sewer system as lateral 0D input. Flooding happens if the capacity of the sewer system is exceeded. This method does not consider ponding and does not consider overland flow to the sewer system.

2.3.2 Implementation of NBS in hydrodynamic models

NBS alter spatial properties, like infiltration rates, roughness, and evaporation rates. By altering these spatial properties they lower runoff peaks and total runoff volumes from rainfall events. These processes can be mimicked in modelling software. In this part the main methods used in previous studies will be clarified. There are two main methods used in literature for hydrodynamic modelling, either by manually altering model parameters or by specifically integrated LID modules. Appendix A2 provides an overview of the previous studies done into the effectiveness of NBS, and an overview of the modelling software used.

Manual implementation

The first method mainly uses artificial storage, adjustments in infiltration capacities and land use changes. This method is mostly used for implementing NBS in more rural and peri-urban areas, where existing green space is altered to provide extra water storage or land use changes, i.e., forestation to lower runoff and erosion rates.

Land use change effects on infiltration/runoff is often represented with a modified CN. This ignores the effects that varying rainfall intensities and event frequencies have on surface infiltration, soil moisture retention and storage capacity. For rural areas this can be justified, because the measures are often applied on large scales and the dominating processes are mostly retention and interception.

For measures in urban areas infiltration becomes more important because this process is more dominant for draining water than in rural areas. Besides, the complexity of the measures increases. This complexity is found in multiple drainage layers and catching runoff from adjacent impervious areas. The discussed method is thus less sufficient for urban small-scale NBS.

LID module

The second method uses integrated LID modules in software like SWMM and MIKE, which is more elaborate (Rossman & Huber, 2016). This paragraph describes the SWMM LID module, which operates similar to the MIKE LID module.

The LID module considers the NBS to be part of a sub catchment, where it is assigned a fraction of the sub catchment's impervious area, whose runoff it captures. It includes the following design variables that affect the hydrological performance: properties of the soil/gravel of each layer, the depth of the vertical layers, the hydraulic capacity of the underdrain if used and the surface area of the measure itself. Measures are treated as an additional type of discrete element, using a unit process-based representation of their behaviour.

As an example the implementation of a bioretention cell will be taken. It consists of three layers: surface layer, soil layer and storage layers. The surface layer receives rainfall and runoff and loses it by infiltration, evaporation, or runoff. The soil layer receives infiltration from the surface layer and loses water by either evaporation and by percolation to the storage layer. The storage layer consists of coarse crushed stone or gravel. It receives percolation from the soil layer and loses water by infiltration in the underlying natural soil and by outflow by an underdrain if present.

The NBS is modelled by solving a set of simple flow continuity equations. Each equation describes the change in water content in a specific layer over time as the difference between the inflow and the outflow water flux rates, expressed as volume per unit area per unit time. The equations can be found in (Rossman & Huber, 2016). The following assumptions must be made for using these equations: cross-sectional area is constant throughout depth, flow is 1D in the vertical direction, inflow is distributed uniformly over the top surface, moisture content is uniformly distributed throughout the soil layer and matric forces in the storage layer are negligible, so it acts as a simple storage reservoir.

2.3.3 Main findings in previous studies

The previous research provides valuable insights for the analysis of the CRCTool in this study, as well as for the development of a D-HYDRO model of the area. This subsection describes important findings from previous research, which are related to the general approach, how NBS are represented and the type of event modelling.

An overview of all the studies shows most modelling of NBS has been done with a hydrodynamic 1D-2D approach. There are many differences in modelling dimensions, event definition, NBS representation, area type and runoff modelling. It can be said that there does not exist a generalized method for modelling NBS. So there is no clearly defined best practice in modelling NBS.

Earlier studies show that (rural) implementation of NBS is mostly done by land use changes or modelling storage areas artificially using weirs and depressions (Ferreira et al., 2020; Watkin et al., 2019; Schubert et al., 2017). Measures in urban areas are most of the time more complex, consisting of multilayered systems that specifically optimizes infiltration capacity and storage. Representing them as just conceptual tanks or land use change will not accurately represent the performance of these measures.

A more elaborate approach for urban implementation is the use of the LID toolboxes in SWMM and MIKE. The studies with these LID Toolboxes have a similar freedom in parameterisation of NBS compared to the CRCTool. Unfortunately, NBS parameters in these studies were standardized and based on the pre-given parameters in the SWMM toolbox (Kong et al., 2017). They also did not consider factors like the underground water level, evaporation, and current water retention on the simulation results in the model simulation.

Most of the previous research into NBS is done by event modelling. The antecedent conditions are guessed. These conditions can potentially have a large impact on the performance of NBS, because their performance depends largely on their initial water content. So these conditions can have a large impact on the overall performance of the NBS. The CRCTool has the added benefit of being able to model continuous rainfall time series and considering processes like evaporation and transpiration.

To conclude, previous research raises the question what the best approach is to model NBS. There is uncertainty in the added benefit of complexity when modelling NBS. It is also uncertain how much added detail in the modelling contributes if the uncertainties in the input are already large. It could be that a conceptual model provides accurate enough results and gives important additional insights due to its ability to model long time series. So, could conceptual modelling be sufficient on its own? This is posing an interesting case in the quest to the applicability of the CRCTool.

2.4 CLIMATE RESILIENT CITY TOOL

The CRCTool is a web-based tool that provides a map view where users can draw NBS as polygons in a self-defined study area. Users can adjust basic parameters of the NBS, such as depth and inflow area, and the tool will calculate the effects of the measures on storage capacity, runoff reduction, groundwater recharge, evaporation, and heat reduction. It also provides information on cost estimations and effects on water quality.

This study focuses on flood risk reduction, and thus the emphasis is on storage capacity and runoff reduction. The tool's calculations are based on precalculated tables with runoff reduction factors, groundwater recharge, and evaporation values. The look-up table that the tool uses is produced by an urban water balance model, which describes all possible urban water flows and associated water resources. It does not calculate flow dynamics and flow routing, resulting in significantly less computational effort and allowing it to handle long rainfall time series.

First the urban water balance model, the conceptual model behind the CRCTool, will be described (subsection 2.4.1). This is followed by a description of the main performance indicators in the CRCTool for determining flood mitigation (subsection 2.4.2).

2.4.1 Urban Water Balance Model

Overview & model requirements

The Urban Water Balance Model (UrbanWB) is a tool designed to determine the return periods of runoff events for small, homogenous urban areas. The model uses statistical methods and requires a large dataset of rainfall and evaporation data, ideally spanning at least 30 years. UrbanWB is a lumped conceptual model that simulates the main components of the urban water cycle, such as rainfall-runoff, shallow groundwater flow, and the sewer system. The model also considers external boundaries like the atmosphere, deep groundwater, and Outside water. The model is divided into different land use areas: paved roof (PR), closed paved (CP), open paved (OP), unpaved (UP), and open water (OW). These areas are connected to below-ground systems like the unsaturated zone, shallow groundwater, and/or the sewer system. Flooding is simulated through two indicators: sewer overflow into the streets and storage height above the target open water level. The model also includes an open water area, which serves as a buffer and discharge point for excess water in the urban area. The schematic overview in Figure 2-11 and the major components described in accompanied table provide a schematic overview of the model's workings.

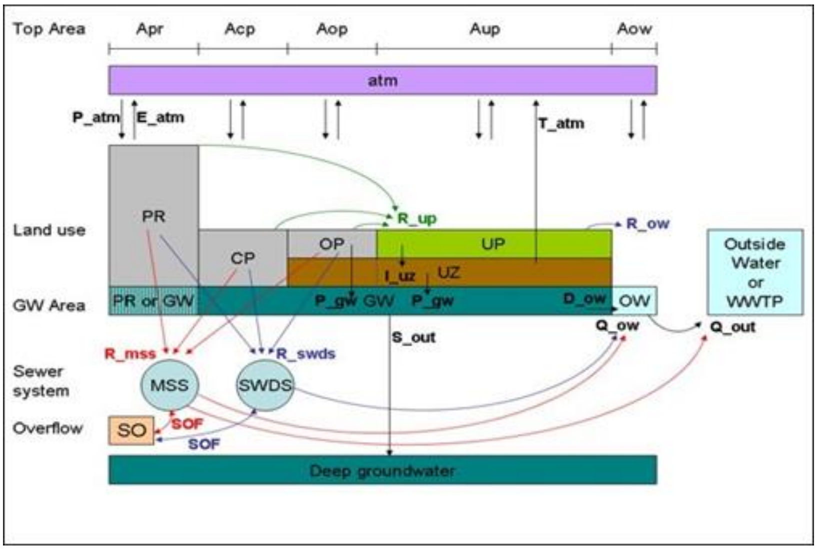


Figure 2-11 Schematisation of main components and fluxes of UrbanWB

Land use area
Paved Roof (PR)
Closed Paved (CP)
Open Paved (OP)
Unpaved (UP)
Open Water (OW)
Below floor level
Unsaturated zone (UZ)
Shallow groundwater (GW)
Sewer system (MSS/SWDS)
Boundaries
Atmosphere (atm)
Deep groundwater
Outside water or WWTP
Other
Sewer Overflow (SO)

Model components & fluxes

The components of the model, as depicted in the Figure 2-11, will be thoroughly discussed in this part. First a description of the various land use areas is given, followed by an examination of the subterranean components and the system boundaries.

Paved roofs are all the buildings, including sloped and flat roofs. Rainwater is collected on rooftops in gutters and drains, which lead to the sewer system. A small amount of water may pond on the roof and this is defined as interception storage, which can only be emptied through evaporation. The model assumes that the roof can drain all rainfall intensities and thus overflow from the gutter cannot occur.

Closed paved areas are all areas that are made of impermeable materials and do not allow water to infiltrate. This includes roads and parking lots. They work similarly to paved roofs, but with additional interception storage which can only be emptied by evaporation. Rainfall exceeding the interception storage will also drain to the sewer system.

Open paved areas are less impermeable surfaces that have relatively limited infiltration capacity. They work similarly to closed paved areas, but with an extra infiltration flux that is connected to the shallow groundwater. This flux is limited by an infiltration capacity.

Unpaved areas are parks and green zones and have no paved surface. Excess water mainly infiltrates to the unsaturated zone underneath. From there it percolates to the deep groundwater or is drained to the open water via the shallow groundwater. It also has an interception storage; however water can infiltrate and evaporate from this layer simultaneously. Water exceeding the interception storage is assumed to drain to the open water. The vegetation type for the unpaved area is predefined and determines the maximum moisture content of the root zone and saturated permeability of the soil.

Open water includes ditches, canals and ponds. In the model, the open water level has a fixed target level. Above this level, water will be discharged to outside water. This discharge capacity is limited by the maximum discharge capacity of the pumps. If the water level gets below the target water level, it will be refilled by outside water.

The unsaturated zone is only connected to the unpaved area, as it is assumed that water flow is mainly vertical in unpaved areas. This area has the same size as the unpaved area. Inflow happens as infiltration from the unpaved area and as capillary rise of groundwater towards the root zone. Outflow happens through soil evaporation, crop transpiration, and percolation to the groundwater. Evapotranspiration from the root zone is modeled as the product of reference crop evapotranspiration and transpiration reduction coefficient. Transpiration reduction coefficient is derived from the concept of Feddes plant water stress factor in the literature (Feddes et al, 1974).

The shallow groundwater layer, which is modeled as an unconfined aquifer, is located beneath the unsaturated zone. It is composed of a pervious layer above an impervious layer. The groundwater level is recharged by percolation from the open paved area and the unsaturated zone and depleted by downward seepage and drainage to the open water. Inflow and outflow in this layer are driven by head differences. It is assumed that the downward seepage is a constant flux, as variations in this flux are minimal and it simplifies the calculation. The equations for the groundwater level during the current time step and its derivation are given in Appendix A7.

Water exchange with external boundaries is defined in the input data. The main driving forces, such as rainfall and evaporation, exchange water with the atmosphere. These are defined as long-term time series that apply to the entire study area. The exchange with deep groundwater is defined as a constant downward flux. This flux is relatively small and can be assumed to be constant, as fluctuations are negligible. Finally, exchange with outside water occurs when there is excess water in the open water areas. This is also defined as a constant flux, based on the maximum pump capacity of the pumps in the study area.

Statistical analysis

The CRCTool is designed to analyze the runoff events rather than the rainfall events, as this approach allows for a more comprehensive understanding of how different initial conditions and rainfall distributions can impact the runoff. This is particularly useful for assessing the performance of NBS, which interact with the runoff. The tool separates events based on rainfall and storage in the system, with an event being defined as a period of 6 hours without rainfall and a single hour without an increase in open water storage above the target level. This means that multiple rainfall events can be included within a single event if the water level has not returned to the target level.

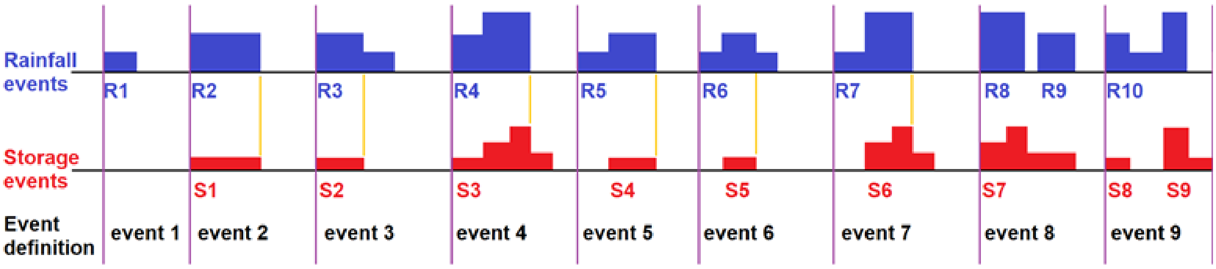


Figure 2-12 Schematisation of event separation, based on rainfall and storage events

The events are ranked by arranging them in descending order of total runoff. The probability of exceedance for each rank is calculated using the Weibull formula, from which the corresponding return period can be determined:

$$P = \frac{m}{N+1}, \quad T = \frac{1}{P} \tag{1}$$

where m is the rank number and N is the number of years of the timeseries.

The runoff depths are plotted against the corresponding return period for all results, an example is shown in Figure 2-13. This analysis is repeated for various NBS retention sizes, causing a shift in runoff return period. The average of this shift is calculated for different runoff depths, which is called the runoff reduction factor. This factor is discussed in more detail in subsection 2.4.2.

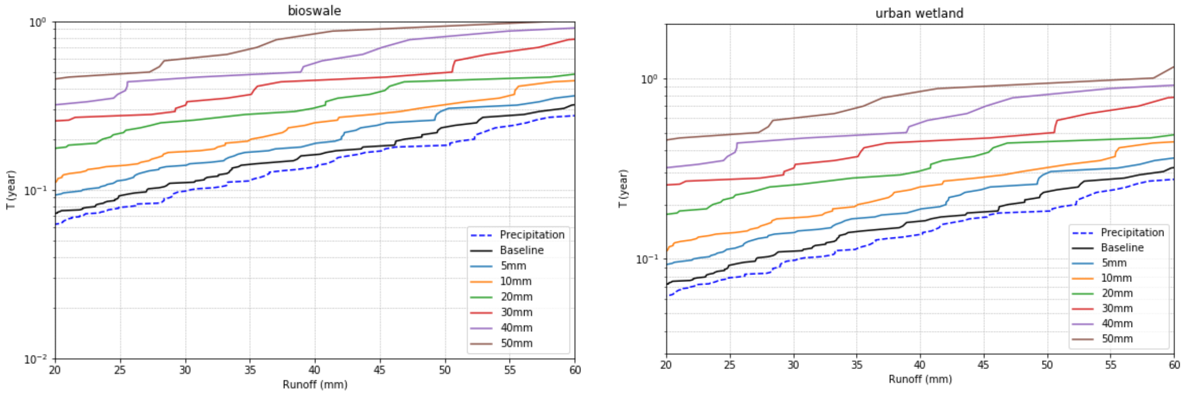


Figure 2-13 Return period shift of runoff volumes for different effective measure depths (Vergroesen T & Brolsma R, 2020)

General assumptions

The runoff from paved areas flows to the sewer systems regardless of their inflow capacities, as the excess capacity is handled separately as sewer overflow on the streets. The discharge capacities of the sewer systems cannot be directly defined in the configuration file. So, for Paramaribo the Dutch standard of sewer overflow occurring once every two years is used. Runoff from disconnected paved areas is directed to the unpaved area and is added to the water available for infiltration and evaporation for the unpaved area. All other runoff water on the unpaved area is assumed to flow to the open water. Internal routing is not considered in the UrbanWB model, as it only applies to relatively small urban areas with homogenous hydrologic conditions. This means that the model is suitable for use at a neighbourhood scale, but its applicability at larger spatial scales may be questionable.

In the model, any water flow from one area to another is limited by three factors: the available water volume in the source area, the available storage in the destination area, and the transport capacity between the two areas. There is no vegetation on the open paved area, and thus no transpiration from the root zone below the surface. As a result, for simplicity, the infiltration from the open paved surface directly percolates into the groundwater and bypasses the unsaturated zone. When implementing a measure, the measure's inflow area comes from one source. For instance, if a measure is defined in the open paved area, the inflow area is also in the open paved area. It is possible to define the measure's inflow area not only in the open paved area but also in the paved roof and closed paved areas. However, these possibilities have not been fully developed and tested yet.

NBS implementation

The UrbanWB model includes a module specifically designed to simulate the mechanisms of NBS and integrate them with the dynamics of the urban water system. NBS are designed to reduce urban flooding by creating temporary storage, facilitating infiltration, and increasing evapotranspiration.

They can be defined as 1-layer, 2-layer, or 3-layer systems. A 1-layer system contains only an interception layer, which creates storage and allows evaporation. A 2-layer system includes an interception layer and a bottom storage layer, which provides water storage, allows for evapotranspiration, percolation to the shallow groundwater, and controlled runoff. Controlled runoff refers to the runoff volume that is temporarily stored in the measure and is released either continuously or delayed at a later time. A 3-layer system includes an interception layer, top storage layer, and bottom storage layer. The additional top storage layer is used to model measures such as green roofs and vegetative swales, which have a growing medium that promotes evapotranspiration and a drainage layer beneath the growing medium that drains excess water to the sewer system. This layered system is hard to implement in hydrodynamic modelling. This gives an advantage to the CRCTool, because it can better represent the differences in flow characteristics of each layer.

2.4.2 Model output: Performance indicators

The CRCTool is designed to estimate the effectiveness of NBS in reducing flood risk. Two key performance indicators used in the tool are the required storage capacity and the runoff return period.

The required storage capacity can be determined by analyzing the storage-discharge frequency (SDF) relationship, which shows the necessary storage demand in a specific area for a specific pump capacity. The storage capacity is determined by the maximum open water storage depth during an event. It should be noted that installing a larger pump alone may not be sufficient to address flood risk, as the capacity of the stormwater drainage system leading to the pump must also be increased. Additionally, the results of the CRCTool should be considered approximate until engineers and planners can assess the effectiveness of conveyance to the pumps. The comparison in D-HYDRO will show the importance of this conveyance, which will tell something about the usability of the approximation of the CRCTool.

The runoff return period is important in controlling the peak flow of stormwater runoff at the discharge point. NBS can store water that would otherwise be runoff, reducing peak flows and reducing the risk of bank erosion, sediment wash-off and sediment transport. The CRCTool allows for setting targets for the normative runoff, which is the runoff return period of an event that should not cause inundation. This target can be adjusted to account for the potential impacts of climate change.

SDF curve

An SDF curve is a graphical representation of the relationship between the storage capacity and the discharge frequency of an event. It is used to determine the amount of storage required to prevent flooding during extreme weather events. The curve is based on the maximum amount of water that needs to be stored during an event and is calculated using extreme value analysis and a Weibull fit. This analysis is used to determine the return periods for different maximum storage capacities, allowing engineers and planners to design systems that can handle the most extreme events.

Runoff reduction factor

The CRCTool calculates the change in return periods of urban runoff volumes as a result of implementing NBS. NBS can reduce the frequency of flooding by decreasing the runoff volume, resulting in an increased return period. For example, if a runoff event that currently occurs every two years can be reduced to an event that occurs every four years, the damage caused by the event will occur 50% less often.

The tool differentiates between controlled and uncontrolled runoff. Controlled runoff refers to water that is released through infiltration or slow/delayed release to the drainage system. Uncontrolled runoff is water that exceeds the storage capacity of the measure. The tool claims that measures change the return periods of runoff volumes by a constant factor, allowing for easy calculation of a single reduction factor for all types of events. However, this claim is based on an empirical finding from a single Dutch case and has not been widely tested, making it necessary to critically evaluate its validity in this research (Vergroesen & Brolsma, 2020).

The return time factor must be extrapolated to the entire project area. The initial reduction factor, which is based on the measure's inflow area, is only applicable to that specific area. The calculation assumes that the inflow area for the measure's runoff is entirely composed of paved areas, and that the fast runoff from non-paved areas is a percentage of the fast runoff from paved areas. This percentage depends mainly on the area relative to the total area and on the soil composition. However, in general the order of magnitude can be estimated at 5% of the fast runoff from paved areas. Additionally, it is assumed that the runoff return period is an exponential function of the event runoff, which implies that the runoff in mm is a Natural Logarithmic function of the return period in years. This results in the following equation:

$$F_{tot} = \left(\frac{A_p * e^{\frac{A_{mi} * \ln(F_{meas})}{A_p} + \frac{Perc_{RA}}{100} * (A_{tot} - A_p)}}{A_p + \frac{Perc_{RA}}{100} * (A_{tot} - A_p)} \right) \tag{2}$$

where F_{tot} = Runoff reduction factor for total area, F_{meas} = Runoff reduction factor for measure inflow area, A_{tot} = Total area, A_p = Paved area, A_{mi} = Measure inflow area and $Perc_{RA}$ = Runoff from the rest of the area, estimated as a percentage from the runoff from paved area.

2.5 CONCISE MODELLING FRAMEWORK

Based on the previous sections in this chapter, a modelling framework for this study can be made and substantiated. This chapter starts with describing how NBS are defined, followed by how the CRCTool fits into the current methods of modelling NBS modelling. The last part substantiates the development of a hydrodynamic model for comparison. The detailed description of the modelling frameworks for the CRCTool and the hydrodynamic model is given in section 3.4 and 3.5 respectively.

Nature-Based Solutions

This study incorporates NBS in the form of second-layer storage, intercepting rainwater before it reaches the urban drainage system and thus reducing peak flows (Figure 2-1). The focus is on small-scale NBS, which are applicable on neighborhood scale and do not require large interventions in existing infrastructure (Table 2-1).

NBS design parameters are based on the elaborate design manual for NBS from the UK (Woods Ballard et al., 2015) and is supported by various research specific into tropical conditions and experiments into the infiltration rates. An overview of the design parameters is given in Table 2-2 and Table 2-4. Effectiveness of the NBS for flood mitigation is based on flooding depths/volumes (section 2.2.4)

CRCTool

The CRCTool is different from the available modelling techniques and their characteristics. The tool is based on long rainfall time series with dozens of different real events. This gives additional insights into long-term effects, which is not possible in hydrodynamic modelling. This way different event progressions and initial conditions are modelled. Furthermore, the tool uses less calculation time and is free to use. It is also more accessible for people from a different expertise. Furthermore, it considers important processes for NBS like groundwater exchange, infiltration, and capillary rise.

However, compared to hydrodynamic modelling it has no routing component. So, it only works at small scales where flow paths are clearly defined. There are no limitations in the sewer system. Water drains directly from the sewer to the pump. This means water is always available at the pump and the pump thus always works in optimal condition.

Regarding the input of NBS in the model, the CRCTool shares the same freedom in NBS parameterization as the LID toolboxes. In this research the given parameter input is supported by a thorough analysis of NBS parameterisation (section 2.2).

The main outputs of the CRCTool for determining the effectiveness of NBS for flood mitigation are the SDF curve and runoff reduction factor. To determine the applicability of the tool, these outputs are examined. This contains testing the methods and assumptions for producing these outputs which are described in subsection 2.4.2. The runoff reduction factor for different parameter ranges and different measures is compared to look for any anomalies.

Furthermore, the conceptual hydrological processes in the UrbanWB described in subsection 2.4.1 are critically assessed. Focussing on the division of precipitation in runoff, evapotranspiration, and infiltration and the interaction of measures with the groundwater component. For the runoff there is also looked at the division in controlled and uncontrolled runoff.

Lastly the absence of internal routing and the assumption that the runoff from paved areas flows to the sewer systems regardless of their inflow capacities is tested by comparing the outputs to a hydrodynamic model, discussed in the paragraph below.

D-HYDRO

To compare the performance of the CRCTool with a more detailed flood modelling approach, a 1D-2D model of the study area was developed using D-HYDRO. This modelling approach was chosen as it is the most detailed method of flood modelling and allows for a better representation of the processes that are absent in the CRCTool. This gives the best possible insight in the effect of these processes. Additionally, this is made possible by the availability of detailed LiDAR data (discussed in section 3.3), which makes it possible to develop a detailed 2D grid.

Furthermore, it is chosen to model rainfall directly onto the grid because this will simulate overland flow. Overland flow is captured by the NBS used in this research as discussed in section 2.1. By modelling the overland flow, it is made possible to represent NBS two dimensionally onto the grid. This way the actual flows that are captured by each measure can be simulated. This method is made possible by the available detailed schematisation of the drainage system of the study area and the detailed LiDAR data (section 3.3).

To prevent additional uncertainties, the implementation of NBS in D-HYDRO was kept as simple as possible. Previous studies that did not use a dedicated LID toolbox also used a similar approach (Appendix A2). The complexity of NBS measures in urban areas makes it challenging to model them accurately using a simple approach. Furthermore, a simple approach makes it easier to compare the output of the two models by minimizing uncertainties and ensuring that model parameters are consistent. Thus, a simple measure was selected for comparison purposes, which is discussed in section 3.5.

3 METHODS AND MATERIALS

This chapter shows the study area characteristics, describes the data collection and processing and the methods for modelling in the CRCTool and D-HYDRO to get the desired output. The first section (3.1) outlines the study area, describes its characteristics, and gives the methods used to analyse the area to provide modelling input. The second section (0) describes the rainfall and evaporation data and the process of analysing this data and the third section (3.3) describes the collection of the additional data needed for the D-HYDRO modelling. Section 3.4 and 3.5 describe the modelling framework proposed in section 2.5 in detail for the CRCTool and D-HYDRO respectively. The last section (3.6) describes how the CRCTool is used in a design workshop with stakeholders. An overview of the research structure is given in Figure 3-1 and Table 3-1 shows the various software programs used for data creation and analysis.

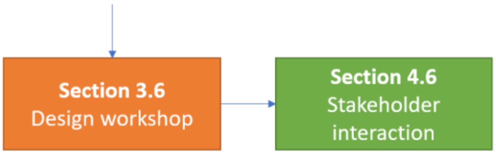


Table 3-1 Types of software used in the analysis performed in this study

Area analysis	Rainfall analysis	Drainage system analysis	Hydrodynamic modelling	CRCTool analysis
Q-GIS 3.22.6	JupyterLab 3.0.14	SOBEK216	D-HYDRO 2023.01	Spyder 4.2.5

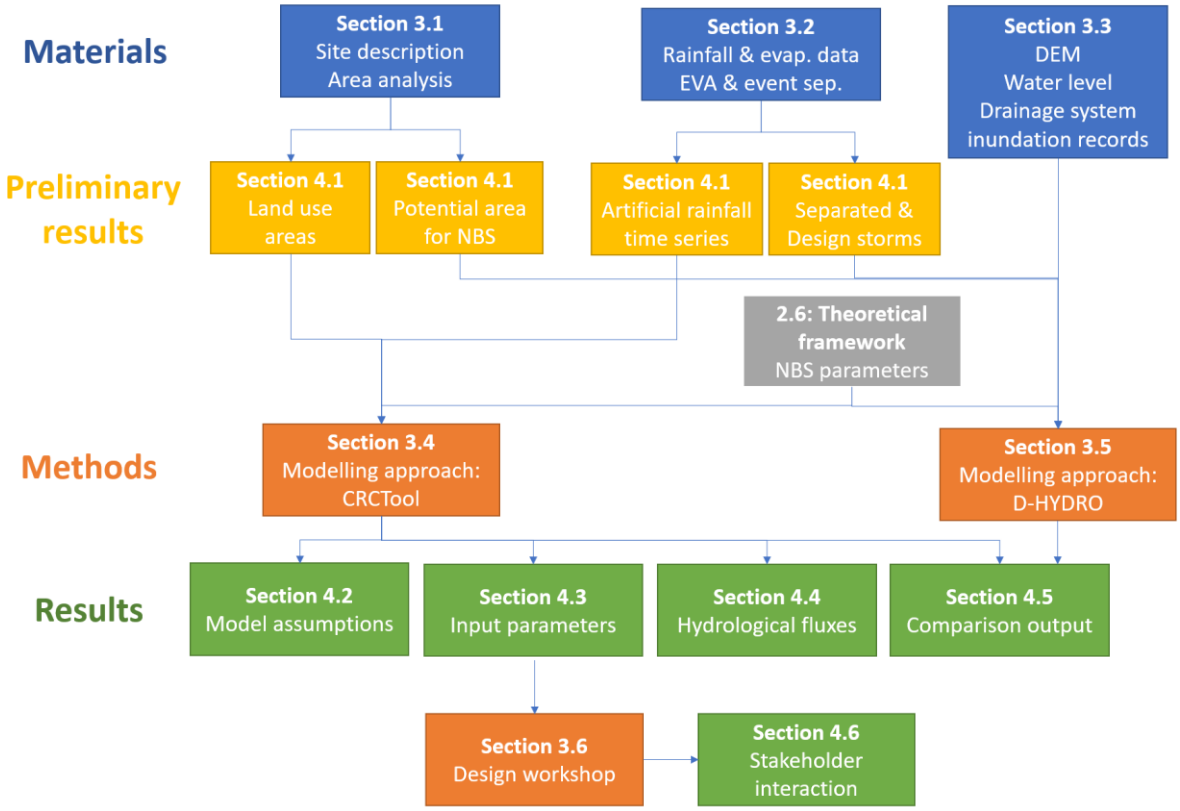


Figure 3-1 Schematisation of the research structure

3.1 SITE DESCRIPTION

This section gives an overview of the study area. The site description is based on topographical data, elevation data and photographs from the study area. The first subsection (3.1.1) describes how the study area is established and relates the geology and historical development to the current flooding problems in the area. The second subsection (3.1.2) provides a detailed description of the study area, including topographic characteristics, the drainage system, and flood-prone areas. The last subsection (3.1.3) describes how the area is analysed for land use determination and suitability of NBS.

3.1.1 Establishment of study area

This research is in collaboration with the Saramacca Canal System Rehabilitation Project Lot 2 (SRCP Lot 2 project) (Prinsen et al., 2021), a project in Suriname carried out by Deltares in partnership with Royal HaskoningDHV, and with subcontractors Ilaco N.V. and Kavel10BV. The objective of the project is to support the Government of Suriname in effectively managing the flooding issues in Greater Paramaribo, which includes the capital city of Suriname, Paramaribo, and parts of the districts of Wanica and Saramacca (Figure 3-2). The area is located along the Suriname River and near the river mouth in the Atlantic Ocean. The city is sprawling, covering an area of 182 km^2 and with a population of approximately 250,000 people (as of 2014). The following information about the study area is provided by the SRCP Lot 2 project.

Within the project three pilots (urban, suburban, and rural) are chosen to study the drainage system more closely. One of the pilots is the "Binnenstad" (urban), which is a densely urbanized area (Figure 3-2). The limited space makes it well-suited for small-scale NBS (Oral et al., 2020). This research focuses on the catchment area of this pilot, which includes the pilot and an upstream area three times the size of the original pilot. This area was selected because it represents a closed hydrological system and allows for the implementation of NBS outside the pilot that still affect the pilot.

Figure 3-2 Satellite image of Greater Paramaribo and the urban pilot 'Binnenstad' with its corresponding catchment

The geology and historical development of the Paramaribo region have a significant impact on the current flood risk. The city was established in 1613 along the west bank of the Suriname River, with its historical center located about 10-15 km from the river mouth. The coastal plain, where the city is located, is characterized by young clay soils and several lines of slightly elevated sandy shell ridges that run in an east-west direction. These ridges are separated by low-lying, swampy areas. The main east-west roads were built on the higher sandy grounds, with residential areas and smaller roads situated in between. The combination of these soils and the low elevation of the region result in inadequate drainage conditions in the areas between the ridges, contributing to the flood risk in Paramaribo.

3.1.2 Study area characteristics

The study area is bounded by the Kwattaweg in the northeast, which is situated on a sandy ridge. In the west, it is bordered by a graveyard that has a slightly higher elevation. The southwest border is a less defined, slightly elevated area. To the east, the study area is bordered by the Suriname River. The pilot area mainly comprises commercial zones, with many stores and parking spaces. It is densely built, with almost no green spaces. The upstream area is less densely populated, with more houses with gardens and other green spaces. It is worth noting that there are hardly any public parks in the area, and most of the open spaces in the upstream area are abandoned lots. The streets in the area are wide, with often ample parking spaces on both sides. The pilot area has sidewalks, which are mostly absent in the upstream area. The street profile is lacking in greenery, with only the Jodenbreestraat and Dr. J.F. Nassylaan having trees along the road.

Figure 3-3 Boundaries of study area based on the Catchment of the study area (OpenStreetMap)

Figure 3-4 Heerenstraat in Paramaribo, representing the general street profile in the Binnenstad (Del Hierro et al., 2021)

Greater Paramaribo can be divided into 8 main drainage directions, with the city primarily draining its water to the Suriname River, which is also the case for the study area. The pilot area comprises a closed pipe system and one functioning pump. This pump is located at the end of the Jodenbreestraat and has two pumps with a capacity of 1.25 m^3/s each. Another pump is located at the end of Knuffelsgracht, which is no longer in operation. The pilot area receives water from the upstream catchment area, which is mainly drained by two primary open drainage canals, the Viotte and Picorni Kreek, and small tertiary drainage pipes along the streets. There is one connection to the area in the northeast, running under the Kwattaweg, and several connections in the southwest. The modelling framework for D-HYDRO describes how the influence of these connections is quantified (section 3.5).

The low-lying areas, depicted in blue and green in the figure, are typically characterized by clay soils, while the elevated areas, indicated by the darker red, mainly consist of sandy soils. There are two depressions visible in the digital elevation model (DEM) (red squares in Figure 3-5). One is located in the northwest at the intersection of the Verlengde Keizerstraat and the Van Idsingastraat. The other one, which represents the lowest point in the area, is located in the southeast at the intersection of the Jodenbreestraat and Maagdenstraat. These areas are the most susceptible to flooding and are identified as the two main problem areas in the study area.

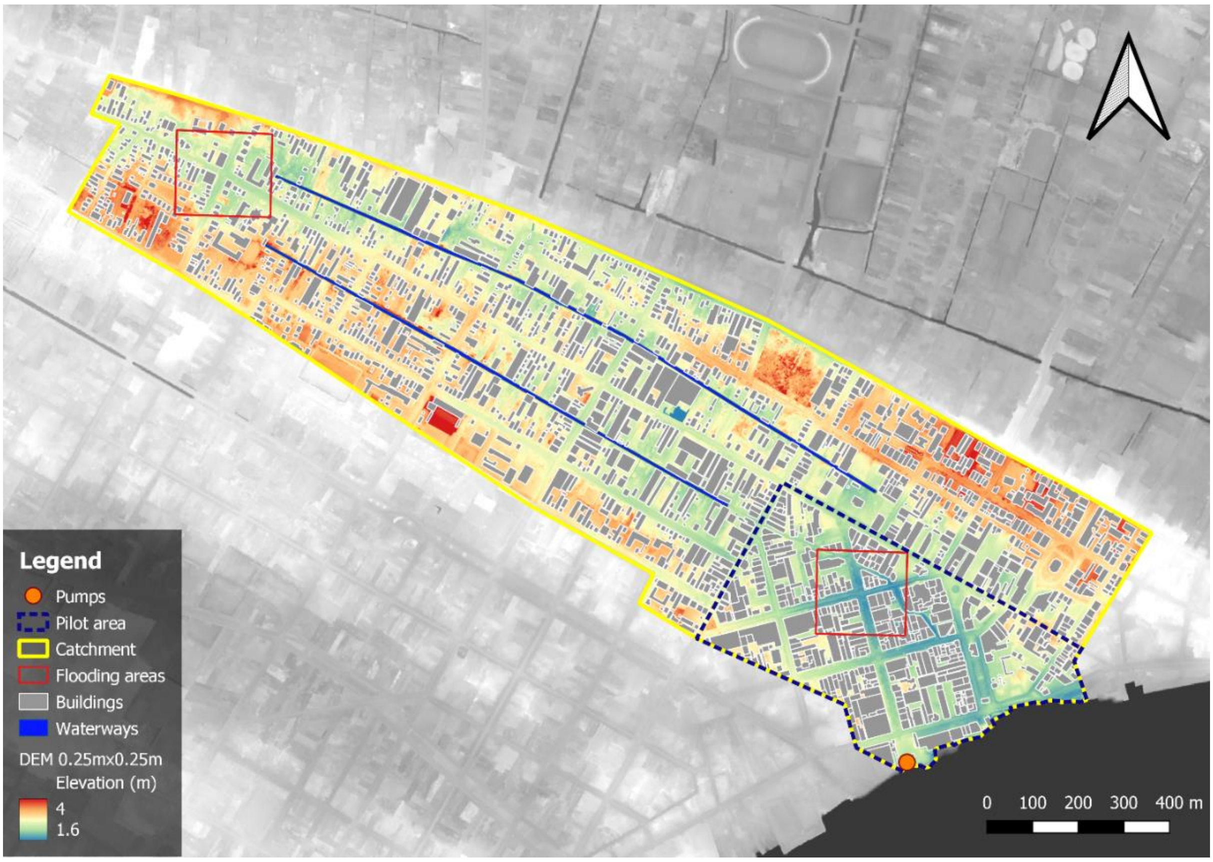


Figure 3-5 Digital Elevation Map (DEM) of study area, highlighting the main canals, pump and problem areas

The entire drainage system in Greater Paramaribo is affected by a lack of maintenance. Canals are overgrown with vegetation, many storm drains are blocked by sediment and waste, and sewer pipes are partially filled by it. This contributes to the local and larger scale flooding problems in the area by lowering the drainage capacity of the system. For the validation of the D-HYDRO model, it is important to adjust the drainage capacity of the system to mimic its maintenance state. In the study area, an additional analysis will be conducted to portray the current state of the system.

3.1.3 Area analysis

The area is analysed to identify land use areas and soil and groundwater characteristics and to define potential places for NBS. Land use areas are defined according to the classification of the CRCTool. The analysis is done with various maps, satellite imagery and a field visit.

In this paragraph the land use areas are described based on the classification for the CRCTool (Figure 2-11). Paved roofs (PR) are defined as the roofs of all buildings and are manually delineated with OpenStreetMap (OSM). Closed Paved (CP) is identified as the streets and parking places in the area. The streets are exported from OSM and buffered in QGIS to have a certain width. This width is selected to be 15 m, which is based on American standards and accounts for available parking on each side. This reflects with Suriname's street design and is checked for overlap with Google satellite imagery. Unpaved (UP) is defined as all the larger green areas visible on Google Satellite imagery, this excludes private gardens and other smaller green areas. There is no permanent water body in the area to define as Open Water (OW), however the CRCTool needs Open Water to function, because the model drains all the water to this area before it can be pumped out of the system. Therefore, the Viotte and Picorni kreek are defined as Open Water (OW) because they serve as water drainage and have often ponding water. All the area that is not classified as one of the above is classified as Open Paved (OP).

Table 3-2 Land use classification, corresponding area types and method for delineation.

	Paved roofs	Closed Paved	Unpaved	Open Paved	Open Water
Area type	Buildings	Roads & Parking	Large green areas	Remaining area	Creeks
method	manually	Buffering (QGIS)	manually	Filling in QGIS	Manually

For the determination of potential areas for NBS the area characteristics are examined. Based on satellite imagery and images from the study area, the main locations suitable for NBS are defined. As each type of measure is applicable on a different kind of area, each measure will be divided over different types of areas. The locations from the preliminary analysis are checked and further examined in the field visit for their suitability.

For a single measure (Retention Pond) two additional sets of potential areas were defined to represent different degrees of uptake. This considers the willingness to use the potential area. One set represents minimal uptake and the other feasible uptake of measures which consist of 10% and 50% of the total identified potential area respectively. The minimal uptake locates measures only in the problem areas, while the feasible uptake is evenly spread across the study area. These sets of potential measure area aim to represent realistic designs for NBS in the area.

3.2 RAINFALL AND EVAPORATION DATA AND ANALYSIS

This section describes from which sources the rainfall and evaporation data is collected and how it was processed to provide the required input for the CRCTool and D-HYDRO model. First, the data collection is described (subsection 3.2.1) followed by the methods used to analyse the collected data (subsection 3.2.2).

3.2.1 Rainfall and evaporation: data collection

For Paramaribo the rainfall data comes from two different sources. There is daily rainfall data until 2017 from the JBA study, described in Diermanse (2022), and daily rainfall data (2016-2021) from the Waterloopkundige Afdeling (WLA). There are also 4 measuring stations that have hourly data available: Cultuurtuin, Zorg en Hoop, Duisburglaan en Celos. These stations have only data for a short period of time. The figure below gives an overview of the rainfall stations from the JBA study. The closest station to the study area is 'Zorg en Hoop', which also has the most complete daily and hourly dataset. This station will be used for the rainfall analysis. To avoid measuring errors the daily rainfall data is compared to other nearby stations like Peperpot and Morgenstond. For the most recent rainfall data (2021-2023) data from a measuring station installed specifically for the SRCP Lot 2 project is used. This station has hourly data and provides insight in the heavy rainfall event from the period of May – July 2022. This data is used for validation of the D-HYDRO, because it can be coupled to inundation records.

Figure 3-6 Location of different rainfall stations in Paramaribo

The CRCTool also requires an evaporation time series in addition to the rainfall timeseries. This is based on evapotranspiration measurements in Suriname (Koopmans & Vochteloo, 1973; Naipal et al., 2013), which gives a value around 4 mm/d. These measurements are taken in rural areas in Suriname, it is assumed that the values in Paramaribo will be approximately similar. The daily value is distributed over the day, with no evaporation at night and peak evaporation around noon. The distribution can be checked in the Appendix A3.

The available hourly rainfall dataset is very limited but is critical for urban flood modelling due to the rapid hydrological response in urban areas. The available data is limited to four stations with relatively short time-series, making it inadequate for extreme value analysis. Furthermore, the time-series have numerous gaps, with the most complete dataset from "Zorg en Hoop" having only 64% data available and only one year with more than 95% of data. This issue is addressed in the following section.

3.2.2 Rainfall and evaporation: data analysis

The rainfall data needs to be processed to provide the right input for the CRCTool and D-HYDRO models. For the CRCTool a long (more than 30 years) hourly dataset is constructed from the daily and hourly rainfall time-series. For D-HYDRO, design storms with different return periods are constructed. Additionally, real storm events are subtracted from the hourly datasets to compare to the design storms and to validate the model.

The CRCTool has the capability to analyse long rainfall time series and perform extreme value analysis (EVA) based on the generated runoff in the model. However, the available 10-year hourly time series has a lot of missing data (60% complete) and only one complete year, making it unsuitable for EVA. On the other hand, the daily time series consists of 60 years of data with 47 complete years, which is suitable for extreme value analysis. So, both datasets are combined to create an artificial hourly dataset of 47 years.

First, analysis is done for the available daily timeseries that are suitable for EVA, which are timeseries longer than 30 years, as proposed by the CRCTool (Vergroesen & Brolsma, 2020). For the EVA a Gumbel distribution is fitted. It was found to be the best fit in a previous study (Diermanse, 2022). The preferred station ‘Zorg en Hoop’ is compared to the other stations to determine if there are any significant deviations between them.

Secondly, the hourly time series is used to create a design event for a return period of T=2 based on the largest events (T>1) in the timeseries. This return period corresponds with the subtracted events and with the SRCP project’s framework. From the largest events an IDF curve is created, and the alternating block method (section 2.3.1) is used to make a design storm with a duration of 24 hours. It should be noted that this design event is only based on a small number of events due to the small hourly rainfall dataset and cannot be statistically supported. However, it provides a general idea of the hourly rainfall intensity.

Thirdly, the design event is combined with the daily time series to create an artificial hourly time series, which will be used as input for the CRCTool. The detailed elaboration of this method can be found in the supplementary materials (Appendix C). This method is validated by comparing the hourly time series and the constructed time series for the years where they overlap (2011-2017).

The D-HYDRO model requires event-based rainfall input, as its calculations are computationally heavy. Additional design events are constructed with a return period of T=10 and T=100. These provide significant different rainfall amounts. Additionally, a real event with a return period of T=100 is subtracted as additional input for D-HYDRO to analyse if differences occur between the statistically derived and real event. This event and another event are also used for model validation (section 3.5.2). Other T>1 events are subtracted to compare the design storm to real storm events that have fallen by using the peaks-over-threshold method (Appendix A5).

3.3 ADDITIONAL HYDRODYNAMIC MODEL DATA

This section describes the additional data collected for the hydrodynamic modelling in D-HYDRO. This consist of elevation data, water level data, data of the drainage system, and flood inundation records.

The elevation data is from a LiDAR survey conducted for the SCRP Lot 2, providing a high-resolution DEM (0.25x0.25m), which is compressed to 2x2m resolution to lower the file size. This resolution provides excellent detail for 2D modelling.

Water level is important input for the D-HYDRO model to simulate the tidal behaviour of the river. The Suriname River at Paramaribo is a tidal river, meaning the water level is dominated by the tides and not so much by the discharge. The data comes from a jetty located approximately 20 km upstream from the river mouth, which is around the project area. The station has data available in the period 2001 up to 2013, with a data coverage of 71.4%. It is reported that the jetty has been subsiding since 2005 and thus must be corrected for it. Subsidence is said to be about 25 cm in 2018.

Data of the drainage system comes from a SOBEK model from a previous Masterplan study in 2001. It contains information on the location and dimensions of canals, sewers, and structures. It is highly detailed, consisting of primary, secondary, and tertiary systems. Adjustments at the pumps at Jodenbreestraat and Knuffelsgracht were necessary to account for changes that have occurred and been recorded over the years (Table 3-3). These adjustments were provided by Deltares and were manually applied to the model. The SOBEK model can be imported into D-HYDRO using an in-built import function.

Table 3-3 Overview of adjusted structures in D-HYDRO model

Structure	Location	Original value	New value
Pump	Pump Knuffelsgracht	Capacity = 1.1 m^3/s	Capacity = 0 m^3/s
Orifice	Pump Knuffelsgracht	Positive flow direction	No flow direction
Manholes	Pump Knuffelsgracht	Width & Length = 0	Width & Length = 1
Orifice	Pump Jodenbreestraat	Type = Orifice	Type = Pump (1.25 m^3/s)
Orifice	Pump Jodenbreestraat	Type = Orifice	Type = Pump (1.25 m^3/s)
Manholes	Pump Jodenbreestraat	Width & Length = 0	Width & Length = 1

The status of the drainage system post-2001 remains unknown. No trustworthy records exist regarding maintenance work carried out or modifications made to the system. The condition of the drainage system has a significant impact on flooding in the area and must be considered in the flood modelling. To account for this despite the lack of data, a broad maintenance factor for the entire system will be applied, but it's important to recognize that this is an overly generalized assumption.

The flood inundation records analysed in this study were gathered from the flooding events that took place between March and June of 2022. The records consist of photographs and videos captured during field visits conducted as part of the SRCP projects. These photos and videos were taken in the two main flood-prone areas and were taken after two separate rainfall events. On May 31st, 2022, photos were taken at 1 PM, following 152mm of rainfall over the preceding 48 hours. This event had a return period of 10 years. The second set of photos was taken on June 14th, 2022, after 155 mm of rainfall in the 24 hours prior to the photos being taken. This event had a return period of 100 years.

3.4 MODELLING FRAMEWORK: CLIMATE RESILIENT CITY TOOL

This section describes the modelling framework for the CRCTool. This consists for one part of the general set-up (subsection 3.4.1) and the implementation of NBS (subsection 3.4.2). For the other part it describes how the data is processed to test the assumptions (subsection 3.4.3), perform a sensitivity analysis (subsection 3.4.4) and show the effect of different hydrological fluxes (subsection 3.4.5).

3.4.1 Set-up of CRCTool

The CRCTool requires neighbourhood parameters, which represent the characteristics of the study area. This includes land use percentages, soil type, infiltration capacities, storage capacity of the Open Water, groundwater level and parameters of percolation to the deep groundwater. All these variables will be display in Table 3-4. Parameters about deep groundwater are unknown. However, it was found that they have a marginal impact (Appendix A10). The parameter values are copied from a case in New Orleans and is modelled as a flux. The groundwater level is based on water levels in the creeks and expert judgement from ILACO B.V. This is validated by 4 weeks of groundwater level measurements close to the study area. The storage capacity in the open water is based on the difference between the groundwater level and the ground level. The soil type is clay, and it is assumed that it has an infiltration capacity of 50 mm/d. Open paved area will have 1/5th of the infiltration capacity (10 mm/d).

Table 3-4 Neighbourhood input parameters of CRCTool

Area characteristics				**Shallow groundwater**			
Area size	**Pump capacity**	**Soil type**	**Crop type**	**Infilcap UP**	**Infilcap OP**	**Storcap OW**	**Gwl**
130 ha	100 mm/d	clay	grass	50 mm/d	10 mm/d	1000 mm	-1m
Sewer system		**Interception storage**		**Deep groundwater**			
Storcap SWDS	**Sewer overflow**	**Intstorcap paved**	**Instorcap unpaved**	**Deep GW level**	**Seepage type**	**vc**	**w**
4 mm	40 mm/h	2 mm	20 mm	-21.5 m	flux	10000 d	50 d

The model is based on a Dutch urban area in a polder system with a controlled water level and outflow through a pumping system. This means the model requires a pump capacity, assumes there is no natural gradient for discharge and applies a controlled target water level.

The study area is relatively flat with heights varying between 1 and 4 m above sea level, so it can be assumed that the natural gradient effects the drainage minimally. The whole area is mainly drained by one pump, so the pump capacity in the CRCTool can be equal to the capacity of this pump. The pump is operated manually and does not use a controlled water level. In this study it is assumed that the water level is controlled and that the pump operates automatically. It must be noted that this currently overestimates the effectiveness of the drainage of the system. However, in a scenario where NBS will be applied it will be necessary to control this water level. So, it is included as an extra recommendation. The controlled water level is set at 1m, which is around a meter below the mean surface level.

Some input parameters for this case study are different from the original Dutch cases the tool is based on. It is thus useful to compare and derive the input parameters from a more comparable case study done with the CRCTool. It is decided to use a case in New Orleans for comparison. This case shares similar soil and groundwater characteristics and has relatively similar rainfall conditions to Suriname, especially compared to a Dutch case.

It was chosen to not validate the flooding volumes with the inundation records, because the outputs of the CRCTool cannot be validated accurately. The CRCTool only provides a total flood volume, lacking information on flood depths at specific locations and the flood extent. There are two methods to project the flooding volume on the DEM, however these both give issues.

One option is to project it evenly over the DEM; however, this excludes effects of the drainage system. Another option is to distribute the flooding from a point source, for example from the pump. However, flooding is not only caused by the pump capacity as is assumed in the CRCTool, but also by local depressions and drainage system capacities. Knowing this means that the tool will probably underestimate the flooding volumes. An estimate of this can be made by comparing the total flooding volumes for a T=2, T=10 and T=100 event with the flooding volumes of a validated D-HYDRO model. From this a factor can be determined, giving a general idea of the accuracy of the CRCTool in representing the total flooding volumes for this area.

3.4.2 Implementation NBS in CRCTool

The NBS will be implemented differently for both models. In the CRCTool a batch run will be performed which calculates the effectiveness of each measure separately. This represents a case in which every measure is applied individually, and all the potential identified places are used. Since each measure is run for 47 years of data the statistics for different return periods is directly available. For comparison with D-HYDRO a single measure is converted to an adjusted effectiveness with the corresponding equation (2) to represent 10% and 50% of the total potential area. This represents a minimal and realistic implementation for this measure. In addition to the measure run there is a Storage Discharge Frequency (SDF) curve run. This is done for the base run to determine flooding volumes and for the single measure to determine its effect on flood volume reduction for comparison with D-HYDRO. An overview of the modelling process is given in the figure below.

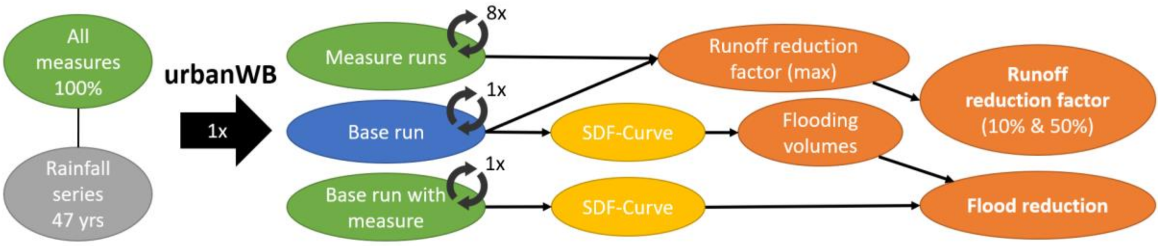


Figure 3-7 Model workflow in the CRCTool

Measure representation and parameterisation

The CRCTool works in a way that the measures are applied on one of the land use areas. It uses the entire land use area as inflow area of the measure. In other words, the inflow area of the measure is the same as the area of the land use type. Figure 3-8 visualizes the representation of NBS in the model.

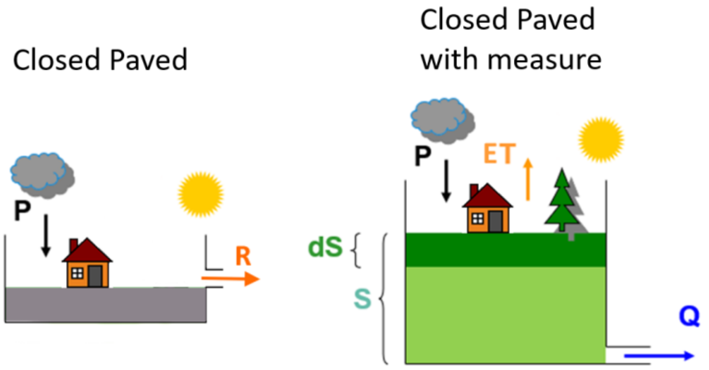


Figure 3-8 Simplified representation of measure implementation in CRCTool: measure becomes entire land use area. This situation represents a measure that reduces all runoff (R), by storage (S), slow discharge (Q) and evapotranspiration (ET).

In this research, 60 different measure parameters are required in the CRCTool. However, only 20 parameters are relevant for this research, the other 40 are either 'settings', constants, or not applicable to this research. All parameter values can be found in Appendix A8, while this subsection focuses only on the important parameters. The values for the 20 parameters of each NBS are determined based on literature and field research, as discussed in the theoretical framework (section 2.2). These values are displayed in Table 3-5.

Table 3-5 Important input parameters of the CRCTool

	Measure area		**Layers**	**Processes**					**Destination of runoff**			**Storage and infiltration**					**Groundwater**		**Outflow from bottom layer**					
title	**Inflow factor**	**area type**	**number**	**EV_**	**ET_**	**IN_**	**SD_**	**FD_**	**controlled**	**surface**	**overflow**	**int layer**	**int layer**	**top layer**	**top layer**	**btm layer**	**connection**	**limited by**	**trans-piration**	**discharge type**	**runoff capacity**	**storage dependent**	**storage factor**	**Discharge level**
Bioswale	10	CP	3	1	1	1	1	0	OW	SWDS	SWDS	300	600	100	2400	variable	yes	yes	yes	flux	200	no	0	0
Green roofs	1	PR	3	1	1	0	0	0	SWDS	SWDS	SWDS	10	4800	50	4800	variable	no	no	yes	flux	2400	no	0	0
Rain garden	10	OP	2	1	1	1	1	0	GW	SWDS	SWDS	200	600	0	0	variable	yes	yes	yes	flux	50	no	0	0
Infiltration trench	20	CP	2	1	0	1	1	0	OW	SWDS	SWDS	100	1200	0	0	variable	yes	yes	no	flux	500	no	0	0
Retention pond	10	OP	2	1	1	1	1	0	OW	SWDS	SWDS	0	1E+06	0	0	variable	yes	yes	no	flux	400	no	0	500
Rain barrel	20	PR	2	0	0	0	0	1	OW	SWDS	SWDS	0	1E+06	0	0	variable	no	no	no	flux	0	yes	0.5	0
Bioretention cell	15	CP	3	1	1	1	1	0	OW	SWDS	SWDS	200	1200	100	2400	variable	yes	yes	yes	flux	300	no	0	0
Permeable parking	5	CP	3	1	1	1	1	0	OW	SWDS	SWDS	100	2400	50	2400	variable	yes	yes	no	flux	300	no	0	0

Output

The two main outputs from the CRCTool were used to analyse differences between measures and to compare to D-HYDRO. These consist of different lookup tables which are used by the online webtool to quickly calculate runoff reduction factors and other variables, and SDF curves. These curves represent the required storage capacity for different pump capacities. An SDF curve was made for a base run and a run with an implemented measure (retention pond) to define the reduction in flooding volumes for different return periods (**flowchart**). This will be done for three degrees of implementation (section 3.1.3) to compare it with the D-HYDRO output.

The UrbanWB's output is utilized to conduct a more detailed analysis, which provides insights into how hydrological processes behave within the model. For this analysis, a year, week, and day were selected. Specifically, the year 2020 was selected as it contained the most complete hourly dataset. From this year, the week and day in which the largest event of that year happened was selected, which occurred in week 48 on November 22nd. By examining the different timescales, the effects of various processes can be examined.

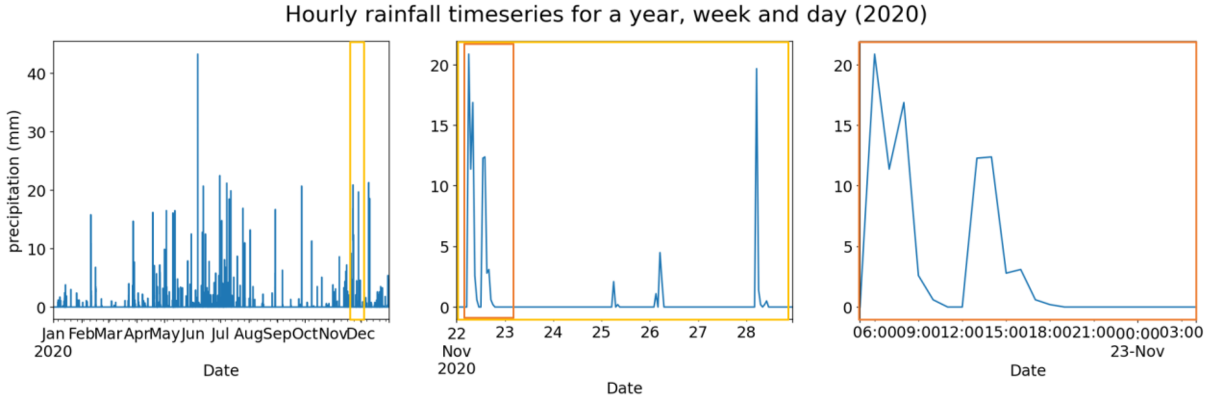


Figure 3-9 Hourly rainfall timeseries from Zorg en Hoop for 2020, week 48 and November 22nd respectively

3.4.3 Testing assumptions in the CRCTool

In this subsection, the assumptions made in the CRCTool are tested to justify certain simplifications. These assumptions are primarily based on findings from Dutch cases, with a case in Laakhaven serving as an illustrative example. However, it is important to note that these assumptions have not been validated for international cases. Therefore, it is necessary to evaluate their applicability in other countries, such as Suriname. By doing so, we can determine whether these assumptions can be generalized beyond the context of Dutch cases.

Average runoff reduction factor

The model's most important claim is that the runoff reduction factor remains uniform across different return periods, justifying the use of one average factor for each measure. This allows for testing measure effectiveness over short periods of time. However, this claim is only supported by empirical evidence from case studies in the Netherlands, such as Laakhaven (Figure 3-10). The figure shows that applying a measure, results in a lower runoff depth, leading to a less common occurrence of a certain depth and an upshift of the line in the figure from the baseline. The uniformity of this shift for different depths is demonstrated by the black arrows, which represent the consistent runoff reduction factor.

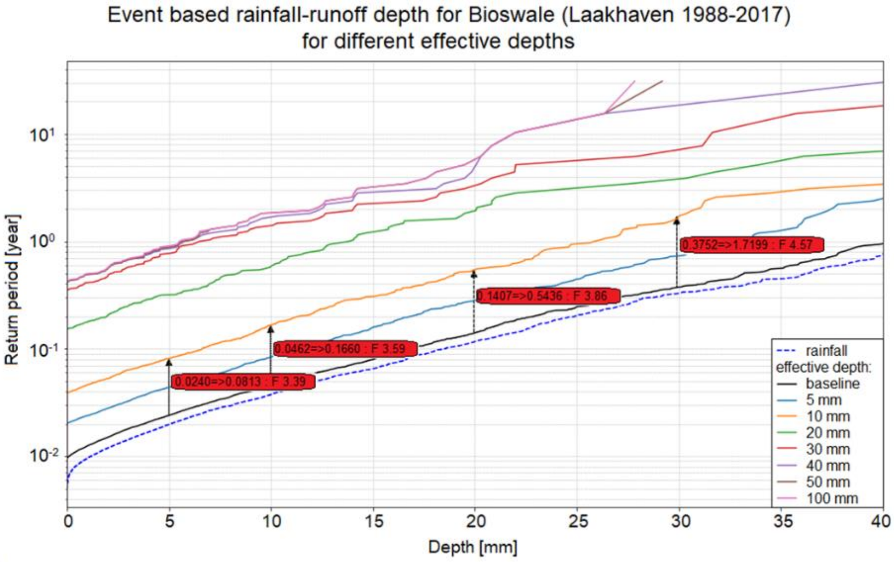


Figure 3-10 Runoff depth plotted against the corresponding return period. For each measure depth the shift in return period for a specific runoff depth is given. The black arrows depict the runoff reduction factor, which is the difference between the return period of a specific runoff depth with and without a measure applied (Vergroesen & Brolsma, 2020)

This assumption will be tested by making similar graphs like Figure 3-10 for each measure. Additionally, a graph for a bioretention cell with variations in the following parameters is made: infiltration capacity, runoff capacity of measure and runoff type of the measure to find out which parameter effects this trend. Each parameter is tested for a limited, original, and infinite parameter value.

Neglecting the controlled runoff in runoff reduction factor

The second assumption concerns the division of the runoff fraction in the CRCTool. The measures implemented to control runoff involve the use of a storage volume, from which the runoff is controlled. In essence, only the evaporation from the measure itself can reduce the total runoff volume. However, a significant portion of the runoff from a measure is controlled via groundwater infiltration or through slow/delayed release to the drainage system.

To determine the effect of these measures on reducing runoff, the CRCTool assumes that the controlled runoff from a measure does not contribute to the overall runoff volume since it poses no threat to the drainage system. While the CRCTool developers acknowledge that this assumption may lead to an overestimation of the measure's effectiveness, they claim that this overestimation is negligible (Vergroesen & Brolsma, 2020). Nonetheless, it is crucial to test how much the controlled runoff contributes to the total runoff volume to determine if it can genuinely be discarded.

This is tested for a single T=1 event (introduce this, give it a name). The original runoff will be compared to the runoff with a measure. This event will give insight in how much the controlled runoff contributes to the peak runoff and if it thus can be neglected.

Event separation based on baseline discharge

Finally, the method employed in event separation of the rainfall time series will be examined. The CRCTool utilizes a "baseline" runoff to determine the event separation, which is chosen to define the length of the storage events. The same event separation is then applied to runs with measures or higher runoff capacities. The CRCTool provides different practical values for the baseline runoff, and it will be investigated how these values affect the results.

The first recommendation is to use the mean daily rainfall as 'baseline' discharge. This is automatically done in the CRCTool. However, in the documentation a value of 3 to 4 times the mean daily rainfall is suggested. Furthermore, there is suggested to use this practical value over the actual discharge capacity if it deviates significantly from this value, which is the case for this study (subsection 3.4.1).

It was attempted to quantify one of these recommendations. Specifically, the impact of utilizing the practical value of the baseline runoff on the CRCTool's results will be evaluated. For this, different baseline runoff values, ranging from the average daily rainfall to the pump capacity, were tested. Graphs displaying the storage capacity in the study area, which is the height of the open water level, were created over the period of a year. This shows where events are separated and if this happens correctly.

3.4.4 Sensitivity analysis of important parameters

A sensitivity analysis has been done for one measure (bioretention cell) to determine the sensitivity for different effective parameters. This analysis consists of comparing the outputs of the CRCTool by using different values for a chosen parameter, displayed in Table 3-6. First the analysis of the infiltration and storage parameters will be described, followed by the inflow factor. Finally, each measure will be tested individually and then compared to one another.

Table 3-6 Parameter ranges for sensitivity analysis

Infiltration capacity	**Discharge capacity NBS**	**Storage interception layer**	**Storage top storage layer**	**Inflow factor**
20 – 10.000 mm/d	0 – 1200 mm/d	10 – 300 mm	20 – 300 mm	1 - 20

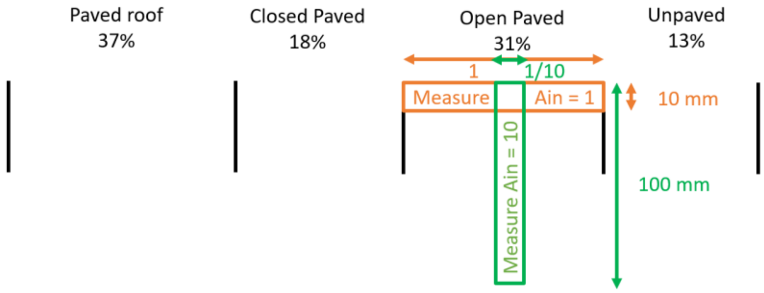
Infiltration and storage

The parameter ranges are based on potential ranges for a measure. The interception layer is a layer which most of the time has a size of around 20 mm but can be designed deeper to have larger ponding depths, like a vegetative swale. The infiltration capacity of layers with soil or substrate is around 500 – 10.000 mm/d. Higher/unlimited infiltration rate are used to model retention ponds for example. Low infiltration rates occur for clogged measures or native impermeable soils. The top storage layer is used in measures who use a top substrate layer. This layer depth thus depends on the depth of the substrate layer. This layer normally has a storage depth between 20 mm for minimal green roofs and 300 mm for large vegetative swales and bioretention cells. The runoff capacity of the bottom storage layer will be varied between 0 and 1200 mm/d, which matches the original infiltration capacity.

Inflow factor
In this paragraph the implementation of the inflow factor is described first. A measure is implemented over the entire land use area it is applied to. The model assumes the inflow area of each measure is equal to this land use area. The inflow factor (X) determines the relation between the inflow area and the measure area. The inflow area is kept constant and thus the measure area becomes X times smaller to simulate that X times the area is draining to the measure. To make sure the measure has the same effective depth, the depth of the measure is also increased X times (see Figure 3-11). A visualisation of this concept is shown in the sketch below for an inflow factor of 1 and 10. The parameters that are affected by the inflow factor are also shown.

The bioretention cell will be implemented with an inflow factor of 1, 2, 5, 10 and 20. For an inflow factor 1 and 10 an event will be analysed to show the effect of different processes.

The bottom storage layer becomes larger to mimic the same effective depth, however, the depth of the infiltration and top layer stay the same. This means that the total volume of the measure with a lower inflow area is larger. Furthermore, the runoff capacity from the bottom of the measure apply to the measure inflow area instead of the measure area. This can be confusing when giving the input to the model. In the next paragraph there is chosen to apply the same discharge capacity for the measure area.



Parameter	Effect inflow factor (X)
Infiltration capacity	X times smaller
Runoff bottom measure	X times smaller
Interception & top layer	No change
Bottom storage layer	X times larger

Figure 3-11 Schematisation of the effects of the inflow factor on the measure schematisation in the CRCTool

The runoff reduction values for different inflow areas per land use area is input for the tool. In the tool the actual runoff reduction factor is given based on estimates from equation (2). The measure must be applied in the tool itself to show the effects on the total runoff reduction value. After the initial calculations done by the model, the user is given the variability to adjust this inflow factor with the equation (2). This is done by multiplying the inflow area with the given inflow factor and dividing the effective depth by the inflow factor. The default inflow factor is the one given in the model.

The measure results from the tool are manipulated with the equation (2) to all represent the same measure with a storage depth of 10 cm, but with different initial inflow factors. It is expected that runoff reduction factors are the same.

Different measures
For the comparison of the effectiveness of different measures, the measure parameters are based on a scenario that all potential areas for measures identified in the area are utilized. The inflow factor is based on the assumption that the measures drain the total land use area which they are applied on to comply with the representation in the tool. The corresponding parameters are those displayed in Table 3-5 Important input parameters of the CRCToolTable 3-5. So, for example, if all potential areas for vegetative swales are utilized they drain all the streets in the area.

3.4.5 Analysis of hydrological fluxes

More thorough analysis was done with the raw output from the UrbanWB model. This made it possible to show how single parameters behaves during an event, week, or full year. This made it possible to investigate certain parameter behaviour and check certain model claims. This was used to answer the questions about parameter sensitivity and model behaviour. First the analysis of hydrological fluxes is described followed by the analysis of the groundwater flow.

Main hydrological fluxes

For the critical assessment of the hydrological fluxes the runoff was quantified and how much it contributes to the total water flows was investigated. This runoff was calculated based on basic hydrological principles and it is one of the main advantages of the CRCTool that uses runoff events for statistical analysis.

First, the runoff was compared to evapotranspiration (transpiration and evaporation) and percolation. Secondly, it was investigated how the runoff is divided into controlled and uncontrolled runoff and how much each flow accounts to the total runoff. Lastly, it was checked how the controlled runoff is defined.

Furthermore, there was looked into the definition of runoff capacities from the bottom storage layer of a measure. This can be defined in two ways: flux or level. The first option, flux, is a predetermined maximum drainage capacity. This capacity can be dependent on the storage capacity. The second option is levelled discharge. This option means the measure is drained in a predefined number of days. This option was used for most measures in the original CRCTool for the Netherlands. However, this implies the drainage factor is variable.

Groundwater flows

The groundwater flow was separately assessed. The groundwater component consists of shallow and deep groundwater. The seepage to the shallow groundwater is defined by the soil type. Seepage to the deep groundwater can either be defined as a constant downward flux or a dynamic flux which is determined by the head difference and resistance. In this chapter the effect of the groundwater component on the measure's effectiveness is investigated and the differences between a constant and dynamic flux are compared.

The effect of the groundwater component was investigated by defining if the measure is connected to the groundwater and if the groundwater level can limit this flow. This was regulated with the parameters 'connection_to_gw' and 'limited_by_gw' respectively. The first parameter determines if seepage to shallow groundwater is possible and the second one limits seepage to the shallow groundwater if the groundwater level reaches the surface. For limiting by groundwater level, the controlled discharge from the measure is defined to flow to the groundwater.

3.5 MODELLING FRAMEWORK: D-HYDRO

The modelling framework for D-HYDRO consists of the model set-up (3.5.1), model validation (3.5.2) and implementation of NBS (3.5.3). Furthermore, it describes how the output is compared to the output of the CRCTool (0).

3.5.1 Model set-up

The D-HYDRO model is built from the SOBEK 1D-model in 2001. The detailed DEM is coupled to the 1D-layout of the drainage system from the SOBEK 1D-model by a generated flexible mesh grid with a higher level of detail at street level. Rainfall is simulated directly on the grid. The DEM is detailed enough to replicate real flows. This means NBS can be implemented in the model by making ditches and depressions in the DEM. This will imitate the real-world behaviour of NBS.

The original 1D SOBEK model was larger than the current study area. So, some connection in the model must be deleted. Each connection that flows over the boundaries of the study area is checked in an example scenario in SOBEK. This is done to get insight if there are significant water flows leaving or entering the system. Figure 3-12 shows that the in- and outflows are reasonably similar. So, it is decided to cut of these connections without assigning a significant in or outflow from the system.

Figure 3-12 Schematisation of SOBEK 1D model. Yellow lines show the boundary of the catchment area. The graph displays all the in and outflows at the boundaries for a T=100 event are low and level each other out.

For grid construction it is chosen to implement a flexible rectangular grid, with added refinement at street level and potential places for NBS. Streets refinement is done because during flooding they act as drainage canals. The grid cell size is based on stability of the grid and calculation times. It is chosen to implement a 16x16m grid which is refined up till 4x4m. This refinement is in check with Bulti & Abebe (2020).

As input four different events were defined, which resulted from the rainfall analysis. The design events of T=2, T=10 and T=100 and an event from June 2022 which represents T=100 were selected for analysis. These return periods were selected because they represent significant differences in rainfall amount for which different outcomes are expected. Furthermore, the return periods are also suggested for design purposes, for example in the Prinsen et al. (2020).

Finally, a specific grid with infiltration values was included. These values are based on the infiltration values of Unpaved and Open Paved from the CRCTool. These values are adjusted for measure implementation to represent increased infiltration capacities or underdrains. Evaporation was assumed to be negligible during the timespan of a single event. Other model parameters can be checked in the supplementary materials (Appendix C).

3.5.2 Model validation

The next step is the model's validation by historical flooding events, which aims to tweak uncertain model parameters to achieve the most accurate representation of the historical flooding situations. The validation was performed using two flooding events from 2022, as the most reliable rainfall and field data is available for these events. The rainfall data was collected from the newly installed Kwattaweg rainfall station, which was specifically installed for the SCRP Lot 2 project. The station collects rainfall data at 15-minute intervals. The field data includes photographs and videos of the flooded areas in the Jodenbreestraat and Verlengde Keizerstraat (problem areas) taken immediately after the rainfall events. These photos and videos were used to estimate the flooding depths and contain information on the exact location and time of capture. Additionally, a flood map created by experts from ILACO was used to assess the flooding extent, as it shows the flood-prone areas and can be used to compare it with the flood patterns in D-HYDRO.

For the D-HYDRO model, the flooded areas are shown on dedicated flood maps of the moment when the videos and photographs are captured. It is assumed that the main factor influencing the flooding depth and extent is the maintenance condition of the drainage system. First, two models are made, representing a perfectly working sewer system and no sewer system. This gives insights in the effect of the drainage system on flooding locations and depths (Appendix A9).

Lack of maintenance will mainly affect the drainage capacity of the system. It causes excessive vegetation growth in channels and partially or fully clogged drainage pipes by sediment and debris. This can be represented in the model by adjusting the friction factor for open channels and pipes. New friction factors are given in Table 3-7 and are based on value ranges from design tables (Appendix A15). Channels are described as not maintained with dense weeds as high as the flow depth. Pipes are described as concrete sewer pipes in poor conditions with flow velocities between 0.5 m/s and 1.0 m/s. 2D-roughness is based on a developed area, medium density (65% impervious area).

Furthermore, storm drains can also get blocked by debris and sediment, which can be represented by removing 1D-2D links. These links are removed by random. The values in Table 3-7 gave a good depiction of the flooding events. They are discussed and approved by experts' opinion from Deltares.

Table 3-7 Roughness values for 1D structures and 2D overland flow

Open channels	**Pipes**	**2D roughness**	**1D-2D links**
Manning = 0.08	White-Colebrook = 3.0	Manning = 0.12	Remove 50%

3.5.3 NBS implementation

In D-HYDRO, a rainwater retention pond was implemented. This measure is chosen for its relative simplicity, which reduces uncertainties in the comparison. The measure is tested for a minimal, realistic, and maximum uptake based on the located potential areas for a retention pond. Realistic and maximum uptake are evenly spread over the study area, where minimal uptake locates measures only locally in the problem areas. This measure was tested for three design events and one real event. There was also a model run where no measure is applied, resulting in a total of 16 runs. Figure 3-13 gives an overview of this.

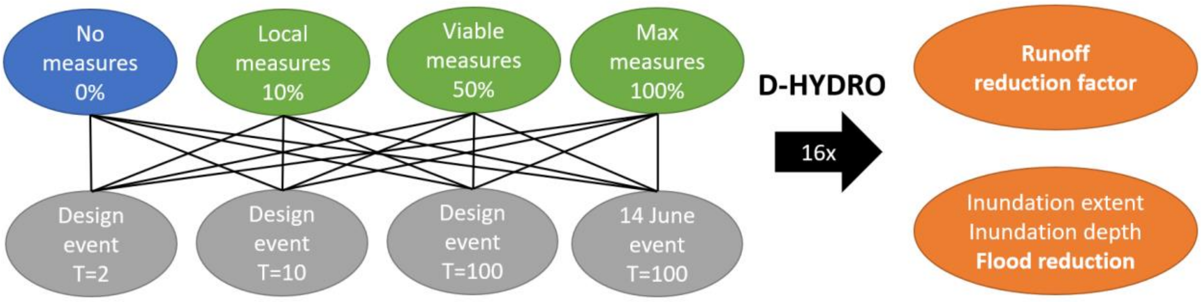


Figure 3-13 Model workflow in D-HYDRO

NBS can be implemented in two ways in the model: one-dimensionally or two-dimensionally. The measures are implemented two-dimensionally in this study, since the DEM is detailed enough to represent NBS as local depressions/ditches in the DEM, because the water flows were represented accurately. Rainfall is also simulated to fall directly onto the grid. This way the real-world capabilities of NBS to intercept the rainwater were simulated. This option will represent the inflow and storage behaviour of NBS accurately. Draining the measure was represented as an infiltration value. It is noted that this assumes that the water leaves the system, while in reality it needs to drain via the sewer system. However, it is assumed this water does not contribute to the stormwater flows which is also assumed in the CRCTool (subsection 3.4.3). Figure 3-14 shows a two-dimensional example of how NBS are implemented in the model. The spatial application of the measures were based on the areal analysis (section 4.1).

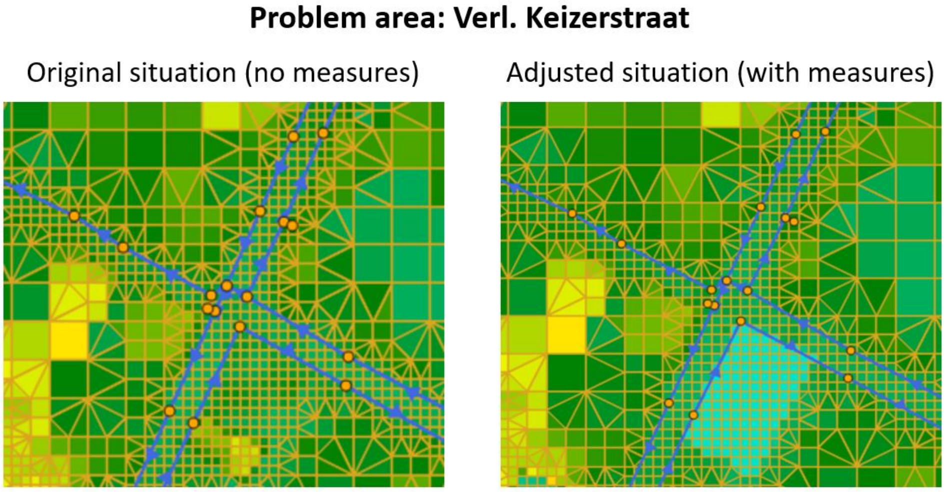


Figure 3-14 Representation of a measure in D-HYDRO at problem area Verlengde Keizerstraat: measure is implemented spatially, and storage is created by lowering the DEM.

3.5.4 Comparison of flood depth

This subsection explains how the output of the CRCTool and D-HYDRO is compared in relation to flood reduction. Furthermore, additional characteristics related to the flood event are investigated. The analysis includes an examination of the flow behavior in the drainage system both with and without NBS, as well as an evaluation of how the maintenance state of the drainage system impacts flooding problems.

Flood reduction

The SDF curves were used to determine reduction in flooding volume with the CRCTool. These curves give the maximum flooding volume for a certain pump capacity. A base run without a measure and three runs with the minimal, realistic, and maximum uptake of a measure are done as well. The SDF curves show many different return periods and thus also the return periods of the events tested in D-HYDRO (T=2, T=10 and T=100). The flood reduction effectiveness is expressed in a percentage of the total volume of the measure that is reduced, which makes it easier to compare the results to the D-HYDRO results.

For the determination of the flood reduction of the measures in D-HYDRO the difference between the total storage volume in the system at maximum inundation is used. It was summed with the total amount of water that stays in the measure, to account for the extra storage that the measures provide. This is based on the flood maps for each corresponding event.

Furthermore, a flood map of the area was made using QGIS resulting from the D-HYDRO model output. This gives insight in the spatial division of the flood depths. Furthermore, the course of the flooding depth during an event is displayed in graphs for the two identified problem areas. The exact area is indicated on the figure below.

Figure 3-15 Exact location of the flood depth measurements in D-HYDRO for the two problem areas

Additional insights

The additional analysis examines the changes in the main flow behaviour of the drainage system caused by NBS. Specifically, the flows in the main drainage channels, the Viotte and Picorni Kreek, are analysed. Furthermore, the effects of cleaning the sewer system and how it relates to NBS as a solution for reducing flooding volumes. This was utilized in D-HYDRO by using the original roughness values of the system from the SOBEK model and restoring all 1D-2D links.

3.6 CRCTOOL DESIGN WORKSHOP

The last part of the research method is to put the CRCTool into practice in a design workshop with stakeholders from the SRCP lot 2 project. The outputs from the CRCTool that result from the methods discussed in section 3.4 are used to set-up the web interface of the CRCTool. A specific version of the tool for the 'Binnenstad' is created under the following URL: https://paramaribo.crctool.org/.

The aim of the design workshop is to gain valuable insight into how people interact with the tool and to receive feedback from the users. The design workshop was held in Paramaribo at the Ministry for Public Works. The workshop was part of a week in the SRCP project that was assigned to give several workshops to stakeholders involved in the project. The topic of the workshop was to show the potential of NBS in the pilot area 'Binnenstad'.

The workshop was divided in two sessions. The first session explained how NBS can contribute to stormwater management and how the CRCTool can help estimating their effectiveness. In this session an example case was given for the pilot area, based on findings from this research. The second session was interactive, where groups of stakeholders tried to solve a certain water surplus for the whole catchment area by implementing NBS with the tool.

In the workshops the focus was on the following aspects:

- **Activation**: Does the tool interest and activate stakeholders in implementing NBS for stormwater management?
- **Accessibility**: Is it easy to use and understand by the stakeholders?
- **Interaction**: How do the stakeholders interact with the tool?

For the assignment the participants were divided in several groups which will use a laptop to draw measures in the study area. Additionally each group receives a printed map of the study area and pens to draw measures on this map as well. The assignment was split in two parts. After each part one group was chosen to present their design, to start a general discussion with the whole group.

The first part of the assignment was to solve the water surplus from a T=2 event, with the current pump capacity. This water surplus is defined based on the SDF curves that resulted from the UrbanWB. The water surplus, which is a certain volume, must be realized in the study area. So the focus is only on the storage volume.

After the T=2 event is solved, the next step is to realize storage for a T=10 event. In this assignment the stakeholders may change the pump capacity and allow a certain amount of flooding on the streets. The goal of the assignment was to show the potential of NBS and how they can be applied together with other measures. Also it is used to understand that in some scenarios we must allow 'controlled' flooding of the streets.

4 RESULTS

In this chapter, the research results are presented and organized according to the sub-questions presented in the problem statement (section 1.4). The first section (4.1) describes the preliminary analysis of the study area and the rainfall time series. The second section (4.2) examines the testing of assumptions in the tool. Section 4.3 describes the sensitivity analysis of critical parameters and the comparison between measure effectiveness. Section 4.4 provides a critical evaluation of model outputs, and section 4.5 compares these outputs to those from a D-HYDRO model. Finally, section 4.6 presents the findings of the design workshop that involved using the tool.

4.1 ANALYSIS OF STUDY AREA AND RAINFALL TIME SERIES

This section starts with the area analysis in which the land use areas and potential places for NBS are determined (subsection 4.1.1). The second subsection (4.1.2) describes the rainfall analysis where an artificial hourly time series is created for the CRCTool and design storms and actual storms are derived for D-HYDRO.

4.1.1 Area analysis

In this section the study area is divided in different land use areas and the potential locations for NBS are identified. For each measure the potential areas are placed in the study area and for Retention Pond/ Rain Garden two additional sets for application are identified as input for the D-HYDRO model.

The land use area map is made based on the methods described in section 3.1.3 and is depicted in Figure 4-1. The corresponding land use percentages are 37% of paved roofs (PR), 18% of closed paved (CP), 31% of open paved (OP), 13% of unpaved (UP) and a resulting 1% of open water (OW). This gives a total paved area of 81%, which means the 'Binnenstad' classifies as a densely built area (Appendix A15**.**

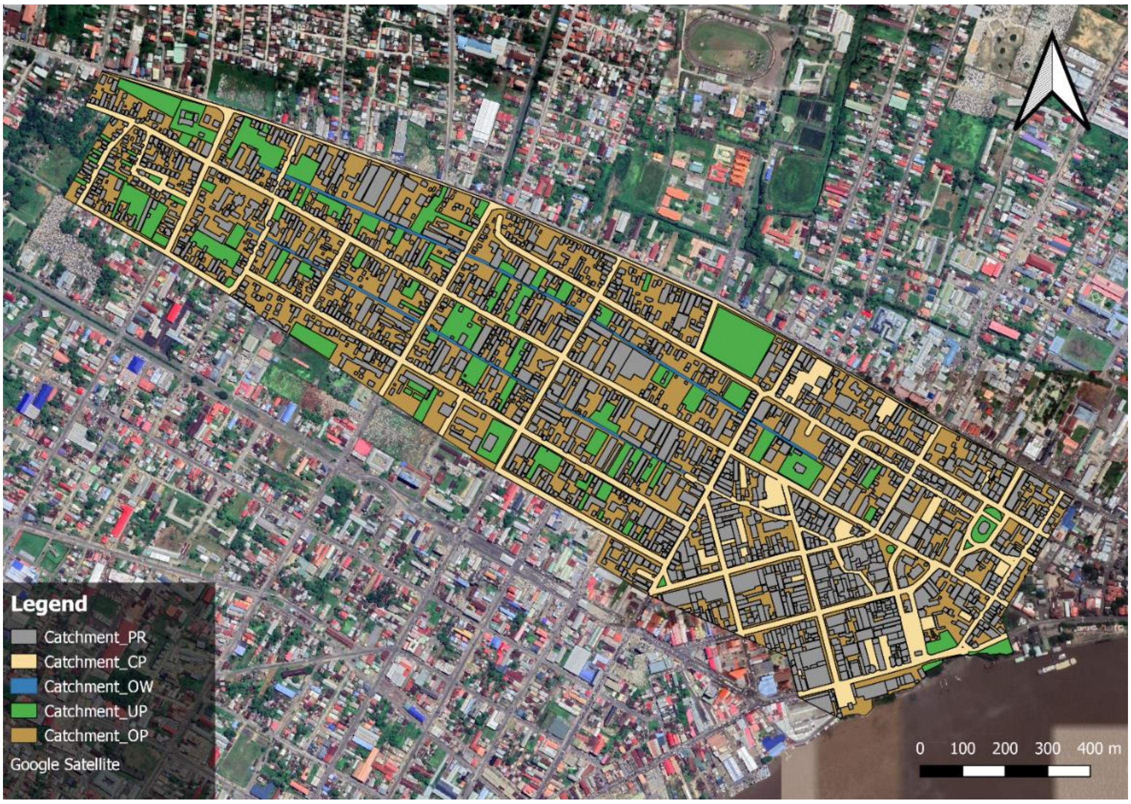


Figure 4-1 Land use area types divided according to the classification of the CRCTool. PR = Paved Roof, CP = Closed Paved, OW = Open Water, UP = Unpaved and OP = Open Paved.

The preliminary analysis of the study area identified several opportunities for implementing NBS. Four types of areas are selected to be suitable for specific types of NBS based on their abundance and suitability for NBS. The first type of area is parking lots, which cover 4% of the area and can accommodate measures such as permeable pavement and bioretention cells. The second type of area is abandoned lots, which can be designed as rain gardens or retention ponds. These could for example be incorporated in new public parks, which are now lacking in this study area. The third type of area is the wide streets in this area, which lend themselves for integration of vegetative swales and/or infiltration trenches. The last type of area are the roofs, which have a significant total area coverage. These can be equipped with rain barrels. Additionally, there are also many large roofs of shopping malls, casinos, ministries, and hotels, which could be equipped with green roofs.

Table 4-1 Potential areas for NBS that are abundant in the study area. Highlighted in orange is used in the CRCTool

	Parking places	**Abandoned lots**	**Wide streets**	**Large roofs**
Measures	Permeable pavement	Rain gardens	Bioswales	Green roofs
	Bioretention cells	Retention ponds	Infiltration trenches	Rain barrels
	Utilizable area	**Utilizable area**	**Utilizable area**	**Utilizable area**
Area %	parking lots: 4%	abandoned lots: 3%	1/5 of street: 3%	large roofs: 4%
	parking spots: 9%	unutilized area: 30%	1/3 of street: 5%	all roofs: 37%

Figure 4-2 Example of parking, vacant lots, wide streets and large roofs in the study area

The types of area with their corresponding solutions and utilizable area percentages are displayed in Table 4-1, including pictures with examples from the study area (Figure 4-2). Approximately 100 areas have been identified as suitable for NBS (Figure 4-3). It is assumed that each NBS can manage runoff from its corresponding land use area. For example, vegetative swales are connected to all the rainwater that falls on the roads (Closed Paved), in line with the calculation method used in the CRCTool. Green roofs are an exception, as only 10% of roofs are used in the figure, representing only large roofs from businesses and government institutions. This is because green roofs require significant structural investments, which may not be feasible for private homeowners.

The Retention Pond has two additional sets of potential areas which represent a minimal and feasible uptake of NBS. The minimal uptake and feasible uptake are 10% and 50% in terms of total potential area of the measure respectively. The minimal uptake locates measures only in the problem areas and the feasible uptake is evenly spread across the study area (Figure 4-4). This is provided as input for the D-HYDRO model.

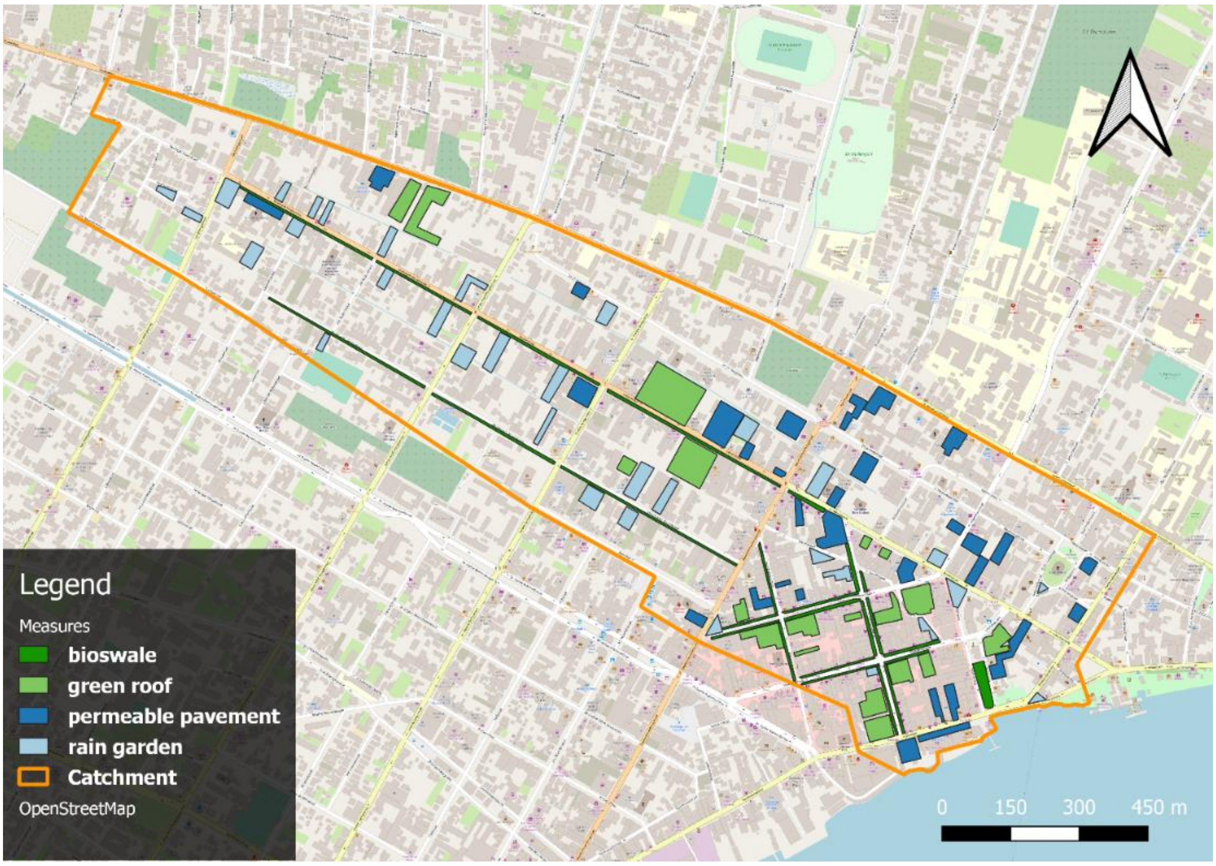


Figure 4-3 Potential places for different types of NBS (based on parking, vacant lots, wide streets and large roofs in the area). Alternative solutions for the displayed measures: bioswale = infiltration trench, green roof = rain barrel,

Figure 4-4 Study area with potential areas for Rain garden/Retention ponds. Green + blue + red represent maximum (100%) implementation, Blue + green represent realistic (50%) implementation and Green represents local measures only (10%).

4.1.2 Rainfall analysis

In this subsection the extreme value analysis of the daily rainfall stations and the comparison between them is described first. Next, the analysis of the hourly rainfall data is described and how this is combined with the daily rainfall time series. Lastly, individual events are extracted from the available hourly datasets.

Extreme value analysis of daily rainfall data

First, the completeness of all daily time series is analyzed. Table 4-2 displays the number of complete years, defined as years with more than 95% of data available, for each time series. Figure 4-5 shows the periods in which data is available for the different stations. For extreme value analysis (EVA), only the time series with more than 30 complete years are considered (subsection **Error! Reference source not found.**), with a preference for stations that have the most recent available data. The time series for all stations can be found in Appendix A4.

Table 4-2 Complete and total years of data for each rainfall station

Stations valid for EVA			**Stations not valid for EVA**	
Station	**Complete years**	**Total years**	**Station**	**Complete years**
Morgenstond	45 years	93 years	K-Jarikaba-Proef	22 years
Peperpot	61 years	93 years	Ma Retraite	21 years
Nieuw Amsterdam	57 years	93 years	Helena Christina	15 years
Uitkijk	38 years	93 years	Houttuin	21 years
Zorg en hoop	47 years	93 years	Landsboerderij Staat	21 years

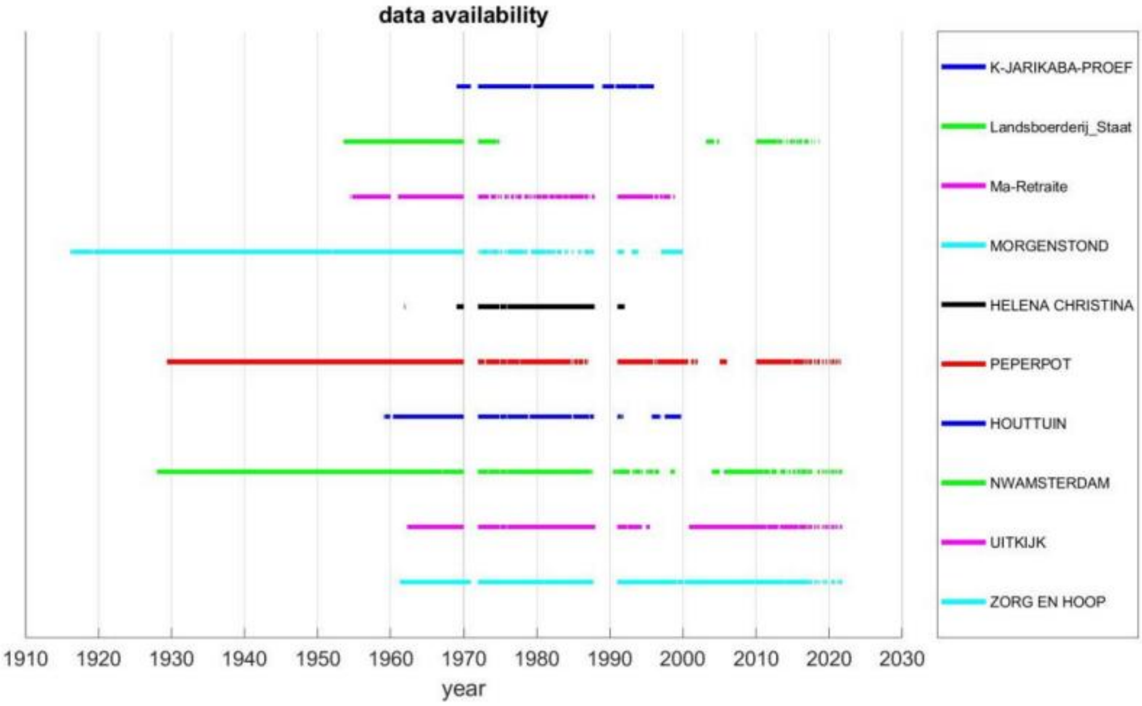
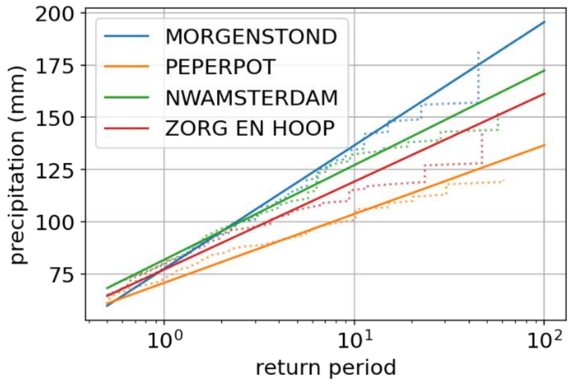


Figure 4-5 Data availability of each rainfall station

A Gumbel distribution is fitted for each station suitable for EVA, except for station Uitkijk, which is excluded due to poor fit (Figure 4-6). The stations show significant deviations, with T=10 event values ranging between 100 and 140 mm. However, station 'Zorg en Hoop' falls within this range without major deviations from its original data, considering it suitable for further analysis.



Return period	**Morgenstond**	**Peperpot**	**Nw Amsterdam**	**Zorg en Hoop**
T = 1	78	71	82	77
T = 2	95	81	95	90
T = 5	119	94	113	107
T = 10	137	104	127	119
T = 20	154	114	141	132
T = 50	178	127	159	149
T = 100	196	137	172	161

Figure 4-6 Gumbel fits for four closest rainfall stations. The dotted lines represent the measured daily rainfall data. Exact values for different return periods (in years) are given in the table on the right (mm).

Analysis of hourly rainfall data

The hourly rainfall data from station 'Zorg en Hoop' spans over approximately 11 years, however, there are several gaps (missing values) in the data which make it challenging to derive extreme value statistics for hourly rainfall (Figure 4-7). Only a single year has more than 90% data availability. To extract more extreme events it is chosen to analyse all the years with more than 50% data availability, resulting in 9 years for the analysis. This may underestimate the yearly extremes, but it gives at least 9 events for the analysis. A comparison is made with the more complete daily dataset for validation of this method. The 24-hour rainfall and the daily rainfall for different return periods are compared, which are presented in Figure 4-8. The 24-hour rainfall is expected to be around 1.1 times the daily values, and this seems to hold true for return periods between T=2 and T=10. An IDF curve present the 2, 3-, 6-, 12- and 24-hourly rainfall statistics for the hourly dataset.

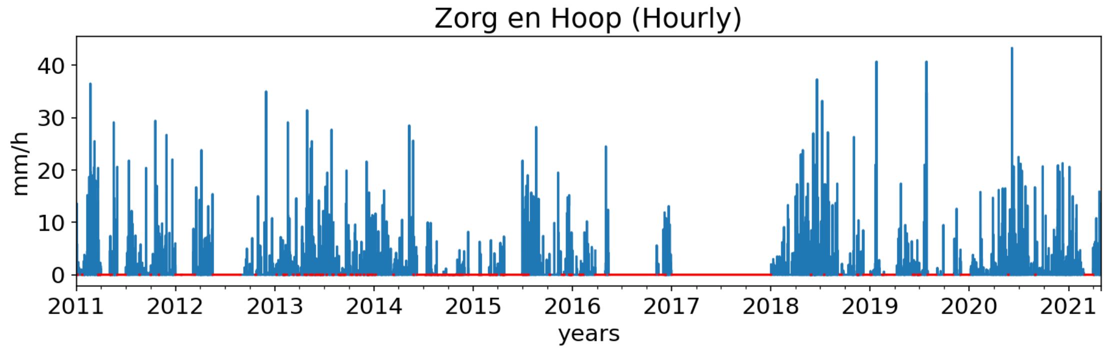
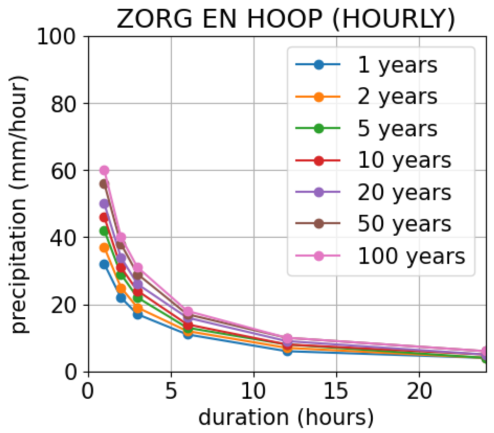


Figure 4-7 Hourly rainfall data at Zorg en Hoop rainfall station. The red line represents where data is missing



Recurrence	Daily (mm)	24 -Hour (mm)	Factor
T = 1	77	96	1.25
T = 2	89	105	1.18
T = 5	106	116	1.09
T = 10	119	124	1.04
T = 20	131	133	1.02
T = 50	148	139	0.94
T = 100	161	144	0.89

Figure 4-8 IDF curve of Zorg en Hoop hourly data and a table showing the Daily, 24-Hourly rainfall data and the factor between them. The red values deviate too much from the expected factor (1.1)

To produce design rainfall events for a return period of T=2, T=10, and T=100, the IDF curve was utilized (Figure 4-8) and the alternating block method was applied (subsection **Error! Reference source not found.**). This method has the advantage of containing the rainfall for all durations of the desired return period in the resulting hyetograph. The derived hyetographs are compared to a hyetograph for T=100 derived in the Diermanse (2022) The results showed that the peaks were generally slightly lower, and events with a lower return period had lower peaks.

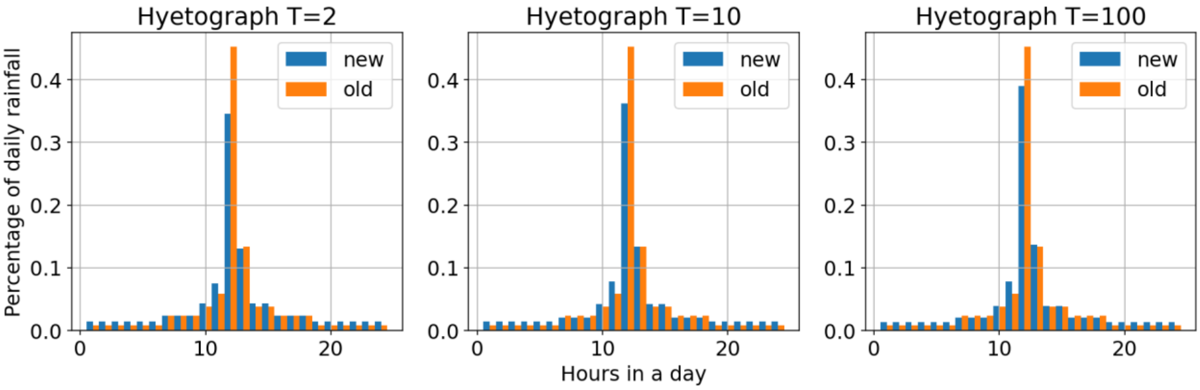


Figure 4-9 Design Hyetograph for a T=2, T=10 and T=100 event. Compared to the Hyetograph from JBA (2017)

To create a long-term artificial hourly dataset, the design hyetograph of T=100 is combined with the filtered daily dataset. The new dataset is plotted against the original hourly dataset for the years 2011-2017 to validate this method. Despite the hourly dataset having many gaps, the peaks in the artificial dataset generally match those in the original dataset. It appears that the daily dataset have more peaks, however this is due to the gaps in the hourly data. Overall, the peaks in the artificial dataset are slightly higher, ensuring the model will be on the safe side.

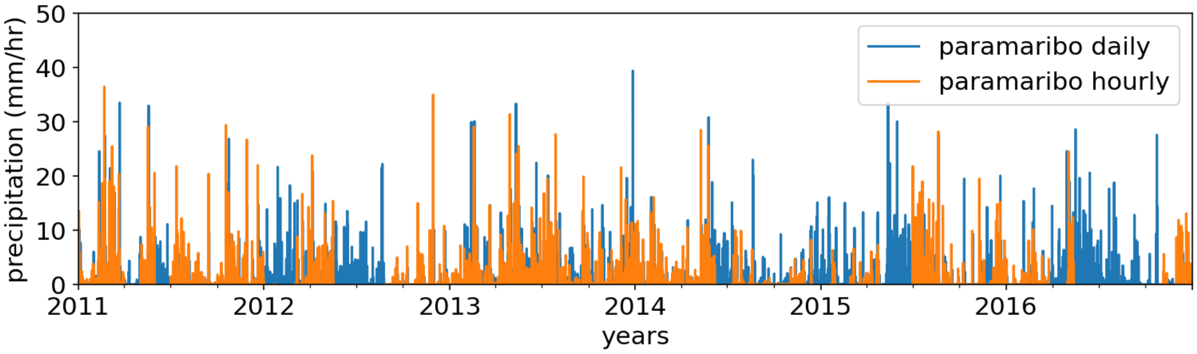
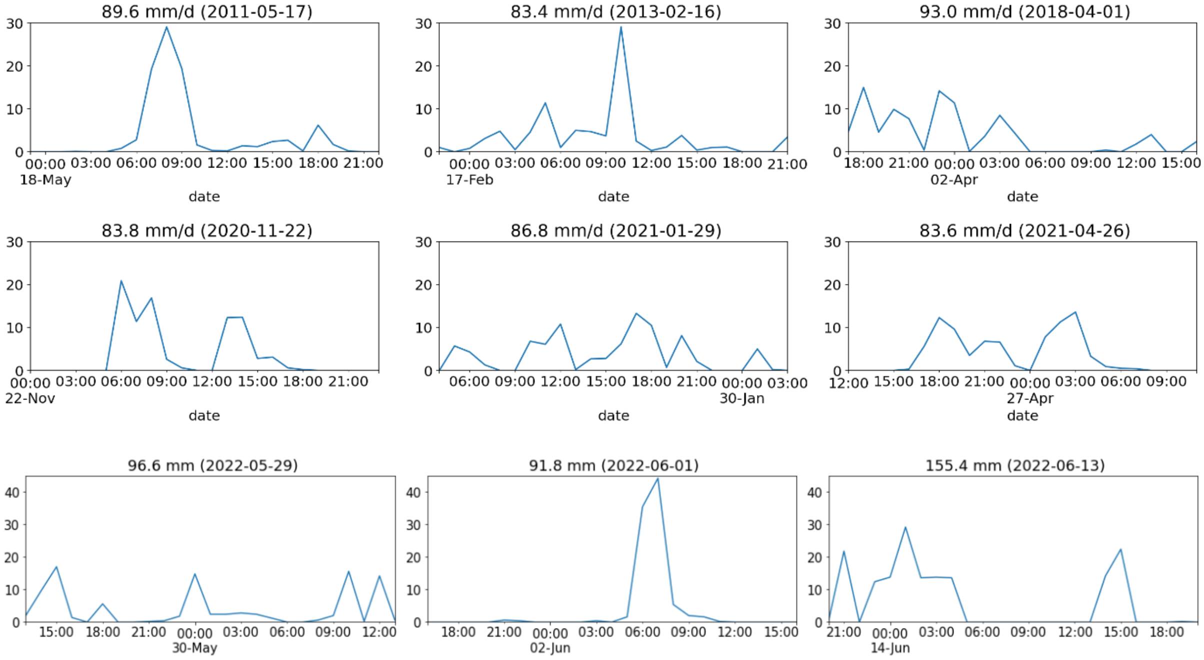


Figure 4-10 Long-term artificial hourly dataset compared to hourly dataset

Extraction of individual storms

The peaks-over-threshold method (Appendix A5) is utilized to extract individual storms from the hourly dataset, with a return period of T>1 (Figure 4-11). In addition, the same analysis is performed on the most recent data from 2022, obtained from a newly installed station at Kwattaweg, covering the period from 16 May 2022 to 12 July 2022. The purpose of extracting storms is twofold: to provide input for the D-HYDRO model and to identify a regular pattern in the rainfall events.

Due to limited data availability, no definitive conclusions can be drawn from the analysis. However, the study reveals that most storms (6 out of 9) are spread over the day and have multiple peaks. Two storms, one with T=3 on 29-05-2022 and another with T=100 on 13-06-2022, are used for validation, with the latter being utilized in the D-HYDRO analysis to compare the results of a design storm with an actual storm.



89.6 mm/d (2011-05-17)

83.4 mm/d (2013-02-16)

93.0 mm/d (2018-04-01)

83.8 mm/d (2020-11-22)

86.8 mm/d (2021-01-29)

83.6 mm/d (2021-04-26)

96.6 mm (2022-05-29)

91.8 mm (2022-06-01)

155.4 mm (2022-06-13)

Figure 4-11 Rainfall events of 24 hours with a return period T>1

4.2 TESTING OF MODELLING ASSUMPTIONS IN THE CRCTOOL

This section focuses on testing the assumptions made in the CRCTool. First, the assumption of using an average runoff reduction factor is examined for each measure and for a Bioretention Cell, several parameters are adjusted to determine the factors on which this assumption depends (subsection 4.2.1). Next, the assumption of neglecting the controlled runoff is tested by displaying the contribution of controlled runoff for a Bioretention Cell during a single T=1 event (subsection 4.2.2). Finally, various outcomes of event separation for different baseline discharges are presented in the last section (4.2.3).

4.2.1 Runoff reduction factor determination

The runoff reduction factors observed in this case study differ from those reported in the Laakhaven study (Figure 3-10). In Figure 4-12 the runoff depth is plotted against the return period, following the same approach as the Laakhaven study (section 3.4.3). The runoff reduction factor is calculated as the difference between the baseline (black) and the measures (colored). If the lines are parallel but shifted upwards, a single average runoff reduction value can be used. However, this assumption does not hold for most measures in this study, as the relationship between runoff depth and runoff reduction factor varies across measures.

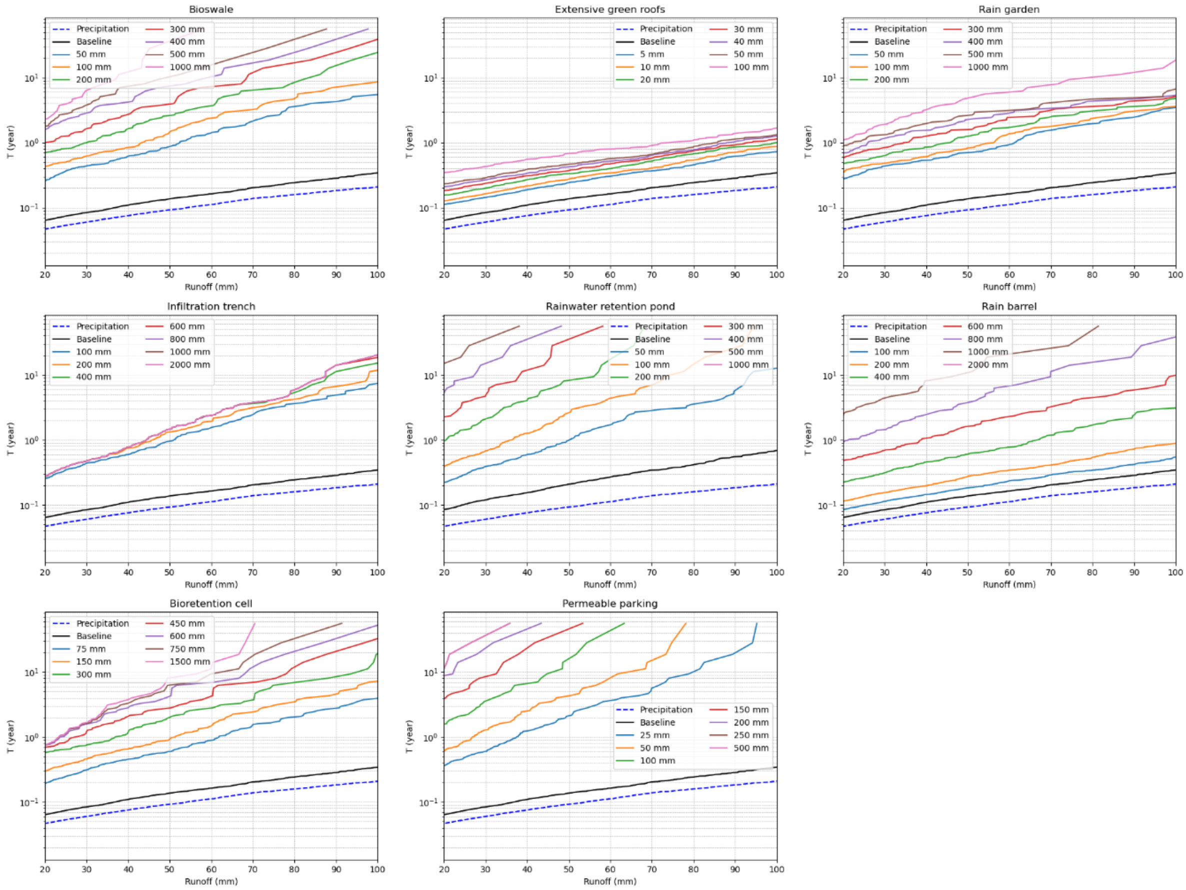


Figure 4-12 Return periods of different runoff volumes for different measure depths (coloured lines) and for baseline runoff (black line). The difference between the black and the coloured lines represents the runoff reduction factor

For most measures, higher runoff depths corresponded to higher return time factors, except for green roofs. The relation found in Laakhaven only holds true for small effective depths and/or low runoff depths. Deviations occur when the runoff depth exceeds 50 mm and the effective depth of the measure is 20 mm or greater. The results suggest that the effectiveness of NBS depend on multiple factors and the relation only holds for low effective depths and/or low runoff depths.

Runoff depths of 50mm have a return period lower than 1 year for Paramaribo. NBS will normally be designed for return periods larger than 1 year and thus this relation does not support the preferred design standard. Effective depths are based on the land use area. The viable cases proposed to implement in the area have effective depths that are below 20 mm (green line), thus the deviation for higher measure depth will not be a problem.

Different factors limit the effectiveness of NBS. This includes the infiltration capacity, drainage capacity of the bottom storage and the type of bottom storage drainage (Figure 4-13). It was observed that the relationship between the effective measure depth and the runoff depth is influenced by the type of drainage and the runoff capacity of the measure. As depicted in the Figure 4-13d lines are found to be parallel when limiting runoff capacities are used. For discharge types related to storage and level (Figure 4-13h & i), the relationship also holds for lower runoff depths, which is consistent with the low runoff capacity that is associated with the low effective measure depths.

These findings show that the current implementation of the CRCTool only supports measures with low runoff capacities. This is often found in measures with low effective depths, according to the rule that a measure must empty in 48hrs (Boogaard, 2022). This is depicted by the blue and orange line in Figure 4-13i. For areas with high rainfall amounts, where higher measure depth and/or higher drainage capacities are required this relationship does not hold.

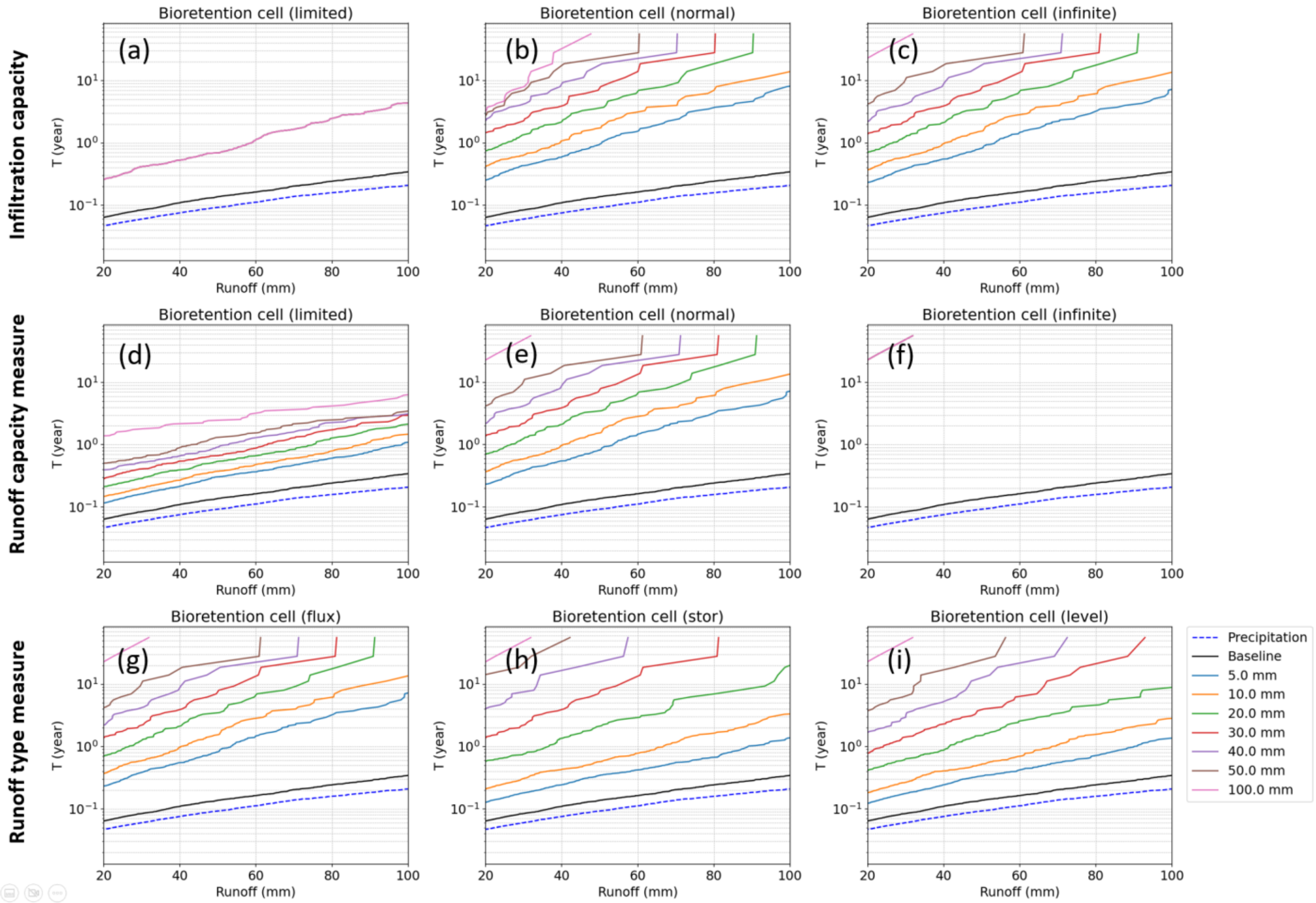


Figure 4-13 Effects of infiltration capacity, runoff capacity measure and runoff type measure on the return period of the runoff volumes of the measure. (a) limited infiltration capacity

4.2.2 Controlled runoff

The CRCTool assumes that any runoff that is controlled from a measure is not part of the overall runoff volume for that measure. To simulate this in the model, any controlled runoff from the measure is directed to a separate "bucket" rather than flowing to the Stormwater Drainage System (SWDS). When calculating the reduction in runoff, only the flows to the SWDS are considered. However, if controlled runoff is assigned to the SWDS in UrbanWB, it is treated as uncontrolled runoff.

However, in this case study, the controlled runoff is discharged via an underdrain, which drains into the SWDS. Figure 4-14 shows that during a single T=1 event, the controlled runoff accounts for 15% - 25% of the peak runoff to the sewer system. Ignoring this would lead to a significant overestimation of the measures' performance.

If the controlled runoff is assigned to the SWDS, the same peak reduction is visible. However, it is important to note that the runoff reduction calculation is performed over the sum of an event, which is defined as the period between the start of one event and the start of the next. This means that any controlled runoff that is discharged via the SWDS after an event is also considered part of that event. The result is that no runoff reduction will be detected.

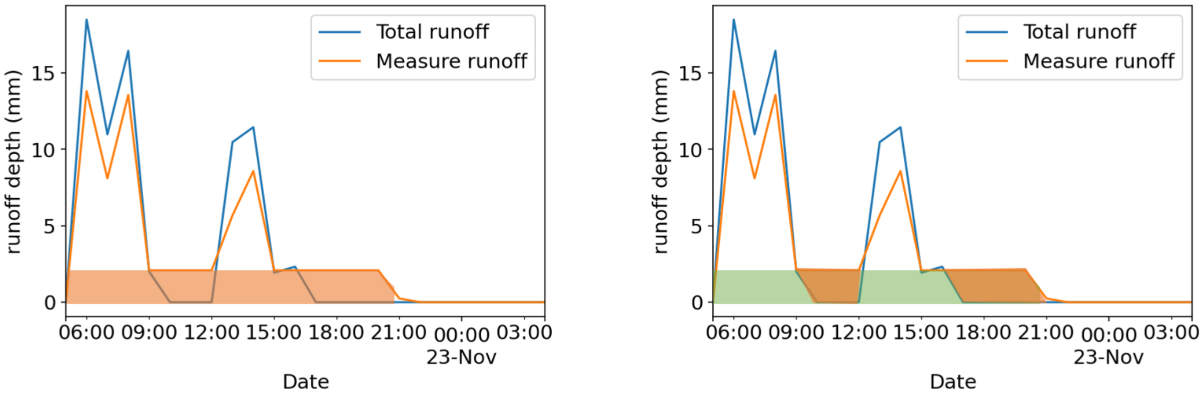


Figure 4-14 Controlled runoff contribution of a measure during an event depicted in the orange area (left) and actual controlled runoff (right) where the green area accounts to uncontrolled runoff

In a situation where measures depend on an underdrain or overflow weir with high bottom discharge capacities, such as in areas with high rainfall intensities, the controlled runoff becomes a significant part of the total runoff. Ignoring this can lead to an overestimation of the measure's effectiveness.

Assigning the runoff to the SWDS results in no observed effect of the measure because the runoff is summed over the whole period of the event and the dry period that follows. However, if the events were defined as the period between the start of rainfall and the point when the runoff returns to a manageable level (i.e. the open water level is back to the target level), any runoff that occurs after this point would not be considered uncontrolled runoff.

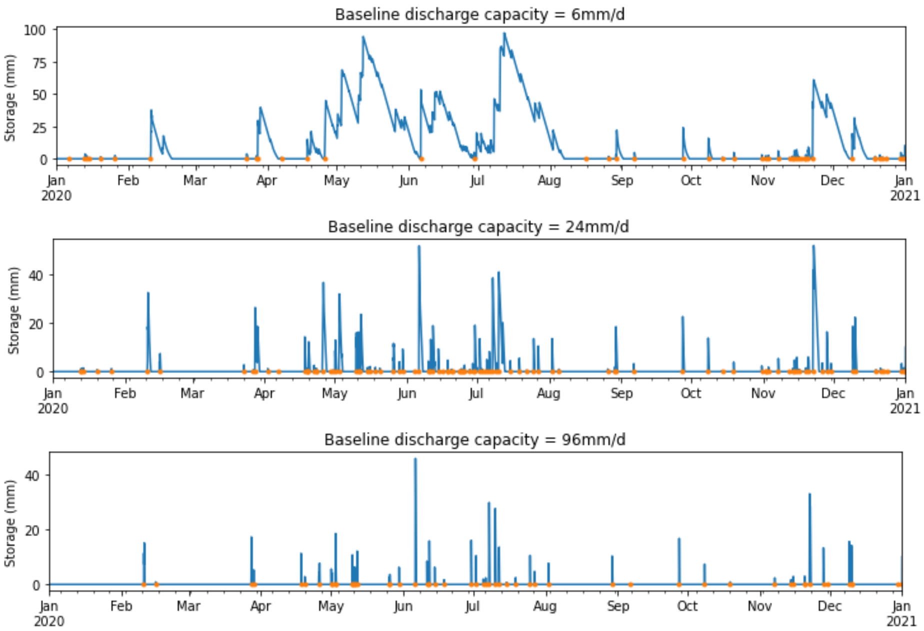
By redefining events in this way, it will be easier to distinguish between controlled and uncontrolled runoff, and more accurately assess the effectiveness of the measure.

4.2.3 Event separation

The separation of events is based on a specific baseline discharge which determines when a storage event is considered ended, and subsequently, statistical analysis is performed on the separated events. For the purpose of determining measure effectiveness, the pump capacity, which is around 100 mm/d, is used as the discharge value. As for the SDF curves, a value of 3-4 times the average daily rainfall (24 mm/d) is recommended, whereas the UrbanWB employs a discharge value of 1x the average daily rainfall (6 mm/d). In this subsection the effects of different baseline discharges is tested.

It has been observed that the event ranking can be significantly affected by different baseline discharges, especially for lower values where the highest ranked events may have significant differences. The actual values can be found in Appendix A16. Figure 4-15 illustrates why this phenomenon occurs. Low baseline discharges lead to the summing of events, which can result in more extreme events or combine large events together, resulting in the exclusion of the lower-ranked event.

The observed differences become smaller for larger baseline discharges. However, there is a trade-off as selecting a higher baseline discharge leads to a lower total number of separated events. This implies that smaller events are neglected and thus not included in the statistical analysis of rainfall.



Baseline discharge (mm/d)	Nr of events (-)
3	11
6	**46**
9	77
12	93
15	95
18	98
24	**101**
30	100
36	97
42	87
48	81
96	**54**

Figure 4-15 Course of storage events over a year for different baseline discharges. Each orange dot represents a separate event. The table shows how many events are separated for different baseline discharges.

The water level in the Open Water storage is illustrated in Figure 4-15 for three different baseline discharges: 1x, 4x, and 16x the average mean daily rainfall. This graph indicates where the events are separated. As shown in the top graph, events that should be separated are combined, particularly during the rainy season (May-August), resulting in stacked events. The next event begins before the last event is drained, leading to the accumulation of events and preventing the open water level from returning to its target level. Consequently, some storage events become exceptionally large. On the other hand, for a high baseline discharge, many rainfall events are ignored and hence not accounted for as events.

4.3 EFFECT OF INPUT PARAMETERS ON CRCTOOL RESULTS

This section describes the results for the sensitivity analysis of the storage and infiltration capacity (subsection 4.3.1) and the inflow factor (subsection 4.3.2). The last section compares the different measures that are tested in this research (subsection 4.3.3).

4.3.1 Storage and infiltration capacity

In this subsection the effect of infiltration capacities of interception and bottom storage layer and the size of the interception and top storage layers on the runoff reduction value will be discussed. These are supposedly the most important factors influencing the effectiveness of the measures.

Figure 4-16a shows infiltration rates between 0 and 10.000 mm/d for different effective depths. It is found that up till 500 mm/d, the infiltration rate is limiting. Between 500 mm/d and 1000 mm/d a strange effect for low effective depths occurs (5-10mm), where the runoff reduction value reduces. Except for large effective depth (50-100 mm), an infiltration rate of 1500 mm/d gives an optimal runoff reduction factor. Remarkably, for low values of infiltration and storage capacity of the interception layer the runoff reduction factor was observed to be higher for lower effective depths.

For the discharge capacity of the bottom layer values between 5 and 1200 mm/d are tested, where 5 mm represents a bucket where only evaporation and percolation occurs and 1200 mm, simulates the same infiltration capacity as the soil layer, so water does not get stored (Figure 4-16b). For all effective depths the runoff reduction factor limits at 22. The results show that this value of 22 is exceeded at some specific runoff capacities and effective depths before returning to this value. This effect is further discussed in subsection 5.1.2. Furthermore, the results shows that the larger the storage capacity the lower the discharge capacity of the storage layer must be to have a significant effect.

The size of the top storage layer shows a very different graph compared to the interception layer (Figure 4-16c & d). For depth larger than 50 mm the top storage layer has no effect on the runoff reduction factor. For depths of 25 mm the runoff reduction factor is the same for each effective depth. Between 25-50 mm the runoff reduction value increases for effective depth higher than 20 mm and lowers for effective depth lower than 20 mm.

The top storage layer does not affect the runoff reduction factor, except for depths that are smaller than the original infiltration capacity, where the infiltration capacity is limited by the size of the top storage layer. For instance, a top storage layer of 100 mm caps the infiltration rate to the bottom storage at 2400 mm/d. Therefore, for green roofs, which have a small top layer storage of 10 mm, the maximum infiltration rate is automatically capped at 240 mm/d. Additionally, there is an unexplained anomaly between 25-50 mm, which is also observed in the infiltration capacity of the interception layer. This is further discussed in subsection 5.1.7.

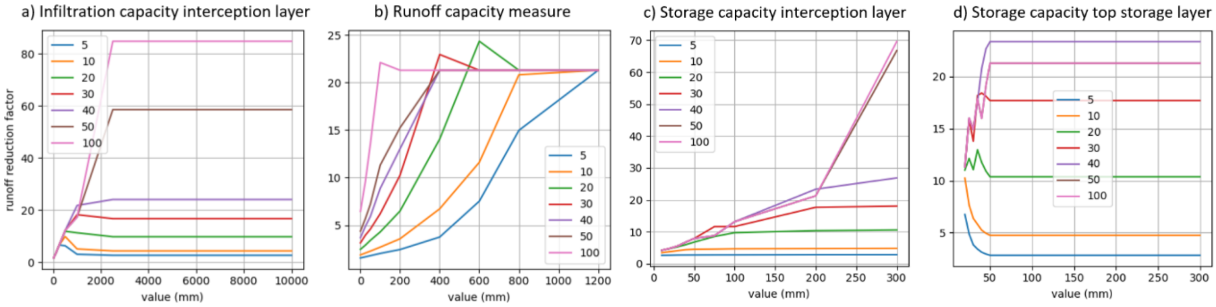


Figure 4-16 Sensitivity analysis of parameters showing the effect on the runoff reduction factor

4.3.2 Influence of inflow factor

The definition of the inflow factor has a large influence on the corresponding area specific runoff reduction factor (Table 4-3). A measure proves to be more effective for lower inflow factors. The difference is especially profound for larger measure depths. A detailed analysis of the flow behaviour during an event for different inflow factors is given in Figure 4-17.

Table 4-3 runoff reduction values for different inflow factors and different measure depths

Inflow factor	**Measure**	**Measure depth over study area**						
		5 mm	**10 mm**	**20 mm**	**30 mm**	**40 mm**	**50 mm**	**100 mm**
1	Bioretention cell	2.82	5.25	11.67	22.95	57.13	160.49	196.82
2	Bioretention cell	2.15	3.6	8.65	15.21	18.13	14.34	14.34
5	Bioretention cell	1.87	2.72	3.58	4.33	4.33	4.33	4.33
10	Bioretention cell	1.7	1.92	1.98	1.98	1.98	1.98	1.98
20	Bioretention cell	1.38	1.43	1.44	1.44	1.44	1.44	1.44

This analysis reveals that the runoff observed at measure A is attributed to the limitations in the infiltration capacity, which occurs when the bottom storage depth is not entirely filled. In the case of measure B, the bottom storage is fully utilized, indicated by the purple line reaching a depth of 20 mm. However, no runoff is generated since the infiltration layer can still store the excess water. This is because the infiltration storage layer accounts for half the depth of the total depth, unlike in measure A where it accounts for only 10% of the depth. The lack of scaling of the infiltration storage layer with the effective depth means that a measure with a lower inflow factor is more effective as it has a higher effective depth. factor more effective because it has in essence a higher effective depth.

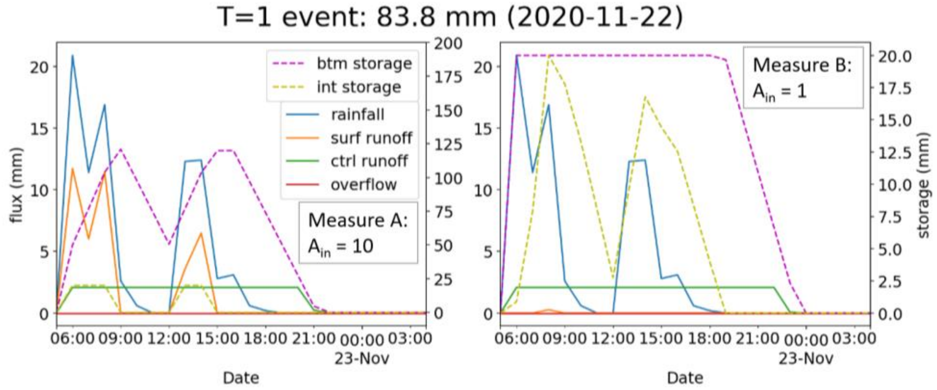


Figure 4-17 displaying rainfall & runoff (mm/d), and storage height (mm) of a measure for a single T=1 event in 2020. On the left a measure with inflow factor 10 (A) and on the right a measure with inflow factor 1 (B) is displayed. Both measures have an effective depth of 20 mm, resulting in a bottom storage layer depth of 200 mm for measure A and 20 mm for measure B.

The measure results depicted in Table 4-3 are manipulated with the equation (2) to all represent the same measure with a storage depth of 10 cm, but with different initial inflow factors. It is expected that runoff reduction factors are the same. The results are given in the table below and it shows that indeed the runoff reduction factors are the same. However, for larger effective depths, the runoff reduction factors for low inflow factors remain the same and thus the difference between inflow factor 1 and 20 increases. Nonetheless, this relation holds if the found logarithmic relation holds.

Table 4-4 Manupilation of runoff reduction factor with eq. (2) (Fmeas is for measure inflow area and Ftot for study area)

Runoff reduction (Fmeas)	**Inflow factor**	**Effective depth**	**Runoff reduction (Ftot)**
1000	1	100	1.21
20.77	2	50	1.19
4.82	5	20	1.22
1.95	10	10	1.21
1.41	20	5	1.21

4.3.3 Differences between effectiveness of measures

In this subsection the runoff reduction factors for each type of measure and different effective depths are discussed. The difference between the measures relating the input parameters is given in Table 3-5 and in more detail in Appendix A8**.**Table 3-5 Important input parameters of the CRCTool

It is found that the runoff reduction factor of retention ponds and rain barrels increases significantly with an increase in measure depth (Figure 4-18). They share an infinite infiltration capacity as they are not limited by a soil layer. This means their effective depth can be optimally used, which is not the case for measures with low infiltration capacities. Nonetheless, high effective depths are not always feasible. For instance, achieving an effective depth of 30 mm with rain barrels would require each household to have 7 tanks of 1000 L.

Compared to other measures, the infiltration trench shows the lowest increase in effectiveness, likely due to its narrow and deep design, which results in a larger inflow factor. As discussed in subsection 4.3.2, the effectiveness of this measure is limited by the inflow factor despite its high infiltration capacity. However, for low effective depths, infiltration trenches can be comparable to other measures and provide an effective solution.

The performance of rain gardens, bioretention cells, and green roofs is comparable. The green roofs effectiveness per measure inflow area is significantly lower (Appendix A12), due to the large roof coverage in the study area its overall effectiveness is high Bioretention cells and rain gardens have comparable effectiveness, with the larger area size of rain gardens compensating for their lower drainage capacity. Appendix A12 shows that for low effective depths (5-20 mm), the difference in effectiveness is marginal, but for higher effective depths, the difference in drainage capacity begins to have an effect.

Vegetative swales show the same increase in effectiveness with effective depth compared to bioretention cells/ rain gardens but are in general more effective. Vegetative swales tend to have larger interception storage capacity. This interception storage is not included in the calculations for effective depth and thus counts as extra storage, which contributes to the higher effectiveness of vegetative swales. This is discussed in subsection 4.3.2.

When it comes to low measure depths, permeable pavement is together with retention pond the best performing measure. It has the same increase with measure depth as observed for vegetative swale, bioretention cell and green roofs. The main difference in this measure compared to the other measures is its lower inflow factor, which means the actual measure area is larger. Section 3.4.4 discusses this effect of the inflow factor.

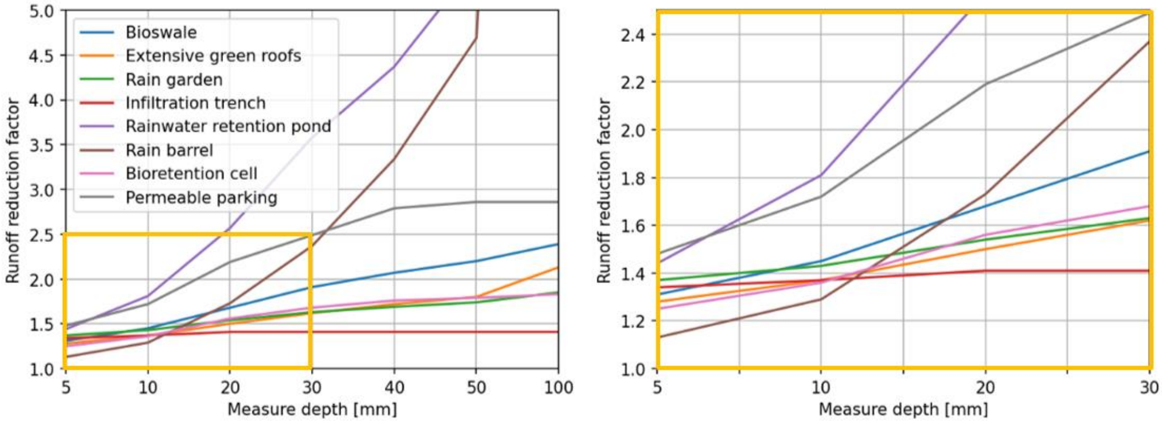


Figure 4-18 Runoff reduction factor for different measures and their measure depth. The right graph is zoomed in and represents realistic measure depths

4.4 CRITICAL ASSESSMENT OF HYDROLOGICAL FLUXES IN CRCTOOL

In this section the representation of hydrological fluxes in the model will be critically assessed. First, the main flows in the system and their contribution to the total flow will be evaluated in subsection 4.4.1. Thereafter, the groundwater component of the model is considered to quantify their influence on the model behaviour (subsection 4.4.2).

4.4.1 Distribution of different type of water flows

First, an analysis was conducted to determine the percentage of precipitation that accounts for percolation, evapotranspiration, and runoff. The analysis was performed using the hourly dataset for the most complete year, which is 2020. The results showed that 72% of the total rainfall contributed to runoff, while 18% contributed to percolation, and 10% to evapotranspiration.

Figure 4-19 visualises these processes over the course of a year (left) and a week (right). The yearly overview shows that during large events (> 20mm/h), runoff (89%) is the main process and groundwater percolation (10%) and evapotranspiration (1%) can be neglected. Especially evapotranspiration has a very limited effect on the total outflow. During smaller events (< 10 mm/h), percolation has a significant contribution. The weekly overview shows that there is no long-term evapotranspiration and transpiration after the events. This means the water level restores quickly to its target water level. These processes stop when the target water level is reached.

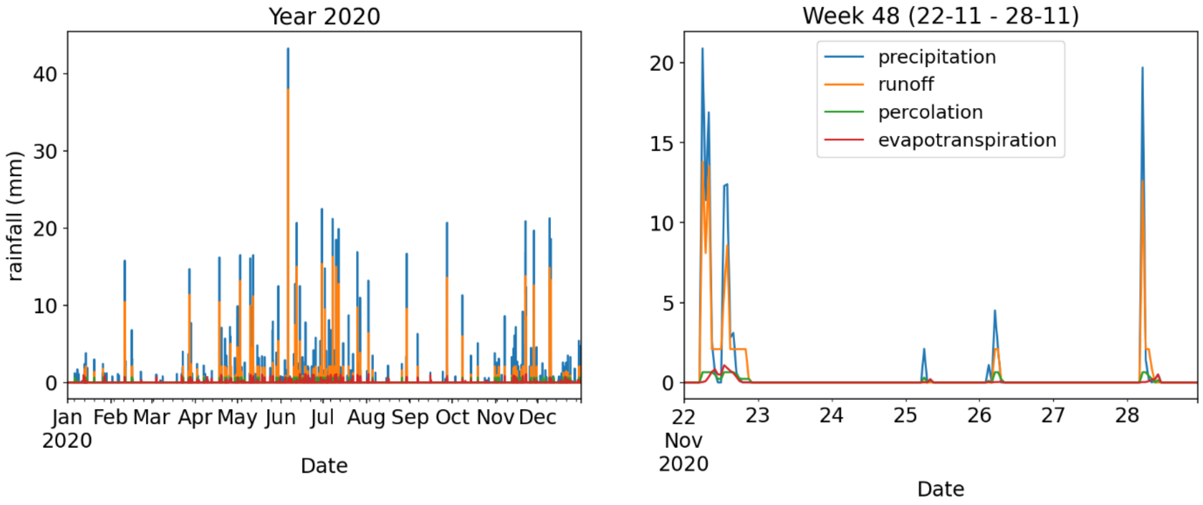


Figure 4-19 Main hydrological fluxes in the study area over a year (left) and a week (right)

Secondly, the analysis examines how the runoff from a measure is partitioned into three distinct processes: surface runoff and overflow, which are uncontrolled runoff flows from the measure, and bottom storage runoff, which is infiltration into the soil or drainage via an underdrain or a controlled weir/gate. Surface runoff refers to the runoff that occurs when the inflow of the measure exceeds its infiltration capacity. Overflow, on the other hand, is the runoff that occurs when the measure's storage volume is at maximum capacity.

Figure 4-20 shows that most of the runoff contributing to the total measure runoff is surface runoff. It is worth noting that overflow never occurs because all water is considered surface runoff if the storage of the measure is full. As a result, overflow is never calculated. The controlled runoff remains constant during an event, as expected. When zoomed in on a single week it is noticeable that the controlled runoff almost immediately stops after the event, indicating that the storage volume empties quickly.

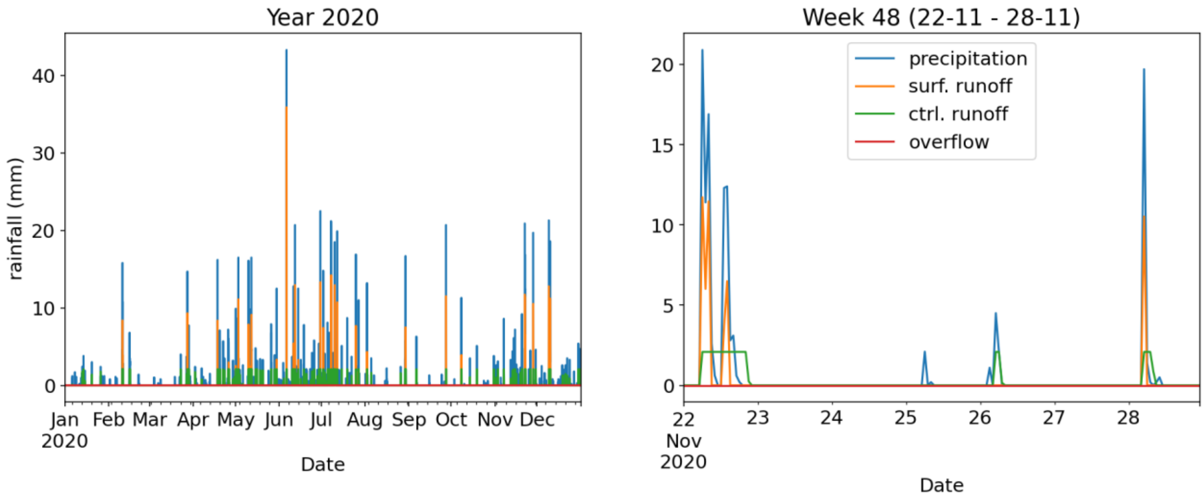


Figure 4-20 Distribution of runoff processes compared to the actual rainfall for a year (left) and a week (right)

Lastly, the difference between the effects of flux and level discharge on the storage capacity of the measure is discussed. Both methods have a different approach of defining the discharge from a measure. Level discharge is set to drain in 48 hours and flux is set to half of the measure's storage capacity. The effects on the storage capacity and actual flux are displayed in Figure 4-21**.**

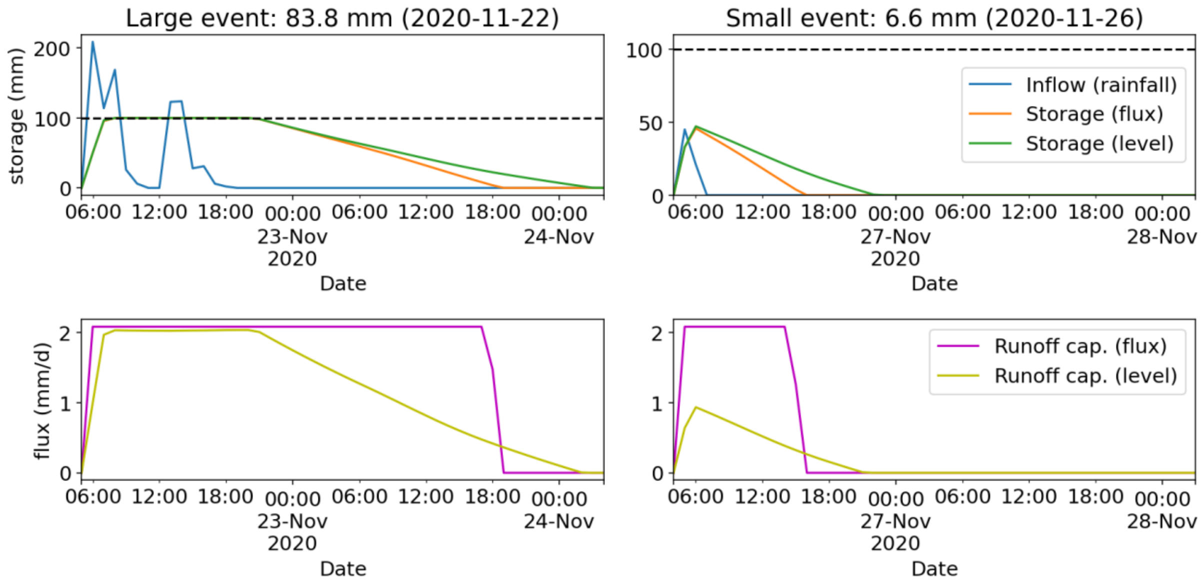


Figure 4-21 Effect of flux and level discharge on the storage capacity of a measure for a large and small event (top graphs). The actual flux draining from the storage layer (bottom graphs). The black dotted line is the maximum storage capacity.

The left figure (Figure 4-21) shows a large event (T=1) and demonstrates that for level discharge the storage is emptied exactly 48 hours after the start of the event. However, with a drainage capacity of 50 mm/d, the storage empties faster than 48 hours due to other processes like percolation, transpiration, and evapotranspiration that also contribute to emptying the storage. The graph displaying the flux reveals how the drainage rates differ for both methods: the level discharge capacity becomes lower after the storage begins to empty. For a small event, the difference between the methods is even greater, leading to a relatively large gap of around 6 hours between the times when the storages empty.

4.4.2 Influence of groundwater component

In this subsection the effect of the shallow groundwater component on the measure's effectiveness is investigated. It is analysed how much it contributes to the outflow of a measure and what the effect is of limiting the outflow by the groundwater level. It was found that the percolation to the deep groundwater is negligible, this is shown in Appendix A10.

The groundwater connection in this study contributes 2 mm/h to the total discharge from the measure as seen in Figure 4-22. This contribution is small due to the limited infiltration capacity of the native clay soils. The effect on the runoff reduction factor is thus also limited (Figure 4-22). The largest differences between runoff reduction factor are visible for measure depth around 30 mm. Note that this situation only applies to clay soils. For sandy soils which has a higher K value, the contribution of groundwater flow can be more significant.

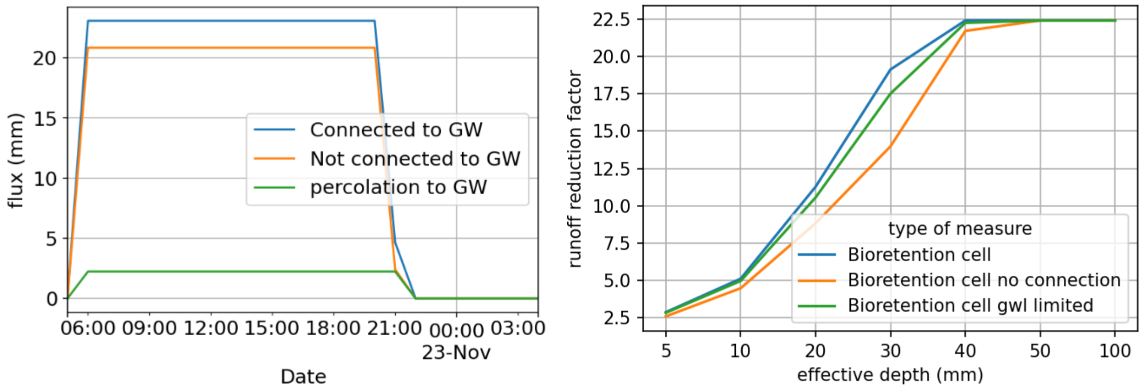


Figure 4-22 Flow with and without 'p_gw_btm_meas' (left) & difference in runoff reduction factor for different gw connections

Restricting the measure by groundwater has a small impact on the runoff reduction factor (Figure 4-22). Upon examining the year 2020, it is discovered that the groundwater level hits the surface 9 times, thus restricting the downward flux to the groundwater (Figure 4-23). Examining the largest event shows that the limitation by the groundwater level only reduces the downward flux by approximately 2 mm. The restriction thus only affects the natural percolation from the bottom layer of the measure to the groundwater, not the user-defined bottom measure runoff to the groundwater, which is applied in this test.

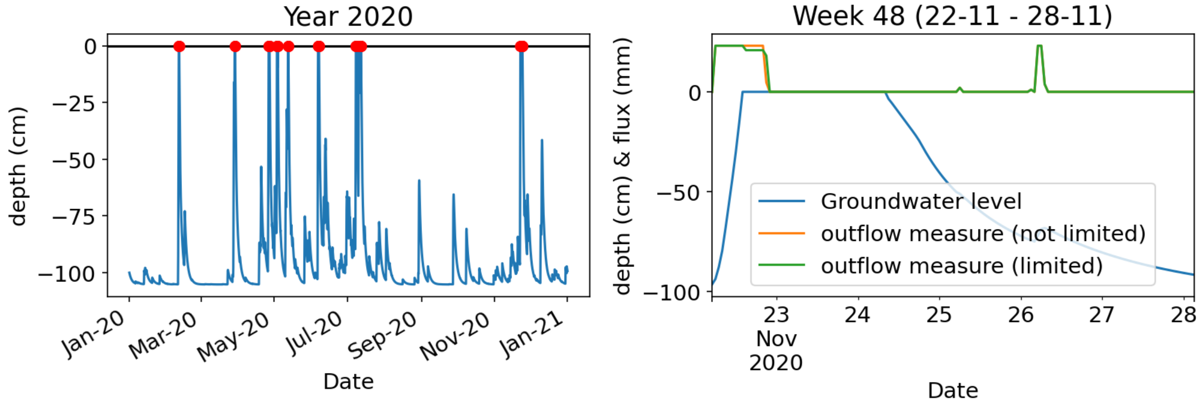


Figure 4-23 Groundwater table over the course of a year with red dots showing groundwater level reaching the surface (left) Groundwater table over the course of a week showing the difference in outflow of a measure if limited by the GW (right)

4.5 COMPARISON OF OUTPUTS FROM CRCTOOL AND D-HYDRO

This section presents a comparison between the outcomes of the CRCtool and D-HYDRO. The comparison is divided into two subsections. Subsection 4.5.1 focuses on the reduction of flooding volume. Section 4.5.2 presents the additional insights provided by the hydrodynamic modelling in the implementation of NBS. For each section, the results from the CRCTool are presented first, followed by the D-HYDRO results.

4.5.1 Reduction in flooding volume

The reduction in flooding volume, as measured by the CRCTool, is displayed in SDF curves (Figure 4-24). Four SDF curves are presented, which show the maximum flooding volume for different pump capacities for no measures, 10% measures, 50% measures, and 100% measures based on the total identified potential area. The flooding volume represents the maximum flooding volume for an event with a specific return period. Table 4-5 shows the corresponding flooding depths for T=2, T=10, and T=100 events. The effectiveness of NBS is expressed as a percentage of flood reduction of the total measure volume. Interestingly, the effectiveness of NBS is independent of measure size in the CRCTool.

Table 4-5 Flood depth for different degrees of NBS volumes for T=2, T=10 and T=100 event at current pump capacity. Flood reduction is displayed in a percentage of the total NBS volume.

Event	**No measures 0 m^3**	**Local measures 2.000 m^3**		**Viable measure 10.000 m^3**		**Max measures 20.000 m^3**	
	depth (mm)	*depth (mm)*	*reduction (% of NBS)*	*depth (mm)*	*reduction (% of NBS)*	*depth (mm)*	*reduction (% of NBS)*
T = 2	26	25	78%	20	78%	13	78%
T = 10	38	36	117%	29	117%	20	117%
T = 100	54	51	163%	41	163%	29	163%

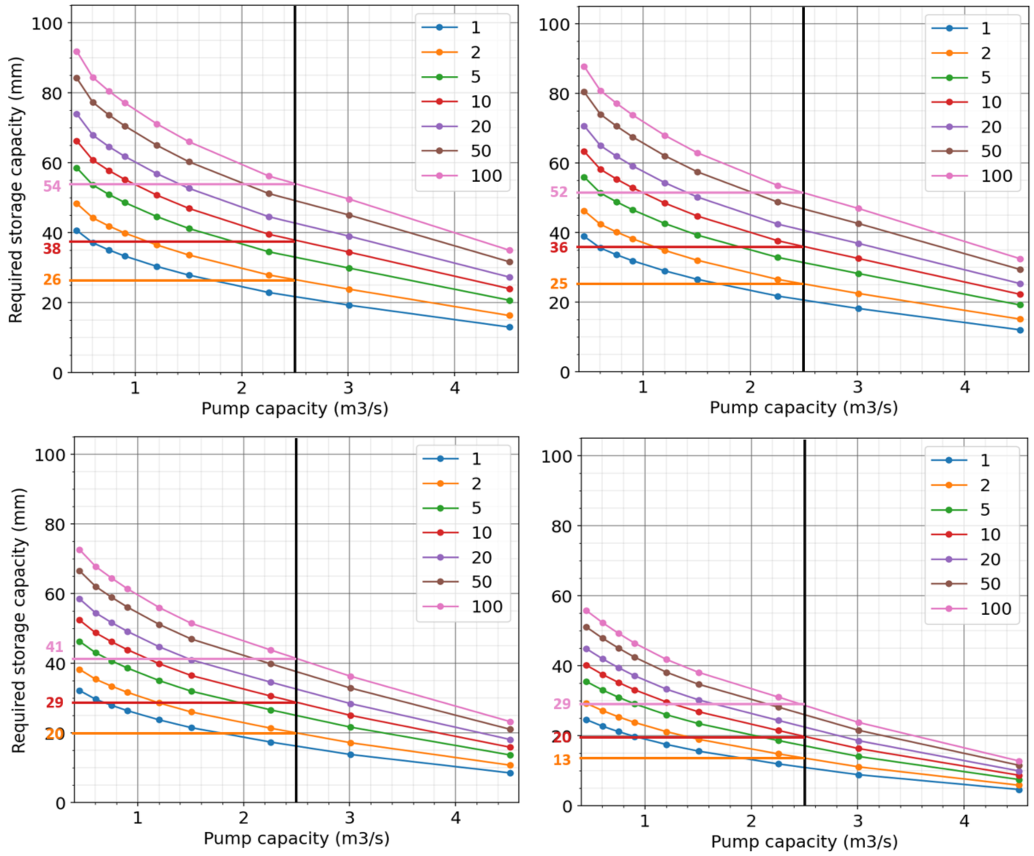


Figure 4-24 SDF curves with a measure implemented for 0% (a), 10% (b), 50% (c) and 100% (d) of total potential area. Each line represents a different return period (in years)

The results from the CRCTool show a linear decrease in flood reduction with an increase in total measure volume. Additionally, it was observed that the decrease in flooding depth increases for events with higher return periods, which is consistent with the increase in runoff reduction factor observed for the measures in the previous section. The reduction in flooding volume can be correlated with the total storage capacity of the measure, providing insight into the effectiveness of NBS with respect to storage volume. Specifically, for T=2, T=10, and T=100 events, the effectiveness of measures is 80%, 120%, and 160%, respectively. This implies that the effectiveness of a measure is twice as much for a T=100 event as it is for a T=2 event.

The reduction of flooding volume in D-HYDRO is visualized in two ways: a two-dimensional flood map (Figure 4-25) and one-dimensional water depth plots for two problem areas (Figure 4-27)**.** Most of the measures are filled with stormwater (indicated by the dark blue color), indicating that they are functioning as intended. Table 4-6 and Table 4-7 show the differences in water depths that remain within the system (i.e., flooding volume) and that leave the system after the measures have been implemented.

The effect of the measures is mainly visible in the upstream part of the catchment around the problem area. Downstream in the pilot area, only a slight reduction in depth is visible. The extent of the inundated area is the same. Measure effectiveness, measured in what percentage of the measure's storage volume is reduced in terms of flooding volume.

Table 4-6 Mass balance of water volumes remaining in the system per event, representing flooding volumes

Event	**No measures 0 m³**	**Local measures 2.000 m³**		**Viable measure 10.000 m³**		**Max measures 20.000 m³**	
	depth (mm)	*d (mm)*	*% of NBS*	*d (mm)*	*% of NBS*	*d (mm)*	*% of NBS*
T = 2	58.2	56.3	123%	48.6	124%	39.9	118%
T = 10	83.6	81.2	160%	72.8	141%	63.2	133%
T = 100	118.1	116.1	126%	108.3	127%	98.9	125%

Table 4-7 Decrease in pumped outflow per event due to measure implementation

Event	**No measures 0 m³**	**Local measures 2.000 m³**		**Viable measure 10.000 m³**		**Max measures 20.000 m³**	
	depth (mm)	*d (mm)*	*% of NBS*	*d (mm)*	*% of NBS*	*d (mm)*	*% of NBS*
T = 2	34.9	34.8	99.6%	34.8	99.5%	32.1	92.0%
T = 10	43.7	43.7	99.9%	41.0	93.7%	39.2	89.6%
T = 100	62.8	62.5	99.6%	56.5	90.0%	53.1	84.5%

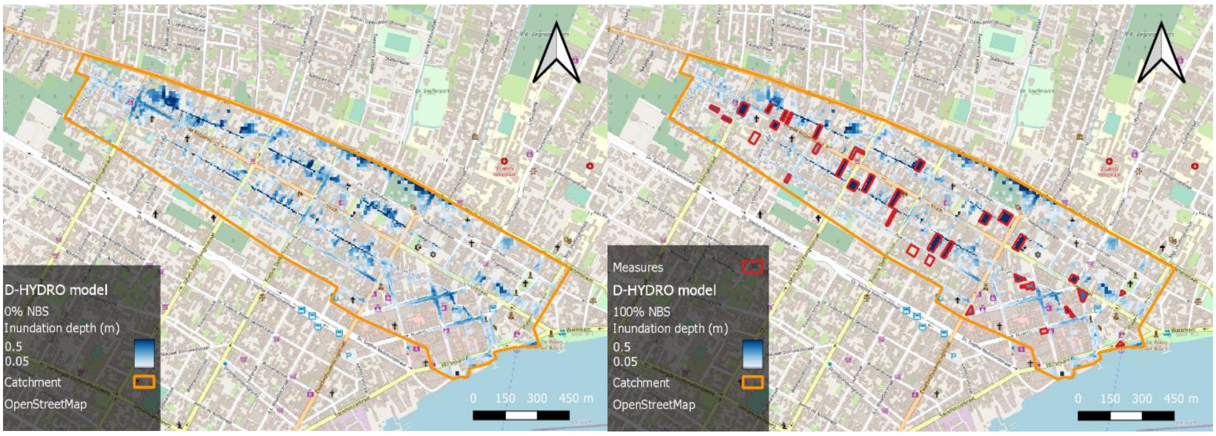


Figure 4-25 Inundation map for a T=100 event in D-HYDRO, showing no measures (left) and all potential measures (right)

The total flooding volumes between the CRCTool and D-HYDRO differ a lot (Figure 4-26). An event with T=100 in the CRCTool has the same flooding volume as an event with T=2 in D-HYDRO and the T=100 flooding volume is double the amount. Furthermore, the water leaving the study area by the pump is lower compared to the CRCTool. For T=100 the average pump capacity during the event is 0.5 m^3/s. In the CRCTool the pump works at full capacity during the full event (2.5 m^3/s). Furthermore, Table 4-7 shows that the implementation of NBS decrease the efficiency of the pumps even more.

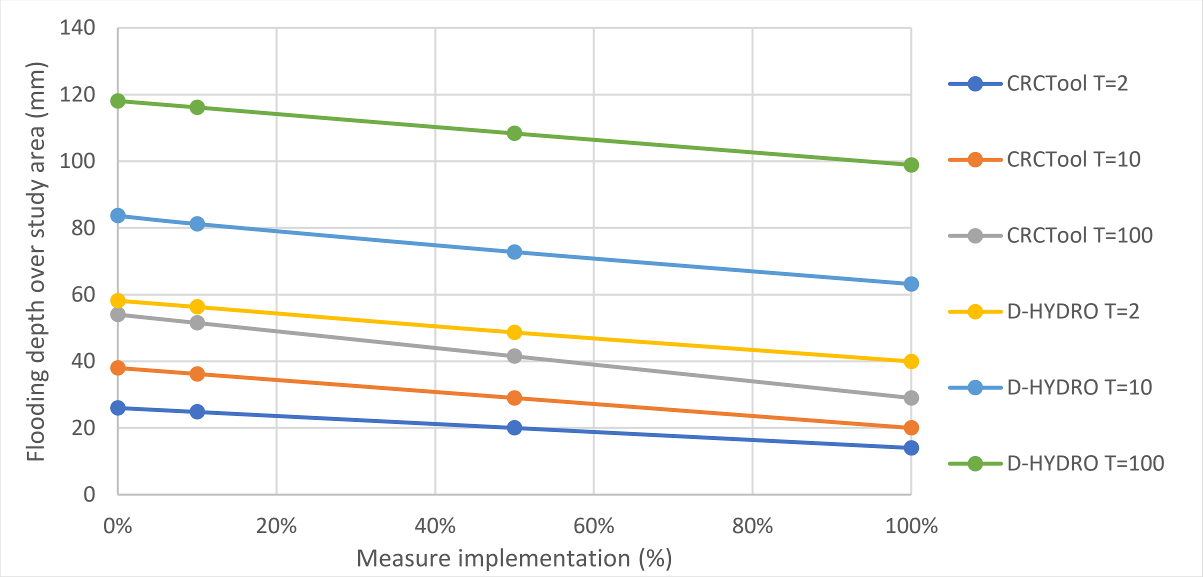


Figure 4-26 Flooding depth for different percentages of measure implementation related to the total potential area

Measure effectiveness is determined as the percentage of reduction in flooding volume compared to the total storage volume of the measure (as shown in the Table 4-6). In the CRCTool, the effectiveness of the measure increases for larger events, which corresponds with the observed increase in runoff reduction factor at higher runoff depths. In D-HYDRO, the effectiveness is relatively consistent across the different events, with slightly higher effectiveness observed for a T=10 event. The study found that the measures are filled to 79%, 92%, and 94% of their total storage volume for T=2, T=10, and T=100 events, respectively. So, for T=2 events, the storage is only partially filled and for T=100 events overflow happens which both results in reduced effectiveness.

The reduction of flooding depth at the two problem areas for different events is displayed in Figure 4-27. The impact of the measures at the Verlengde Keizerstraat is significant, particularly for a T=2 event. However, for a T=10 event, the impact of the measures diminishes significantly over time, indicating that they are becoming full. In contrast, the measures implemented at Jodenbreestraat have a very limited effect, and there is no significant difference observed between different types of events.

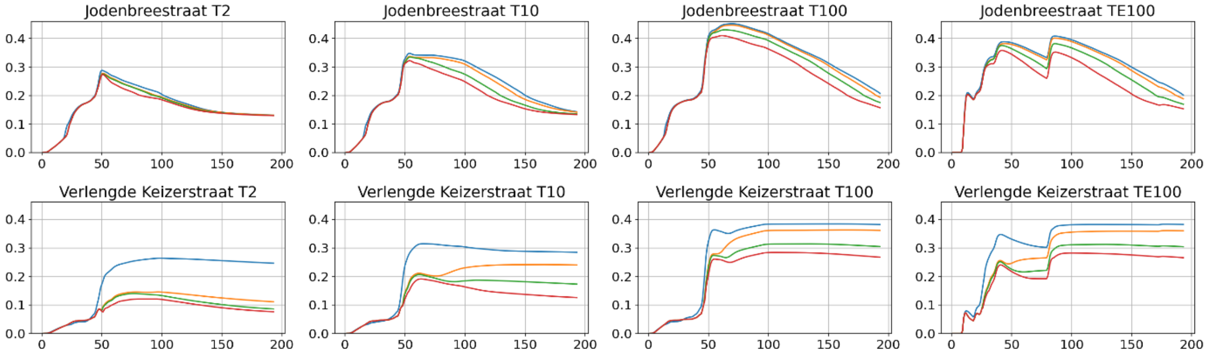


Figure 4-27 Flooding depth at problem areas during different events (T=2, T=10, T=100 and actual event (T=100))

Table 4-8 Reduction in flooding volumes in percentages for the Jodenbreestraat (JBS) and Verlengde Keizerstraat (VKS)

	Design event T=2		**Design event T=10**		**Design event T=100**		**Event T=100**	
	JBS	*VKS*	*JBS*	*VKS*	*JBS*	*VKS*	*JBS*	*VKS*
Local	3%	42%	3%	34%	1%	5%	1%	5%
Realistic	3%	46%	3%	36%	4%	17%	5%	17%
Maximum	5%	50%	7%	41%	9%	26%	14%	26%

Significant differences in the flood reduction percentages between the CRCTool and D-HYDRO have been observed, with the local conditions such as DEM and sewer system having a significant impact. These differences are evident in the two problem areas, Jodenbreestraat and Verlengde Keizerstraat, highlighting the area-specific nature of the flooding problems. It is clear that the causes of flooding in these areas are distinct and unique, requiring tailored solutions to address the specific limitations posed by each location.

Table 4-9 Flood reduction percentages for CRCTool and D-HYDRO (total area, Jodenbreestraat, Verlengde Keizerstraat)

	Design event T=2			**Design event T=10**			**Design event T=100**		
	local	*real*	*max*	*local*	*real*	*max*	*local*	*real*	*max*
D-HYDRO Jodenbr.	3%	3%	5%	3%	3%	7%	1%	4%	9%
D-HYDRO Verl. Keiz.	42%	46%	50%	34%	36%	41%	5%	17%	26%
D-HYDRO Binnenst.	3%	16%	31%	3%	13%	24%	2%	8%	16%
CRCTool Binnenst.	5%	23%	46%	5%	23%	46%	5%	23%	46%

4.5.2 Additional insights of hydrodynamic modelling

The use of D-HYDRO modelling allows for a more comprehensive analysis of results. In this subsection, we present two additional analyses. The first analysis investigates the effects of restoring the drainage system and how it relates to NBS in reducing flooding volumes. The second analysis examines the changes in the main flow behaviour of the drainage system caused by NBS. Specifically, the flows in the Viotte and Picorni Kreek channels are analysed.

Restoring the drainage system has a very different effect compared to the NBS (Figure 4-25). This approach significantly mitigates the flooding problems downstream at the Jodenbreestraat, but only slightly reduces the flooding problems upstream at the Verlengde Keizerstraat (Figure 4-28).

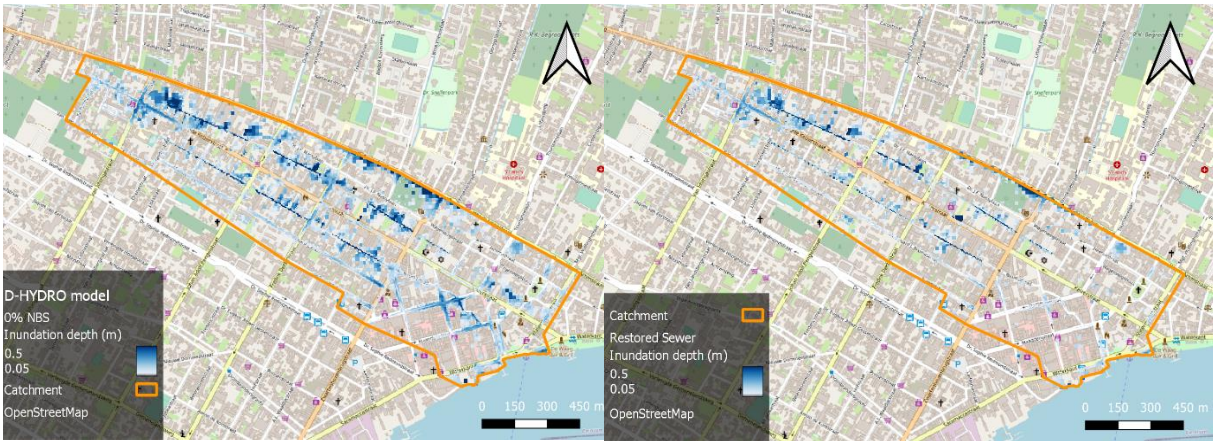


Figure 4-28 Flood inundation map showing the effect of a restored drainage system

The Viotte and Picorni Kreek are the main channels responsible for draining the upstream area. They both go underground at a location indicated on the map, where the water level has been modelled in D-HYDRO. The results show a significant effect of NBS on the Picorni Kreek, with a noticeable lowering of the peak discharge for a T=2 event and a shorter peak duration for a T=10 event. However, for larger events like T=100, the impact becomes less visible, indicating the reduced effectiveness of NBS for such events. On the other hand, there is almost no effect of NBS on the Viotte Kreek. This suggests that the discharge capacity of the Viotte Kreek is already at its maximum capacity, which could be very limited, and could explain the upstream flooding problems, which are related to limited discharge capacity. Although NBS can reduce flooding locally by temporarily storing flooding water in upstream areas, downstream areas will not benefit from these measures since the discharge is already limited.

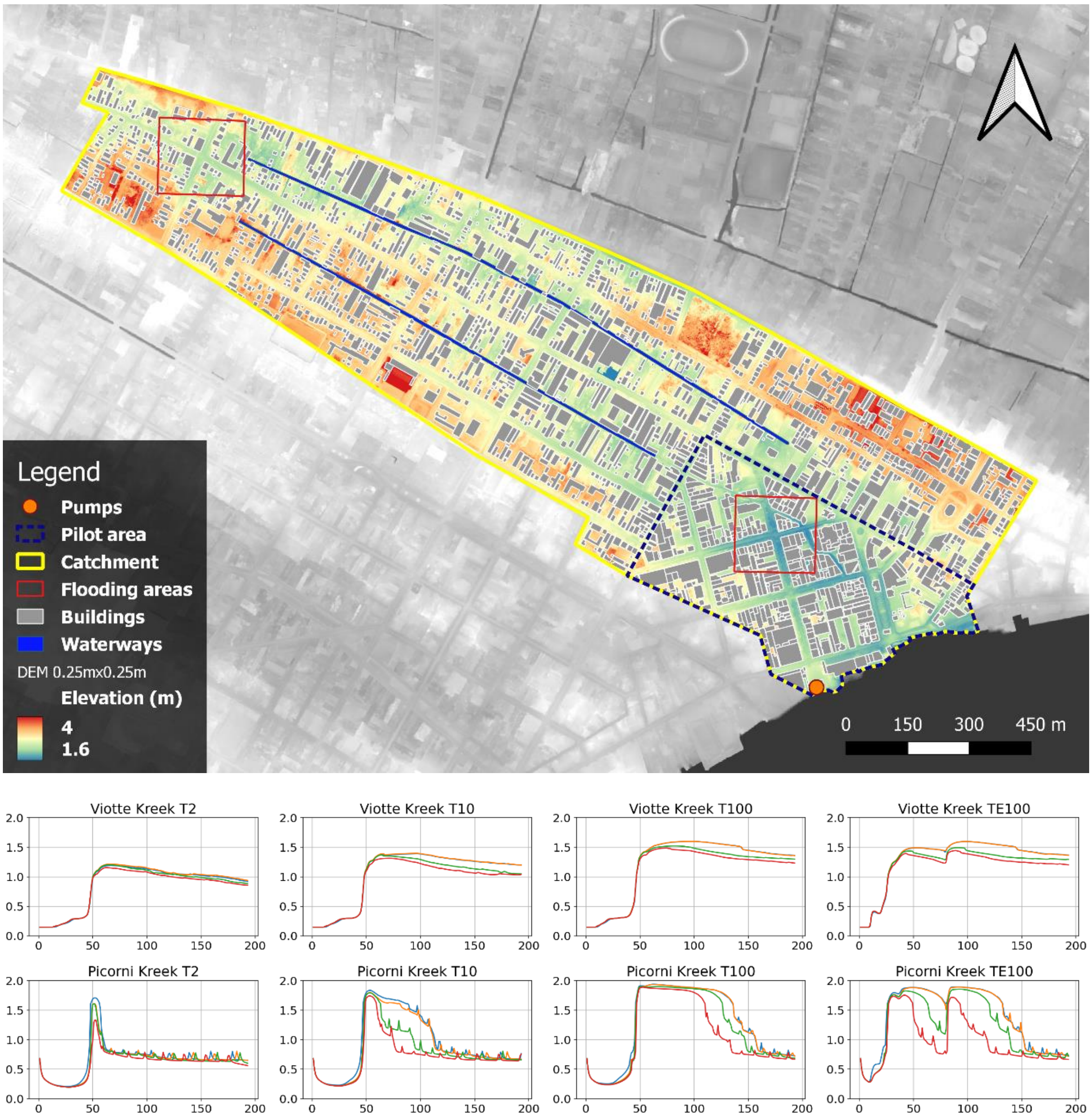


Figure 4-29 Map displaying the location of the two main discharge channels and graphs of their corresponding water height for different design events (T=2, T=10 & T=100) and a real event (T=100)

4.6 PERFORMANCE OF CRCTOOL IN DESIGN WORKSHOP

An important part of determining the applicability of the CRCTool is to experience how stakeholders interact with the tool itself. This gives a general view about the activation of stakeholders and what kind of discussions it starts. It will also provide useful feedback for possible improvements in the tool. Subsection 4.6.1 describes the experiences of using the tool in the workshop sessions. Subsection 4.6.2 dives into the feedback given by the stakeholders after the workshop sessions and proposes ways to implement these in the tool.

4.6.1 Experiences of using the tool in stakeholder sessions in Suriname

The stakeholders who participated in the workshops, a list is given in Appendix A13, had a positive experience and were enthusiastic about implementing solutions using the CRCTool. They demonstrated a strong interest in finding solutions and showed a positive attitude towards the use of NBS as an important tool for stormwater management in the project. They recognized the potential value that NBS could bring to Paramaribo and believed that it was necessary to implement them.

It was discovered that providing users with a design case based on a straightforward assignment of achieving a specific storage volume through a combination of SDF curves and storage capacities of measures was effective. This approach does not rely on complex calculations of runoff reduction factors and instead relies on simple calculations with less room for error. This approach is less affected by the discussed limitations in the previous sections.

The concept of using NBS for stormwater management in urban areas was new for most stakeholders who were more familiar with implementing and maintaining grey measures. However, the CRCTool provided a simple approach for them to understand the value of NBS, and because of their experience with grey measures, they had a good sense of how to use the tool as a design tool and valued their role in the process. As a result, the tool proved to be a suitable solution for stakeholders.

The stakeholders found the CRCTool easy to understand. There was a clear difference in understanding compared to an earlier workshop about hydrodynamic modelling with D-HYDRO. In the previous workshop, the stakeholders lacked knowledge about hydrodynamic modelling, which made the interaction limited. In contrast, the workshop with the CRCTool was easier to comprehend, leading to more interaction with the stakeholders.

The stakeholders successfully used the CRCTool as intended, demonstrating no difficulty in defining the study area and drawing measures to address the given problem. They actively and enthusiastically sought solutions to the problem. However, there were differences in the way that measures were drawn, with some groups creating individual measures, while others drew larger areas where measures would be implemented. For instance, some groups assigned a city block to have 50% green roofs.

Summarizing, the tool serves as a crucial initial step towards designing and executing NBS for stormwater management. It raises awareness and emphasizes the importance of incorporating NBS into the agenda. The tool effectively engages stakeholders in considering NBS when developing stormwater management strategies, as indicated by their ease of use, positive attitude towards NBS, and interest in the measures themselves.

4.6.2 Feedback from stakeholder sessions

The feedback received during and after the session was mainly focused on adding and extending features to the CRCTool. First of all, there was a high demand for an offline version of the tool due to the weak internet connection experienced during the workshop. This issue prevented the tool from functioning on most laptops, limiting the workshop to only two devices. Stakeholders assured the internet connection at other places in Suriname could be even worse or totally absent. For a tool that shows a lot of potential for developing countries an option for an offline version could be a valuable improvement.

Stakeholders also expressed great interest in using the CRCTool for other areas in Paramaribo and Suriname. To make this possible, one option is to predefine different neighborhoods that represent most of Paramaribo, including urban, sub-urban, and rural areas. Alternatively, area characteristics can be determined afterwards, as the current version of the tool requires defining the "neighborhood" beforehand and using it in the calculations. The tool's calculations are based on the urban water balance, which estimates measure effectiveness over a single land use area and then scales up to the whole project area using assumptions about runoff from paved and unpaved surfaces. By applying the same assumptions and defining the land use area sizes after the calculations, the tool can be adapted for different areas with comparable soil and crop properties. The stakeholders' interest in expanding the tool's application highlights its potential for supporting NBS design and implementation in developing countries.

Stakeholders wanted to be able to implement measures differently. Currently each measure must be drawn exactly the size of the measure. Some groups wanted to indicate that a whole street block would implement, for example, green roofs by drawing in the entire block and assigning 50% of the area as the measure. This approach would enable the designation of zones for measure application, which would keep the project clearer and avoid the need to draw in each individual roof separately.

Summarizing, there are several improvements that could be made to enhance the CRCTool's usability. The most pressing need expressed by stakeholders was for an offline version of the tool, as internet connectivity is often unreliable in developing countries. Additionally, allowing users to input land use percentages would increase the tool's applicability to other neighborhoods. Lastly, it was suggested that the tool should allow measures to be drawn as areas to apply measures in, with the option to assign a percentage of the area as the measure. This would simplify the drawing process and improve project clarity.

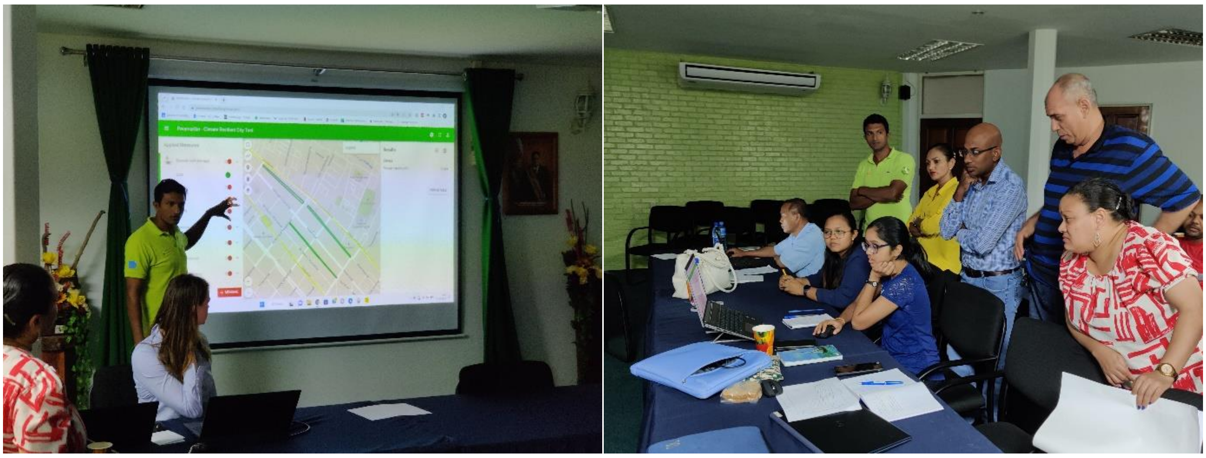


Figure 4-30 Photos during the CRCTool workshop at the Ministry of Public Works in Paramaribo

5 DISCUSSION

This chapter discusses the results to substantiate the answer to the main research question in the conclusions and recommendations (Chapter 6). The first section (5.1) discusses the interpretation of the findings, which involves answering the research sub-questions, contextualizing the results with current research, and discussing unexpected outcomes. The second section (5.2) examines the implications of the results for conceptual modelling of NBS and highlights the new insights gained. In the final section (5.3), the study's conclusions are discussed in relation to limitations associated with input data for the CRCTool and D-HYDRO, as well as general uncertainties related to NBS.

5.1 INTERPRETATIONS OF THE RESULTS

The applicability of the CRCTool depends on various variables. This is ordered by the sub-questions of this research (section 1.4). This relates to underlying assumptions in the tool (subsection 5.1.1), how the tool reacts to variations in certain parameters (subsection 5.1.2), if outputs comply with hydrological principles (subsection 5.1.3), how the results compare to a hydrodynamic model D-HYDRO (subsection 5.1.4) and how it performs in stakeholder analysis (subsection 5.1.5). The findings are contextualized in subsection 5.1.6 . Finally, unexpected findings are addressed subsection 5.1.7.

5.1.1 Substantiation of model assumptions

The main assumptions in the tool concern the application of an average runoff reduction factor, neglecting the controlled runoff in runoff reduction calculations and the determination of a baseline discharge for event separation. The impact the findings have on testing these assumptions is discussed in the following paragraphs.

First, it appears that the general assumption of applying an average runoff reduction factor is not valid for this study, because the observed shift is not linear especially for higher runoff depths. In Paramaribo, where higher runoff depths occur quite frequently due to the tropical climate, this assumption does not hold. Further analysis showed that the assumption holds for measures that are not limited by anything other than their measure depth and have a limited drainage capacity. This implies that only very basic storage measures can be correctly implemented.

Despite the abovementioned limitations, it should be noted that for low effective depths and runoff depths, an average reduction factor is found for more complex measures as well since the limiting factor in this case will only be related to the storage capacity. This implies that for areas with low rainfall rates, the relationship still holds. However, for this case study, the rainfall rates, and thus the runoff depths and measure depths, are generally too high for the relationship to hold. A workaround is to use a single runoff reduction factor as performance indicator, representing a specific return period. Measures are typically designed for a specific return period, so a tool could be incorporated to determine the runoff reduction factor for a standardized or user-defined return period.

Another important finding is that the CRCTool is applicable for measures where the controlled runoff is relatively small and preferably related to infiltration, because the controlled runoff is ignored from the runoff calculation. This cannot be ignored for measures where natural infiltration is limited or for measures that must manage large amounts of runoff. In this case measures must be connected to the sewer system by underdrains or overflow weirs, and it has been observed in the findings that the runoff from these structures can contribute significantly to the peak runoff and thus cannot be neglected. The classification of controlled runoff can be refined by defining not only the start of the rainfall event, but also the end. This refinement would allow all the runoff from a measure after the event to be categorized as controlled runoff and all the runoff during an event as uncontrolled runoff.

The final assumption concerns event separation, which is based on a baseline drainage capacity that is currently set as the average daily rainfall. However, the study discovered that a value of approximately four times the daily rainfall provides the best ratio between event separation and the number of events for Suriname. This ratio was also observed for Dutch cases, according to Vergroesen and Brolsma (2020), but not yet implemented into the model. Higher baseline discharges also separate events correctly, however they neglect the smaller events. How this effects the statistical analysis has not been investigated. It is thus recommended to adjust the 'baseline discharge' value to four times the average daily rainfall in the model. This adjustment will help to ensure more accurate calculations.

5.1.2 Effect of model input parameters

The model parameters that were displayed in the sensitivity analysis where the ones that had the largest effect on the runoff reduction factor. These parameters are the infiltration and storage capacities of different layers and the inflow factor which are discussed below.

Infiltration and storage capacity

The sensitivity analysis of the infiltration and storage capacities of different layers yielded results that aligned with the expectations. However, some minor artifacts were observed, such as the maximum runoff reduction factor being exceeded for measure runoff capacities and effective depths, and a higher effectiveness observed for lower effective depths in cases of low storage and infiltration capacity of the interception layer. These artifacts are assumed to be modelling errors, but further investigation is required to confirm this claim. Furthermore, an issue arose that the infiltration rate was limited by the storage capacities of the interception and top storage layer occurring for very low capacities. This posed a problem for measures that have small infiltration and storage layers like Green.

The results from the sensitivity analysis provided insight into finding optimal parameters for designing NBS relating to the infiltration and storage capacities with the CRCTool. This could be implemented in the tool directly, as one of its strengths is its ability to quickly model long timeseries. This will provide users with recommendations on how to best apply NBS in their study area, increasing the value for the design phase of NBS. The sensitivity analysis can be performed by simply assigning low, average, and high values to the parameters or including a range of parameters.

Furthermore, it is found that the inflow factor has a significant impact on the effectiveness of the measures. The tool provides an option to adjust the inflow factor in the web interface, but it assumes that the effective depth is only dependent on the depth of the bottom storage of the measure. However, higher inflow factors increase the likelihood that other factors, such as infiltration rates, become limited. Therefore, this assumption restricts the correct implementation of measures that have limited infiltration rates.

Inflow factor

The implementation of the inflow factor only increases the depth of the bottom storage layer to maintain an equal effective depth compared to measures with a lower inflow factor (subsection 4.3.2). However, the storage depth of the infiltration and top storage layer does not scale with this adjustment, which means that the actual storage capacity of a measure with a lower inflow factor is higher. As a result, the measure with a lower inflow factor is more effective for the same effective depth.

Furthermore, it is found is that some input parameters are not correctly scaled with the inflow factor. For example, the bottom discharge capacity is taken over the measure inflow area and not the measure area. So, for a different inflow factor but the same discharge capacity the measure’s actual drainage capacity is larger.

To better quantify the runoff reduction factors, it is important to relate the effective depth to both the infiltration capacity and inflow factor. Currently, the measure's storage depth is used as the effective depth. However, if this storage depth does not fill completely due to limited infiltration capacity, it may result in an inaccurate determination of the runoff reduction factor, particularly with higher inflow factors where the infiltration capacity is reached more quickly.

Furthermore, it is recommended to use an inflow factor of 1 during initial calculations. The general equation (2) can be used for higher inflow factors. Currently, implementing an inflow factor of 1 is cumbersome because the measure is applied to the entire land use area, which results in an infinite effectiveness for the area, making it impossible to scale up or down. To resolve this issue, it is suggested that the measure inflow area will be defined as a part of the land use area. If an inflow factor is used, the storage depth of the infiltration and top storage layer should also be considered.

5.1.3 Critical assessment of model outputs

To critically assess the hydrological fluxes resulting from the model output, this study examines the division of rainfall into evaporation, percolation, and runoff, as well as the division of runoff into controlled and uncontrolled runoff, and the behaviour of groundwater flow. The results illustrate these flows for different time periods, including yearly, weekly, and daily periods.

Rainfall division

The results show that the added value of continuous modelling, which accounts for long-term effects of percolation, groundwater flow, and evapotranspiration, is minimal. This is because the effects of percolation and evapotranspiration have little impact once the rainfall events have ended since the pumps restore the water level quickly. This does not reflect the actual conditions where not all the water can reach the pump directly or at all. In such cases, percolation and evapotranspiration can have a more significant effect.

All the water in the current model is directly transported to the open water storage, which means that even when the drainage capacity of the pumps is low, there will still be no effect on the percolation and evapotranspiration of the measure, because the flow to the open water is not limited. As a result, the effects of evapotranspiration and percolation are limited due to the instant flow to the open water, which neglects the potential benefits of NBS in slowly evaporating or percolating water when storing it for a longer period of time.

To better account for the effects of percolation and evapotranspiration, it is recommended that water is not allowed to drain from the measure if the open water is full. By simulating standing water in the measure during and after a heavy rainfall event, the model can accurately capture the contribution of evapotranspiration and percolation to the overall water balance.

Runoff division

Runoff division in surface, overflow and bottom storage is currently not correctly divided. Runoff that occurs due to overflow is assigned to surface runoff and thus all uncontrolled runoff is currently surface runoff. Division of these runoff components could give valuable insights in limiting factors and helps with defining correct effective depths.

Defining discharge from the measure based on drainage time instead of drainage rates gives unrealistic drainage behaviour. The results indicate that level drainage (discussed in subsection 4.4.1) results in lower drainage capacity when the storage is not fully filled, rendering them less effective for smaller events. Furthermore, the drainage rate slows down significantly after the event, as the storage starts to empty, resulting in a longer time to completely drain the measure.

It is worth noting that natural variations in drainage may occur, however this effect is not represented by the model. The drainage capacity of a measure is influenced by factors such as the native soil or the capacity of an underdrain and can be reduced due to soil saturation during an event. This would lead to a temporary reduction in drainage capacity during the event, followed by a gradual increase as the soil dries. Level drainage, on the other hand, behaves in the opposite way. This behaviour thus contradicts with expected hydrological behaviour.

It is important to accurately differentiate between surface runoff and overflow to gain valuable insights into the limiting factors of NBS. Overflow would mean the storage capacity is the limiting factor in the design and surface runoff would be related to the infiltration capacity. This will enable more precise evaluations of the performance of different measures under varying conditions.

Groundwater flow
The effect of groundwater modelling, which provides interaction with a shallow and deep groundwater reservoir, can potentially limit groundwater drainage in wet periods. Furthermore, groundwater level has a limiting effect during large events when it reaches the surface. However, it only limits the percolation from the measure to the groundwater, which depends on the soil type. This factor is separated from the controlled runoff. So even when controlled runoff is assigned to groundwater it does not get limited and this explains that there is no observable effect on the runoff reduction factor. Furthermore, it could be argued that the limitation of the groundwater level needs to be set to a level equal to the bottom of the measure from which outflow from the measure gets restricted. If the groundwater level reaches the surface the inflow to a measure should also get limited.

Many of the differences in effectiveness between the measures are related to findings discussed above. As it stands, the model is only able to accurately represent measures that have a constant inflow factor, unlimited infiltration capacity and variable discharge capacity. This includes simple storage measures like rain barrels.

The controlled runoff assigned to groundwater should also be limited by the groundwater level. Other factors that may limit the flow to the sewer system or open water should also be considered to provide a comprehensive assessment of the effectiveness of the measures. By incorporating this in the model, the tool will be able to better capture the complexities of urban water management.

5.1.4 Comparison to D-HYDRO

The importance is of hydrodynamic modelling became clear in the comparison with the D-HYDRO model. The results showed that the actual flooding volumes were significantly higher compared to the CRCTool. This can be related to the fact that less water gets pumped out of the system. This highlights the importance of flow routing and maintenance of the system. The fact that the CRCTool models water flows instantly causes significant underestimation of the flooding volume. Furthermore, the effectiveness of the measures differed largely between the two problem areas, which can also be related to flow routing and local elevation. This provided valuable insights, indicating that each problem area needs different solutions.

The comparison also showed a different relation in measure effectiveness for different rainfall return periods. For the CRCTool the measure effectiveness increased with an increase in rainfall return period. For D-HYDRO the effectiveness increased until T=10 and decreased for higher return periods. This can be related to the fact that for low return periods the storage of the measures is only partially filled and for large storm events measure overflow and reduced pump capacity occurs which both results in reduced effectiveness. This suggests that the applied measure configuration is optimally designed for a T=10 event in terms of volume, which overall presents a more realistic outcome compared to the results from the CRCTool.

Lastly, the effect of flow routing and natural elevation was evident in the significant differences between measure effectiveness between the two problem areas and the effectiveness of restoring the sewer system. In the upstream region, the natural gradient is minimal, and even if the canal is restored, it would still have a limited discharge capacity. Consequently, restoring the drainage system would have a limited impact.

NBS on the other hand are more abundant upstream due to more available potential area and can be placed closer to the problem area. Furthermore, the results from section 4.5.2 indicate the drainage capacity from upstream to downstream is limited and that measures are not able to lower the drainage rate, thus only mitigating the upstream flooding effects. This means they have a minimal effect on the flooding downstream. This is a possible explanation for the large differences between the measure effectiveness between the two problem areas.

To demonstrate the significant differences in the flooding problems for the two problem areas hydrodynamic modelling plays a crucial role, which is primarily due to flow routing and elevation. The model is able to illustrate how different measures, such as NBS and restoring the drainage system, can have a varied impact on these areas. These findings highlight the need for customized solutions for each of the problem areas which cannot be shown by the CRCTool.

In summary, the D-HYDRO modelling results indicate that flow routing and elevation have a significant impact on the study area, making it unsuitable for the lumped approach used in the CRCTool. This could be overcome by dividing the study area into smaller neighbourhoods with more clearly defined flow directions. The outflow of upstream neighbourhoods can be given as inflow to the downstream neighbourhoods. This will allow for a more accurate representation of the hydrological processes occurring in the study area.

5.1.5 Stakeholder engagement

The interactive sessions with the stakeholders showed the strength of the CRCtool. It activated and enthused stakeholders about the potential of NBS, started dialog and created awareness. Especially in countries where there are no financial resources for expensive hydrodynamic models the CRCTool can be a cheap and easy alternative.

Focussing on developing countries it is important that an offline version of the tool becomes available due to the often-limiting internet connection. Furthermore, giving the users freedom to determine land use percentages makes the tool applicable for a larger variety of study areas instead of a single precalculated neighbourhood. This process could also be automated by building in a tool for Maximum Likelihood Classification (Vojinovic et al., 2021). This would automatically classify the land use areas in the drawn area based on satellite imagery.

5.1.6 Contextualization of research findings

This subsection discusses how the findings fit into earlier studies into the effectiveness and implementation of NBS. Studies into the effectiveness mostly used hydrological and hydrodynamic models and implementation-based studies try to develop frameworks or highlights the main challenges posed by current NBS practices. Furthermore, earlier studies have been done with the CRCTool.

Determining the effectiveness of NBS

No additional findings were discovered regarding the effectiveness of NBS compared to earlier studies, even though the CRCTool includes a more detailed parameterization of NBS parameters, continuous modelling, and a groundwater component. The study shows that the current implementation of NBS in the CRCTool provides only basic information about effectiveness and does not significantly improve the quality of current modelling techniques. Additionally, the D-HYDRO model gave overall the same results as previous studies that used hydrodynamic models, which show effectiveness of NBS for events with low return periods, with a decrease in this effectiveness for higher return periods (Eckart et al., 2017; Kong et al., 2017).

The main findings of this study centre on improving the CRCTool to make it more widely applicable and potentially provide new insights into determining the effectiveness of NBS. Further improvements to the tool could enable more nuanced analysis of the impacts of NBS and help decision-makers select the most effective strategies for their specific circumstances.

Quantification of a conceptual design tool

Even though the findings do not provide additional insight in the determination of the effectiveness of NBS, they do add to the gap in quantification of conceptual design tools like NBS. Van de Ven et al. (2016) states that conceptual designs are so far made without quantified information on performance of proposed adaptation measures. Earlier research with the CRCTool were mainly in experiences and lessons learned while applying the tool. Additionally, there are not many tools available like the CRCTool. McEvoy et al. (2018) highlights two other planning support tools, however these tools do not provide online based visualisation of measures or any interactive information about the effectiveness.

Earlier research with the CRCTool itself used the tool mainly for conceptual designs and program formulations. The tool has been used in other studies, but without critically evaluating the outputs. So, the studies with the CRCTool did not evaluate the quality of the outputs (Chen et al., 2021; McEvoy et al., 2020). Only the case in Laakhaven, which is used in the documentation of the CRCTool (Vergroesen & Brolsma, 2020), is further examined to substantiate certain model claims. Furthermore, the tool is mainly applied in the Netherlands, with only a few cases internationally (van de Ven et al., 2016)**.**

This research thus provides valuable insights in the accuracy of the CRCTool results by quantifying information on performance of proposed adaptation measures and critically evaluating behaviour of hydrological principles in the model. Furthermore, this research takes into account the value of the urban planning and design practice and tested the added value of this by a design workshop.

5.1.7 Unexpected results

Some unexpected outputs resulted from the CRCTool modelling. One concerns the artefacts observed in the relationship between infiltration and storage capacities, while the other concerns the low runoff reduction factors observed for small runoff events.

The relationship between infiltration and storage capacities of the interception and top storage layer and the runoff reduction factor exhibits artifacts. Specifically, a decrease in the runoff reduction was observed for low effective depths after a point where the runoff reduction factor for all effective depths was equal. However, the reason for this phenomenon is not yet fully understood.

Furthermore, it was initially anticipated that small events would result in high runoff reduction factors, as these events could potentially be completely mitigated. However, it was discovered that the runoff reduction factor is dependent on a particular volume of runoff and the corresponding return period of that runoff. Consequently, the runoff reductions achieved by very small events are not considered in the calculation of the runoff reduction factor.

5.2 RESEARCH IMPLICATIONS

This research shows the implementation and limitations of a conceptual design tool for determining the effectiveness of NBS in a different environment compared to the Netherlands. It reveals its limitations and gives recommendations on how to improve them. The results provides users of the tool insight in how to rate the quality of the performance indicators and give developers options to improve on them. It is also the first research that shows insights of a direct comparison of the outputs of a conceptual tool against a hydrodynamic model, which highlights the main differences between both modelling approaches.

Subsection 5.2.1 discusses the implications for conceptual modelling related to existing literature and subsection 0 describes the new insights provided by this research.

5.2.1 Implications of conceptual modelling of NBS

The findings contradict the idea that a simplified conceptual approach is sufficient for assessing the function of NBS in stormwater reduction (Liu et al., 2014). Furthermore, the current configuration of the CRCTool is not able to show if the oversimplification in the hydrodynamic models is cumbersome as stated by Eckart et al. (2017). The results did not show a significant impact of processes related to groundwater flow, infiltration, and evapotranspiration. This is related to how these processes are modelled in the CRCTool. Instantaneous outflow from the measures makes that evapotranspiration and percolation stay limited. Besides, high groundwater levels can only limit the natural percolation of the measure and not the assigned controlled runoff. Further research in which adjustments are made to the CRCTool must show the impact of these long-term processes and if a simplified conceptual approach can indeed be sufficient.

This research also found that the instant calculation times of the CRCTool are a little misleading. Model run times are often referred to as a disadvantage of hydrodynamic modelling (Van Dijk et al., 2014; Löwe et al., 2017; Ebrahimian et al., 2021; Teng et al., 2017). However, the run times of the CRCTool requires the setup and multiple runs of the UrbanWB. The setup needs to be done manually and requires substantia effort. The model runs require time series of at least 30 years to have reliable statistical analysis. This has a run time of around 1 hour per measure. Compared to D-HYDRO, where the run time took 1 hour and 20 minutes for a single measure and 4 different return periods. The run times of the different models thus are not very different. Nonetheless, the set-up of a hydrodynamic model, like D-HYDRO model, still requires more time and expertise.

Previous research into the added value of the CRCTool is mainly focussed on the urban planning and the design practice. The importance of this is addressed in Raymond et al. (2017), which describes all the stages of implementation of NBS. It highlights the knowledge transfer partnership between key stakeholders as one of the main challenges for the design stage of NBS. Furthermore, Eckart et al. (2018) says that NBS will require a multidisciplinary approach and successful coordination between different stakeholders. Scientific problems may not be the main problem. Thorne et al. (2018) claim reducing the scientific uncertainties is not sufficient to trigger the public support and political backing needed to sustain actions that must be coordinated across multiple agencies, implemented over a wide area, or sustained for a long period. The importance of this multidisciplinary approach is also addressed in Liu & Jensen (2018).

5.2.2 New insights

This research provides insights into the strengths and the limitations of the CRCTool. This can be valuable for urban planning and design practitioners using the tool. In its current form, the tool works best in conjunction with hydrodynamic models. The CRCTool is able provide estimates about where and how much storage needs to be realized in a small study area. Hydrodynamic modelling is still necessary for connecting these smaller areas and implementing the required storage spatially to evaluate its effectiveness.

The current abilities to provide details in runoff reduction factors in the CRCTool for tropical conditions are limited. It is advised to only take these factors into account for simple storage measures without an infiltration layer and an underdrain, like retention ponds and rain barrels. For simple storage measures an interesting design case can be made by using the provided storage volume combined with the SDF curves.

It is important to consider not only the size of the study area but also its hydrological conditions before determining the applicability of the CRCTool. While the tool recommends its use for areas ranging from 10 to 500 hectares with a maximum size of 1000 hectares, during the study, it was found that certain processes related to elevation differences and flow routing had a substantial impact on flooding issues in the study area, which had as size of 130 hectares. Therefore, the recommended area size is not solely dependent on area size, but also on hydrological conditions. As such, it is crucial to carefully consider these conditions when evaluating the suitability of an area for the CRCTool, which may result in using lower area sizes than those recommended by the tool.

The tool mainly fills the current gap of implementing adaptation measures in the actual urban planning and design practice. It will help to bring NBS more on the map and can be a valuable tool to show stakeholders the importance of this. For this function the accuracy of the results is of less importance. The availability of a more or less reliable performance estimation is a valuable contribution to informed decisions on the selection and design of adaptation measures.

5.3 RESEARCH LIMITATIONS

This section discusses what can be concluded from this study concerning the limitations (subsection **Error! Reference source not found.**). Subsection 5.3.2 and 5.3.3 dive deeper into the limitation concerning data availability for modelling in the CRCTool and D-HYDRO. Subsection 5.3.4 describes the uncertainties related to NBS. The last section touches upon other challenges related to the implementation of NBS.

5.3.1 Insights from this study with respect to the limitations

This study focuses on assessing the effectiveness of NBS for flood mitigation in a specific area of Paramaribo, Suriname. This gives a general idea of the applicability of the tool in a developed country with a tropical climate. This tells something about the general transferability from the Netherlands to other countries and places. It highlights general limitations that came to light during this change, which were mostly related to more extreme rainfall conditions. However, it is important to note that the specific characteristics of the study area and the NBS implementation context may affect the applicability of the results to other areas or situations.

The evaluation is restricted to the effectiveness of NBS in reducing flood risk, without considering other co-benefits that NBS may provide, such as groundwater recharge, heat stress reduction, or water quality improvement. Furthermore, the analysis is limited to the conceptual design phase, aimed at identifying the general performance of different NBS options. Thus, factors related to maintenance, long-term effects, and measure-specific design considerations are not considered.

In summary, the study sheds light on the limitations that arise due to different conditions compared to the Netherlands and provides recommendations for overcoming these constraints. However, as the applicability of the CRCTool has only been tested on a single case, no general conclusions can be drawn. Further testing will be required to determine the broader applicability of the tool.

5.3.2 Limitations in input data CRCTool

Insufficient data and uncertainty surrounding NBS were the most significant limitations in this research. The CRCTool was constrained by the absence of long hourly rainfall time series and reliable groundwater data, while D-HYDRO was impacted by the lack of suitable calibration data.

One of the key strengths of the CRCTool is its ability to perform extreme value analysis over the runoff, accounting for potential differences between rainfall events with the same return period. However, in this study, due to a lack of data, all the rainfall events were assumed to have the same hyetograph, which could have nullified this effect. While analyzing six years of hourly rainfall data did not reveal any impact, it is possible that longer time series with more extreme events could yield different results. Therefore, further research is necessary to determine if this approach to analysis produces different outcomes compared to conducting extreme value analysis on individual rainfall events.

The second limitation is related to the absence of groundwater data. The study assumes a normative groundwater level of 1 meter. However, variations in this parameter could potentially have a significant impact on the effectiveness of the measures. Nonetheless, the current implementation of the groundwater limitation in the study suggests that it would not have a significant effect on the effectiveness of the measures. Further research is necessary to better understand the role of groundwater in the context of NBS and its impact on flood mitigation.

In summary, the limitations in the modelling effect on the accurateness of the model results. This research focusses on the applicability of the CRCTool, which focusses on modelling principles, assumptions, and processes. Only the limitations in the available rainfall data prevent drawing any conclusions regarding the effectiveness of performing extreme value analysis over the runoff instead of the rainfall.

5.3.3 Limitations in input data D-HYDRO

The following paragraphs discuss the data scarcity related to the D-HYDRO model. This includes the validation of the model, the rainfall input, the initial conditions, the sewer system characteristics, and the data from inundation events.

The model validation in this study is limited to only two rainfall events and the adjustments made were restricted to the roughness of the pipes and channels. To improve the validation process, the model should be tested on a larger number of cases and an assessment of the sewer system could provide valuable insights. Nonetheless, for the purpose of this study, the model's accuracy is not of highest importance as the focus is on the variations observed due to the different modelling techniques.

Secondly, there is uncertainty in the rainfall input, as it is assumed that rainfall is evenly distributed across the study area. However, local rainfall events can result in lower amounts of rainfall falling on the study area. Moreover, the rainfall event used in the study comes from a station which is located 15 km away from the study area and may not accurately represent the actual rainfall in the study area at that exact time. This can lead to errors in the validation process. Therefore, it is essential to check and compare the rainfall data from other nearby stations for validation purposes, which will provide a better estimation of the event's locality and suitability for validation. Additionally, the rainfall measurements themselves may have errors, which can also be identified by comparing the data from nearby rainfall stations.

Thirdly, the initial conditions of the model affected the modelling results. The calculation of the total storage volume is based on the initial conditions, which include the one-dimensional and two-dimensional water level at the elevation of the Jodenbreestraat (1.6m). This means that the calculation includes natural interception and the 1D sewer storage in elevated areas, which are not actual flooding volumes. Therefore, the actual flooding volume is likely smaller than the calculated value.

Fourthly, it is worth considering that area-specific exceptions may have a significant impact on the flooding depths. For example, a fully clogged pipe in one of the problem areas may have a considerable influence on the flooding depth. Therefore, two problem areas were selected to identify such potential area-specific deviations. If these deviations are found in both areas, another area can be analysed. Another concern is that model-specific ranges for different parameters can result in several potential parameter sets that accurately fit the validation data. However, some parameter sets may produce the right results for the wrong reasons, leading to a misleading representation of a well-performing model. This effect is mitigated by minimize the ranges for certain parameters.

Finally, the inundation data collected for this study also introduce several uncertainties. These data points are only snapshots of the flooding events and do not provide information about the progression of the flooding or its timing, such as the peak flood stage. In addition, the estimation of flooding depths relies on observations such as the depth of water that cars pass through or recognizable objects, introducing the possibility of errors.

5.3.4 Uncertainties involving NBS

In this research, NBS design is considered on a neighbourhood scale. This means measure specific characteristics like vegetation types are not considered. Design parameters are based on Dutch and British design standards, which share similar soil characteristics as Suriname. They are adjusted for a tropical climate if reliable data was available. Infiltration rates are also based on Dutch examples, which consists of full-scale infiltration tests.

The design does not consider long-term effects like measure deterioration or effects of climate change, and it does not include maintenance costs in the design (Thorne et al., 2018). Only initial infiltration rates are adjusted based on studies into the decline in infiltration capacity of these measures over the years. These studies have been done in high income countries with temperate climate. It can be expected that the decline in tropical low, mid-income countries is higher. Due to less maintenance and the presence of sediment.

The current research thus only examines the general effectiveness of NBS and does not consider actual deterioration, maintenance, or feasibility. Further research is needed to assess how these aspects affect the effectiveness of NBS in Paramaribo.

It is expected that the main challenge for the feasibility of NBS in Paramaribo is focussed on the maintenance. The tropical climate creates faster vegetation growth compared to European countries. Furthermore, there is an abundance of fine sediment which can easily clog the measures. This is due to the presence of unpaved roads and high rainfall rates. A pilot measure could first be implemented to show how much this effects the measure and if maintenance cost can be kept in check.

Nonetheless, this research considered maintenance cost by providing a low-maintenance alternative for each measure specific area, which is mostly at the expense of urban amenity. An overview of this is given in Table 5-1 where the measures are organized per application area and degree of required maintenance.

Table 5-1 Measures organized per land use area and degree of required maintenance

Land use type	**High in maintenance**	**Low in maintenance**
Roofs	Green roofs	Rain barrels
Parking places	Bioretention cells	Permeable parking spots
Streets	Vegetative swales	Infiltration trenches
Green spaces	Rain gardens	Retention pond

5.3.5 Other challenges related to the applicability of NBS

For the applicability of NBS other aspects also play a role. First, in this research it is assumed that the groundwater level will be controlled at 1 m below the surface. Currently, the groundwater level is not controlled, and soil properties must determine if this is even possible for the study area. Especially because of the sand ridges in the area. Without the control the groundwater level is around the surface level around the rainy season, making NBS other than green roofs and rain barrels useless.

Furthermore, the application of measures depends on other characteristics of the potential areas. For example, many of the vacant lots are private property and thus cannot be utilised by the government without content of the owner. Besides, green roofs are only applicable if the roof construction suffices. Most roof in the study area have corrugated roof plates, which possibly does not support the load of potential green roofs.

6 CONCLUSION AND RECOMMENDATIONS

The purpose of this research is to quantify the applicability of the Climate Resilient City Tool (CRCTool) in determining the effectiveness of Nature-Based Solutions (NBS) of tropical urban flood mitigation. The applicability of the CRCTool depends on the applicability of general assumptions in the tool, how the tool reacts to variations in certain parameters, if outputs comply with hydrological principles, how the results compare to a hydrodynamic model and how the tool performs in stakeholder interaction. To achieve this, a case study with the CRCTool and a developed hydrodynamic model in D-HYDRO is conducted in the city centre of Paramaribo.

It was found that the CRCTool in its current state is not widely applicable for accurately determining the flood mitigation in terms of runoff reduction for tropical conditions. The assumptions only hold for low runoff volumes, which is the case in temperate climates but not for tropical climates. Measures cannot be limited by their infiltration capacity and need to have limited drainage capacities, which is unrealistic for tropical rainfall conditions.

Besides, the additional strength of continuous modelling and a groundwater component were not optimally utilized. The effects of long-term processes like evapotranspiration and percolation were limited due to the instantaneous flow from the measure to the pump in the model. Furthermore, the groundwater level limits only the percolation from a measure and not the assigned controlled runoff, which effect is marginal for clay soils. For tropical climates like Suriname the effect of the abovementioned processes can potentially be important because they can have a significant effect during rainfall seasons where measure volumes potentially have no time to empty. Currently these effects are not visible in the CRCTool.

Additionally, the D-HYDRO model outputs highlighted the significant impact of flow routing and local elevation in the study area, resulting in larger total flooding volumes compared to the CRCTool output and different causes and solutions for various flooding areas. Hence, it is important to carefully consider the area size while evaluating the suitability of the CRCTool for a specific area, which may lead to the utilization of lower area sizes than those recommended by the tool and used in this research.

Despite its limitations, the tool proved to be a valuable resource for stakeholder engagement. It stimulated interest in and enthusiasm for NBS, initiated dialogues, and raised awareness on the subject. The tool's accessibility was also a positive aspect, especially for countries where there are no financial resources for and knowledge about expensive hydrodynamic models.

By making minor adjustments to the tool, its general applicability can be enhanced, by applying the following modelling improvements:

- Use a single runoff reduction factor based on the desired design return period. This way the tool loses its limitations related to an average runoff reduction factor.
- Limit controlled runoff from the measure to the groundwater, open water, and sewer system. This will be more realistic and long-term processes will have a more significant effect.
- Limit the effective depth by the infiltration capacity and inflow factor of the measure.
- Couple smaller more clearly defined study areas as separate neighbourhoods. This will mimic the effects of flow routing and local elevation.
- Use a flux as measure drainage based on design capacities, field measurements or drainage requirements to better represent a measure’s drainage behaviour
- Define the end of an event for better controlled runoff calculations
- Fix small modelling mistakes in baseline discharge definition and runoff separation

For future research it is recommended to apply the abovementioned model improvements to advance the applicability of the CRCTool. Additionally, to minimize the impact of flow routing and elevation on the results, it is advised to test the tool on smaller areas where the hydrological conditions are more clearly defined. If the tool’s applicability is enhanced for smaller areas, more smaller areas can be analysed and coupled into a single model to investigate the effect this has on the applicability for larger areas. Implementing these modifications could potentially increase the applicability of the tool significantly.

Moreover, the CRCTool is currently integrated with the results from the Urban Water Balance Model (UrbanWB), but it could also be integrated with the results from D-HYDRO. Since the calculation times for both models were not substantially different. Future research should explore the best way to incorporate the advantages of both models into the CRCTool. This will help to enhance the tool's effectiveness and make it a more valuable resource for urban planning and design practitioners.

Lastly, it is recommended to conduct a more in-depth analysis of the model artifacts observed in the runoff return period for different infiltration and storage capacities. A decrease in the runoff reduction factor was observed for low effective depths after a point where the runoff reduction factor for all effective depths was equal, which was not expected.

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APPENDIX

A. SUPPORTING MAIN TEXT

A1. Description of flood modelling methods

Simplified conceptual models require significantly less computational effort than the hydrodynamic models. These models produce predictions of inundation extent, overbank volume and water depth that compare well with 2D models if flow paths are clearly defined. It cannot model flow velocities and does not represent flow dynamics or flow routing. It can be applied on small scale in urban settings and is suitable for modelling long rainfall time series or probabilistic approaches.

The simplest representation of hydrodynamic modelling is to model the flow as one dimensional along the center line of a river, stream, or pipe. This is done in 1D sewer modelling, where the flow in the storm sewer is modelled in 1D and the overflow is considered as stagnant water storage above the manholes. This approach enables to identify potential overflow locations and the corresponding volume of floodwater. If a DEM is used inundation depths can be approximated from the virtual storage above the manholes. However, this method rarely represents the inundation depth accurately (Mark et al., 2004).

1D modelling can also be used to model overland flow, by assuming the flow is in one direction and taking one cross-section averaged velocity to represent large differences in overland flow velocities. Different catchments in the DEM can be identified and discretized as a set of linked nodes. The governing equations are solved like pipe flow. If the overland flow is well channeled and the water is confined in the surface network this method will work adequately. However, it is not capable of simulating multidirectional flow. This can pose problems if the flow direction changes during a flooding event, for example if the water level raises above the curbs of a street. This makes this method unreliable to produce accurate and reliable flood maps.

2D modelling of surface flow adds a multidirectional component to the flow modelling, which enables maximum inundation extent and dynamics of the flow, such as velocity and water depth. The 2D grid can be either structured (rectangular), unstructured (triangular) or flexible (combination of both). Furthermore, it can represent flow along small-scale structures, which gives it a main advantage for using it in urban settings. This requires a detailed DEM (less than 5m), which requires a lot of computational power and makes run times usually at least an hour. Most approaches solve the 2D shallow water equations, which represent mass and momentum conservation in a plane, and can be obtained by depth-averaging the Navier-Stokes equations. This approach assumes a design sewer capacity, which assumes the catchments of the sewer system and the corresponding surface area are similar (Van Dijk et al., 2014) .

By coupling 1D-sewer and 1D-overland or 1D-sewer and 2D-overland the interaction between aboveground and belowground flow can be captured. For this approach the interaction takes place at manholes, gullies, river nodes and corresponding 1D overland flow nodes or 2D grid cells. The 1D-1D approach keeps the computational time limited, but it is not able to provide flood information if the water leaves the predefined surface flow pathways. 1D-2D coupling can provide this information and in general produces also the most accurate results compared to other methods (Bulti & Abebe, 2020), at the cost of long computational times and a large data input. It is recommended to use this for analysis of complex systems, where a full interactive approach is required.

A2. Overview modeling software and studies into NBS implementation

Current research into the effects of NBS has been done in different modelling software and with different methods. Table 0-1 provides an overview of the different modelling software and how they can be used to model NBS. Table 0-2 provides an overview of different research and their main approach to modelling rainfall, runoff, their area of application, which NBS are implemented and the method of implementation. This puts the CRCTool in perspective with other modelling options.

Table 0-1 Overview of how NBS are implemented in different hydrodynamic modelling software ((Ahiablame et al., 2012; Haris et al., 2016; Teng et al., 2017)

Model software	Type	NBS simulation
D-HYDRO	1D2D	Aggregate simulation by altering general properties
HEC-RAS	2D	Aggregate simulation by altering general properties
InfoWorks	1D2D	Aggregate simulation by altering general properties
MIKE URBAN	1D2D	LID control toolbox (similar to SWMM)
MUSIC	1D	Stochastic, NBS have individual properties (implemented)
SWMM	1D2D	Process, physically based toolbox NBS are represented by a combination of vertical layers with their own properties NBS in sub-catchment are coupled in parallel
TUFLOW	2D	Aggregate simulation by altering general properties
LISFLOOD	2D	Land use input changes

Table 0-2 Overview of research into NBS (F = Forest, WL = Wetland, RB = Retention Basin, RT = Rain Tank, IT = Infiltration Trench, BC = Bioretention Cell, GR = Green Roof, VS = Vegetative Swale and PP = Permeable Pavement)

Source	Model	Rainfall	NBS input	Runoff	City	NBS	Extra info
(Wagenaar et al., 2019)	MIKE-FLOOD	prob. event	Land use change	SCS-CN	Urban + Rural (LK)	WL	1D-2D model
(Lallemant et al., 2021)	LISFLOOD	prob. event	Land use change	SCS-CN	Rural (MM)	F	1D-2D model
(Ferreira et al., 2020)	HEC-HMS HEC-RAS	det. event	Weir	SCS-CN	Peri-urban (PT)	RB	1D-2D model
(Watkin et al., 2019)	MIKE-HYDRO	det. continue	Art. storage Weir	Green Ampt	Rural (TH)	Furrows	1D layout
(Schubert et al., 2017)	MUSIC	det. continue	Conceptual tanks	-	Sub-urban (AU)	RT, IT, BC	6 lumped catchments
(Ahilan et al., 2014)	ISIS + TUFLOW	det. event	-	-	Urban (UK)	GR, PP, RB	1D-2D
(Qin et al., 2013)	SWMM	det. event	LID toolbox	non-lin. reservoir	Urban (CN)	VS, GR, PP	Sensitivity analysis
(W. Liu et al., 2014)	Conceptual	det. event	Runoff equations	Green Ampt	Urban (CN)	RB, VS, PP	
(Eckart et al., 2017)	SWMM	det. event	LID toolbox	SCS-CN	Urban (CA)	RB, PP, BC, IT	
(Kong et al., 2017)	SWMM	det. event	LID toolbox	Horton	Urban (CN)	PP, GR, VS, BC	
(Vojinovic et al., 2021)	MIKE URBAN	det. event	LID toolbox	-	Urban (TH)	All types	
(Zölch et al., 2017)	MIKE SHE	det. event	LID toolbox	-	Urban (DE)	GF, trees	
(Cui et al., 2019)	PCSWMM	det. event	LID toolbox	Horton	Urban (CN)	PP, RG	
(Costa et al., 2021)	InfoWorks	det. event	Catchment properties	Horton	Urban (NL)	PP, GR, streets	

A3. Distribution of daily evaporation values over the day

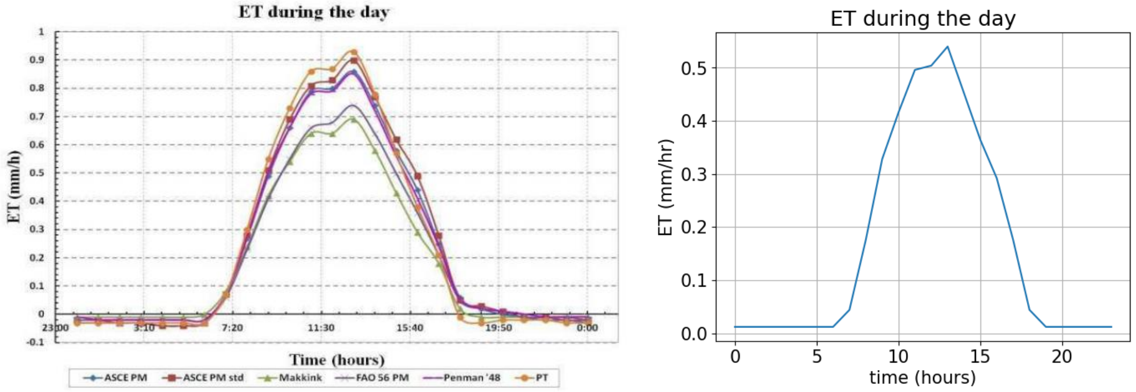


Figure 0-1 Daily distribution of evaporation from Naipal et al. (2013) and reproduced variant based on 4 mm/d

A4. Rainfall timeseries for all rainfall stations

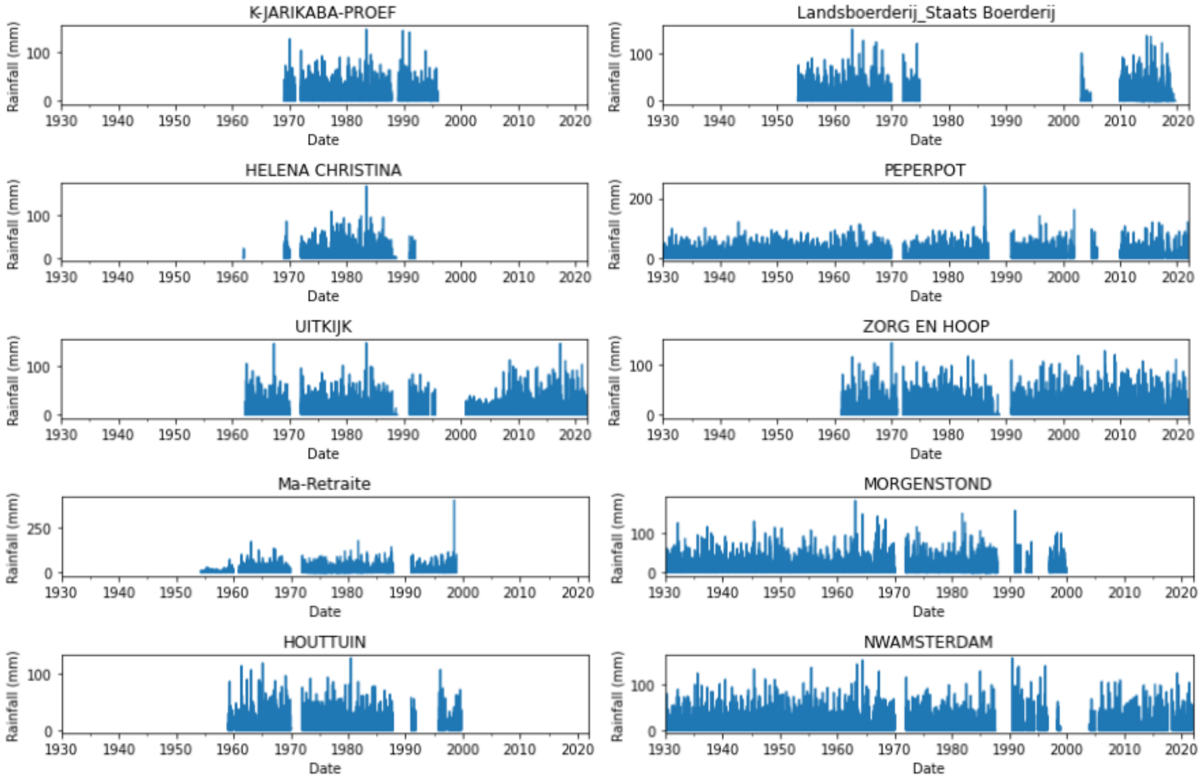


Figure 0-2 Rainfall timeseries for all daily rainfall stations in Paramaribo

A5. Identified events with peaks-over threshold method

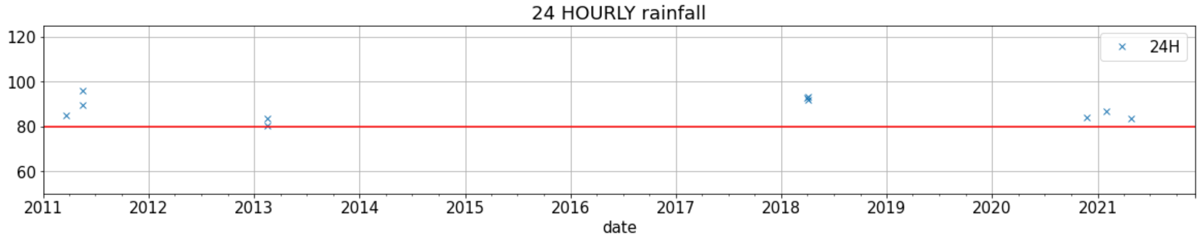
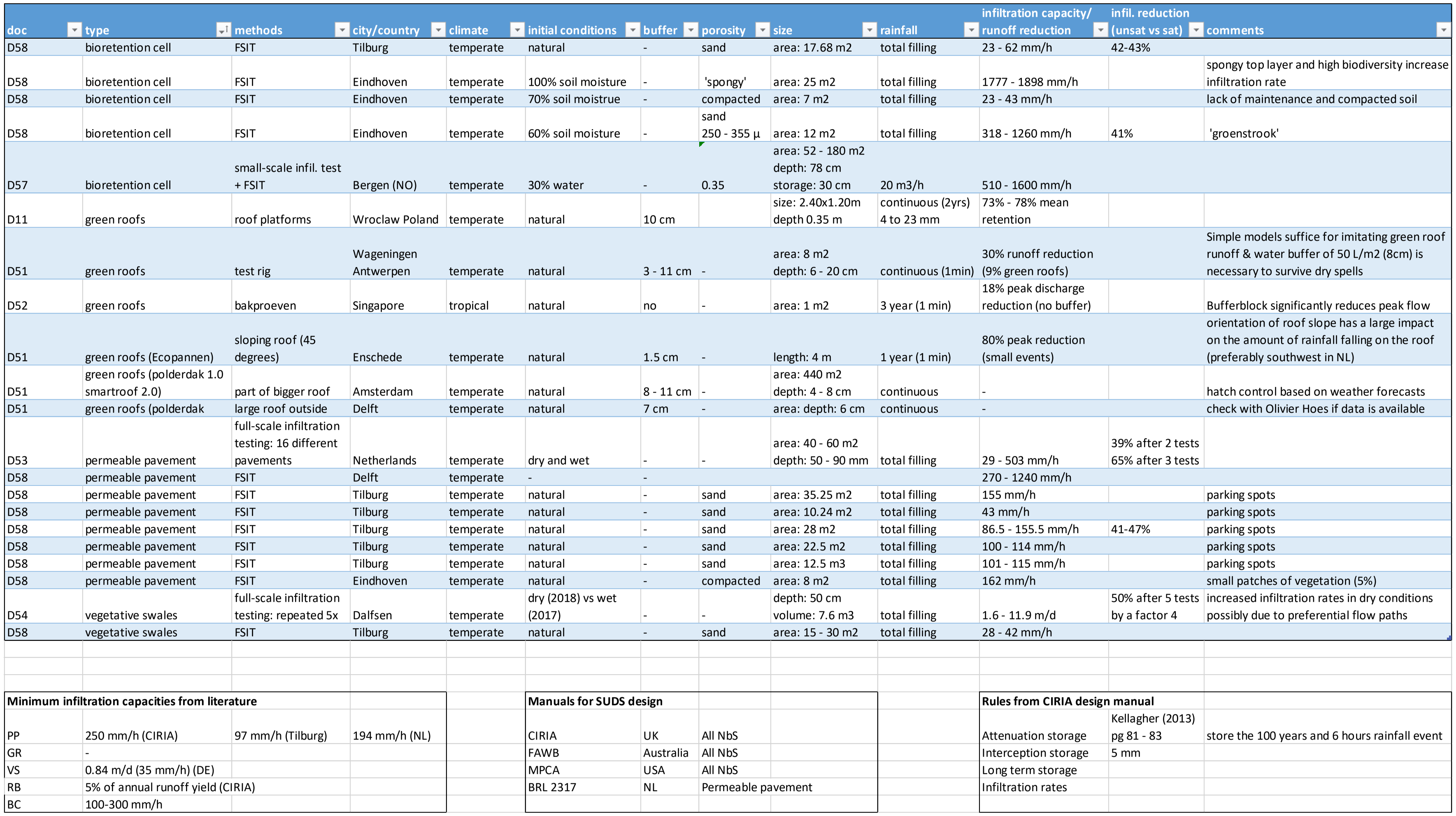


Figure 0-3 Peaks over threshold for T>1 (80 mm) for Zorg en Hoop hourly rainfall timeseries

A6. Detailed overview of NBS experiments



doc	type	methods	city/country	climate	initial conditions	buffer	porosity	size	rainfall	infiltration capacity/ runoff reduction	infil. reduction (unsat vs sat)	comments
D58	bioretention cell	FSIT	Tilburg	temperate	natural	-	sand	area: 17.68 m2	total filling	23 - 62 mm/h	42-43%	
D58	bioretention cell	FSIT	Eindhoven	temperate	100% soil moisture	-	'spongy'	area: 25 m2	total filling	1777 - 1898 mm/h		spongy top layer and high biodiversity increase infiltration rate
D58	bioretention cell	FSIT	Eindhoven	temperate	70% soil moistrue	-	compacted	area: 7 m2	total filling	23 - 43 mm/h		lack of maintenance and compacted soil
D58	bioretention cell	FSIT	Eindhoven	temperate	60% soil moisture	-	sand 250 - 355 µ	area: 12 m2	total filling	318 - 1260 mm/h	41%	'groenstrook'
D57	bioretention cell	small-scale infil. test + FSIT	Bergen (NO)	temperate	30% water	-	0.35	area: 52 - 180 m2 depth: 78 cm storage: 30 cm	20 m3/h	510 - 1600 mm/h		
D11	green roofs	roof platforms	Wroclaw Poland	temperate	natural	10 cm		size: 2.40x1.20m depth 0.35 m	continuous (2yrs) 4 to 23 mm	73% - 78% mean retention		
D51	green roofs	test rig	Wageningen Antwerpen	temperate	natural	3 - 11 cm	-	area: 8 m2 depth: 6 - 20 cm	continuous (1min)	30% runoff reduction (9% green roofs)		Simple models suffice for imitating green roof runoff & water buffer of 50 L/m2 (8cm) is necessary to survive dry spells
D52	green roofs	bakproeven	Singapore	tropical	natural	no	-	area: 1 m2	3 year (1 min)	18% peak discharge reduction (no buffer)		Bufferblock significantly reduces peak flow
D51	green roofs (Ecopannen)	sloping roof (45 degrees)	Enschede	temperate	natural	1.5 cm	-	length: 4 m	1 year (1 min)	80% peak reduction (small events)		orientation of roof slope has a large impact on the amount of rainfall falling on the roof (preferably southwest in NL)
D51	green roofs (polderdak 1.0 smartroof 2.0)	part of bigger roof	Amsterdam	temperate	natural	8 - 11 cm	-	area: 440 m2 depth: 4 - 8 cm	continuous	-		hatch control based on weather forecasts
D51	green roofs (polderdak	large roof outside	Delft	temperate	natural	7 cm	-	area: depth: 6 cm	continuous	-		check with Olivier Hoes if data is available
D53	permeable pavement	full-scale infiltration testing: 16 different pavements	Netherlands	temperate	dry and wet	-	-	area: 40 - 60 m2 depth: 50 - 90 mm	total filling	29 - 503 mm/h	39% after 2 tests 65% after 3 tests	
D58	permeable pavement	FSIT	Delft	temperate	-	-				270 - 1240 mm/h		
D58	permeable pavement	FSIT	Tilburg	temperate	natural	-	sand	area: 35.25 m2	total filling	155 mm/h		parking spots
D58	permeable pavement	FSIT	Tilburg	temperate	natural	-	sand	area: 10.24 m2	total filling	43 mm/h		parking spots
D58	permeable pavement	FSIT	Tilburg	temperate	natural	-	sand	area: 28 m2	total filling	86.5 - 155.5 mm/h	41-47%	parking spots
D58	permeable pavement	FSIT	Tilburg	temperate	natural	-	sand	area: 22.5 m2	total filling	100 - 114 mm/h		parking spots
D58	permeable pavement	FSIT	Tilburg	temperate	natural	-	sand	area: 12.5 m3	total filling	101 - 115 mm/h		parking spots
D58	permeable pavement	FSIT	Eindhoven	temperate	natural	-	compacted	area: 8 m2	total filling	162 mm/h		small patches of vegetation (5%)
D54	vegetative swales	full-scale infiltration testing: repeated 5x	Dalfsen	temperate	dry (2018) vs wet (2017)	-	-	depth: 50 cm volume: 7.6 m3	total filling	1.6 - 11.9 m/d	50% after 5 tests by a factor 4	increased infiltration rates in dry conditions possibly due to preferential flow paths
D58	vegetative swales	FSIT	Tilburg	temperate	natural	-	sand	area: 15 - 30 m2	total filling	28 - 42 mm/h		

Minimum infiltration capacities from literature			
PP	250 mm/h (CIRIA)	97 mm/h (Tilburg)	194 mm/h (NL)
GR	-		
VS	0.84 m/d (35 mm/h) (DE)		
RB	5% of annual runoff yield (CIRIA)		
BC	100-300 mm/h		

Manuals for SUDS design		
CIRIA	UK	All NbS
FAWB	Australia	All NbS
MPCA	USA	All NbS
BRL 2317	NL	Permeable pavement

Rules from CIRIA design manual		
Attenuation storage	Kellagher (2013) pg 81 - 83	store the 100 years and 6 hours rainfall event
Interception storage	5 mm	
Long term storage		
Infiltration rates		

Figure 0-4 Data from experiments with NBS

A7. equations for seepage, drainage, continuity, and substitution in the continuity equation

Seepage: $q_s(t) = \frac{H-h(t)}{c}$

Drainage: $q_d(t) = \frac{PP-h(t)}{w}$

Continuity: $\frac{dh(t)}{dt} = \frac{-q_{in}(t)}{\mu} = \frac{q_s(t)+q_d(t)-\frac{P}{t}}{\mu}$

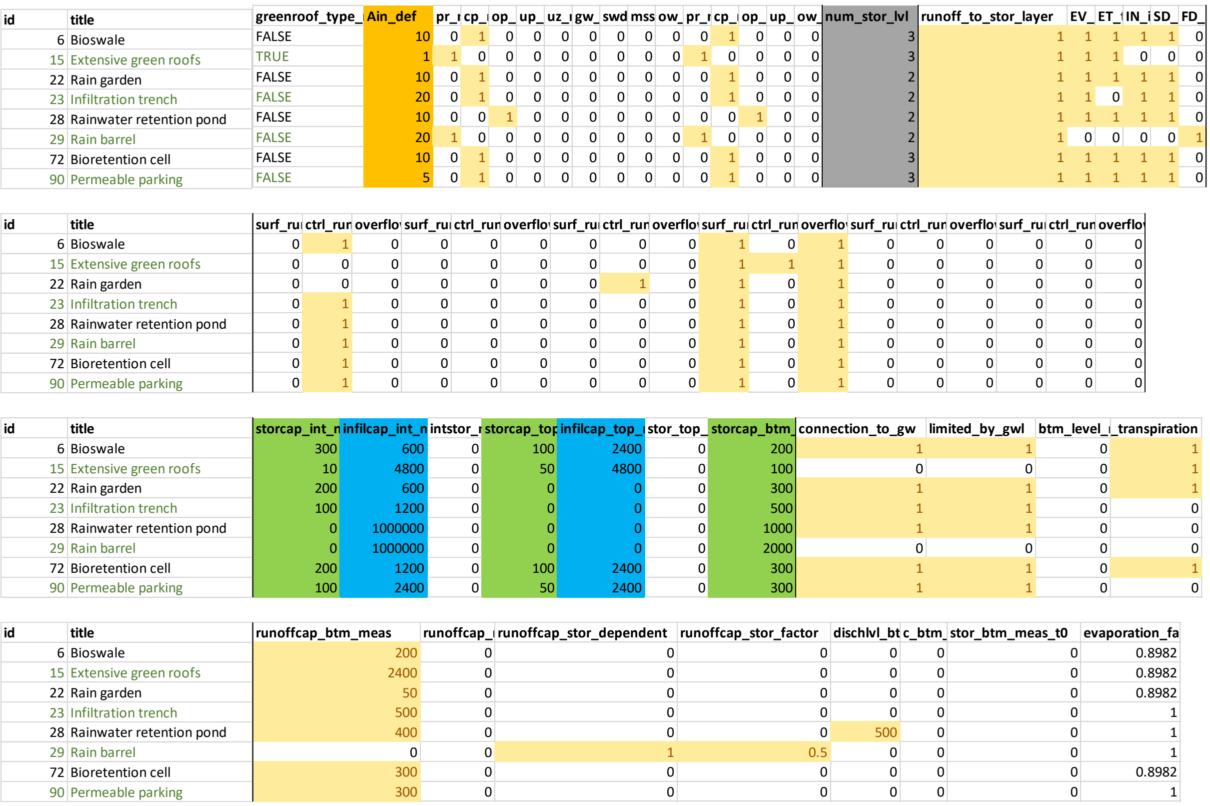
Substitution in continuity equation (seepage is groundwater dependent):

$$\frac{dh(t)}{dt} = \frac{\frac{H-h(t)}{c} + \frac{PP-h(t)}{w} - P/_t}{\mu} = \frac{H \cdot w + PP \cdot c - \frac{P}{t} \cdot m}{\mu \cdot w \cdot c} - \frac{w+c}{\mu \cdot w \cdot c} h(t)$$

Substitution in continuity equation (seepage is constant):

$$\frac{dh(t)}{dt} = \frac{q_s + \frac{pp-h(t)}{w} - \frac{P}{t}}{\mu} = \frac{PP + w \cdot \left(q_s - \frac{P}{t}\right)}{\mu \cdot w} - \frac{1}{\mu \cdot w} h(t)$$

A8. All parameter values for CRCTool measure input



id	title	greenroof_type_	Ain_def	pr_	cp_	op_	up_	uz_	gw_	swd	mss	ow_	pr_	cp_	op_	up_	ow_	num_stor_lvl	runoff_to_stor_layer	EV_	ET_	IN_	SD_	FD_
6	Bioswale	FALSE	10	0	1	0	0	0	0	0	0	0	0	1	0	0	0	3	1	1	1	1	1	0
15	Extensive green roofs	TRUE	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	3	1	1	1	0	0	0
22	Rain garden	FALSE	10	0	1	0	0	0	0	0	0	0	0	1	0	0	0	2	1	1	1	1	1	0
23	Infiltration trench	FALSE	20	0	1	0	0	0	0	0	0	0	0	1	0	0	0	2	1	1	0	1	1	0
28	Rainwater retention pond	FALSE	10	0	0	1	0	0	0	0	0	0	0	0	1	0	0	2	1	1	1	1	1	0
29	Rain barrel	FALSE	20	1	0	0	0	0	0	0	0	0	1	0	0	0	0	2	1	0	0	0	0	1
72	Bioretention cell	FALSE	10	0	1	0	0	0	0	0	0	0	0	1	0	0	0	3	1	1	1	1	1	0
90	Permeable parking	FALSE	5	0	1	0	0	0	0	0	0	0	0	1	0	0	0	3	1	1	1	1	1	0

id	title	surf_ru	ctrl_run	overflo	surf_ru	ctrl_run	overflo	surf_ru	ctrl_run	overflo	surf_ru	ctrl_run	overflo	surf_ru	ctrl_run	overflo	surf_ru	ctrl_run	overflo
6	Bioswale	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0
15	Extensive green roofs	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0
22	Rain garden	0	0	0	0	0	0	0	1	0	1	0	1	0	0	0	0	0	0
23	Infiltration trench	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0
28	Rainwater retention pond	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0
29	Rain barrel	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0
72	Bioretention cell	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0
90	Permeable parking	0	1	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0

id	title	storcap_int_	infilcap_int_	intstor_	storcap_top	infilcap_top_	stor_top_	storcap_btm_	connection_to_gw	limited_by_gwl	btm_level_	transpiration
6	Bioswale	300	600	0	100	2400	0	200	1	1	0	1
15	Extensive green roofs	10	4800	0	50	4800	0	100	0	0	0	1
22	Rain garden	200	600	0	0	0	0	300	1	1	0	1
23	Infiltration trench	100	1200	0	0	0	0	500	1	1	0	0
28	Rainwater retention pond	0	1000000	0	0	0	0	1000	1	1	0	0
29	Rain barrel	0	1000000	0	0	0	0	2000	0	0	0	0
72	Bioretention cell	200	1200	0	100	2400	0	300	1	1	0	1
90	Permeable parking	100	2400	0	50	2400	0	300	1	1	0	0

id	title	runoffcap_btm_meas	runoffcap_	runoffcap_stor_dependent	runoffcap_stor_factor	dischlvl_bt	c_btm_	stor_btm_meas_t0	evaporation_fa
6	Bioswale	200	0	0	0	0	0	0	0.8982
15	Extensive green roofs	2400	0	0	0	0	0	0	0.8982
22	Rain garden	50	0	0	0	0	0	0	0.8982
23	Infiltration trench	500	0	0	0	0	0	0	1
28	Rainwater retention pond	400	0	0	0	500	0	0	1
29	Rain barrel	0	0	1	0.5	0	0	0	1
72	Bioretention cell	300	0	0	0	0	0	0	0.8982
90	Permeable parking	300	0	0	0	0	0	0	1

Figure 0-5 All measure parameters of CRCTool, parameter explanation is given in Vergroesen & Brolsma (2020)

A9. Results perfect and no sewer system

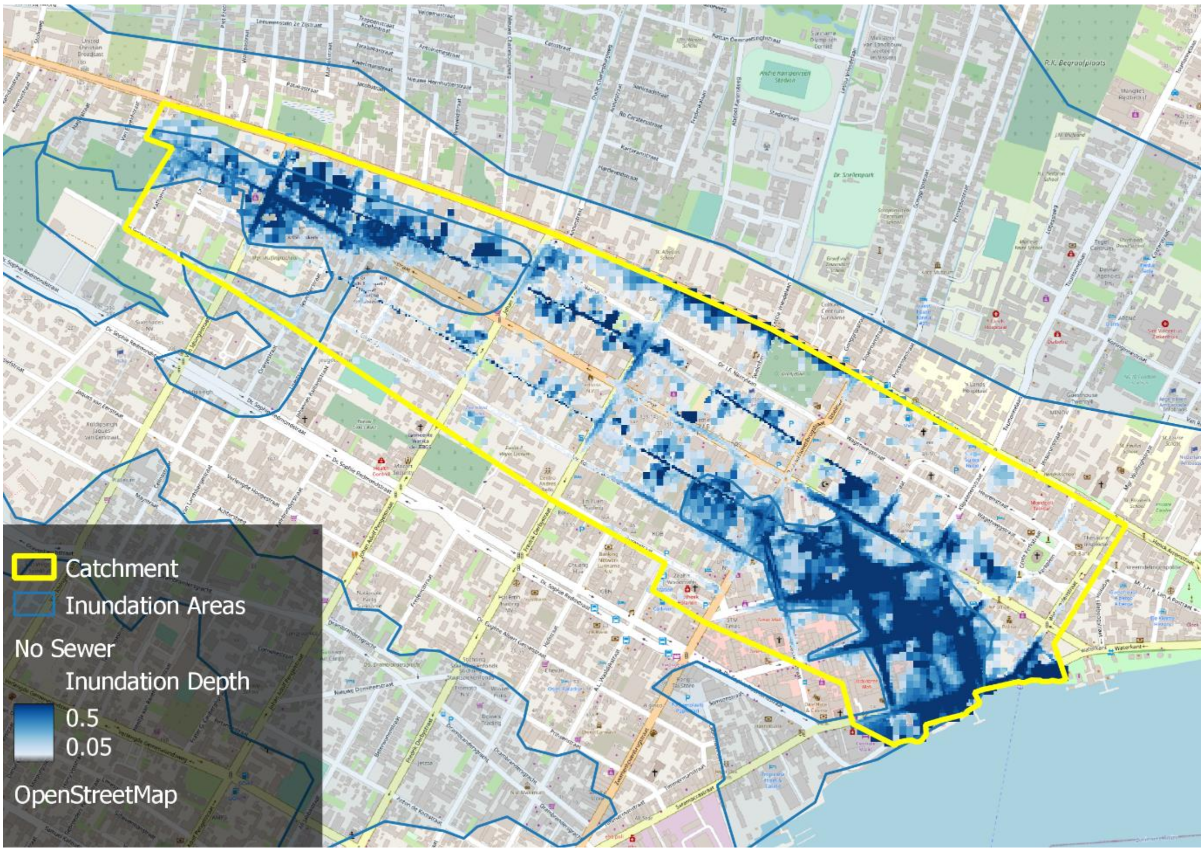


Figure 0-6 Inundation map for a situation without a drainage system

Figure 0-7 Inundation map for a situation without adjustments to the sewer system (in perfect conditions)

A10. Deep groundwater

The deep groundwater acts as one of the external boundaries. The seepage to this layer can be defined as a dynamic flux means the downward seepage is calculated based on the head difference between the shallow and the deep groundwater. The seepage fluctuates based on the groundwater level if it is dynamic. Higher groundwater levels mean more seepage. If the seepage is defined as a flux the seepage is constant. The contribution of downward seepage is so small that calculating it dynamically has no significant effect on the model outcome (see **figure**).

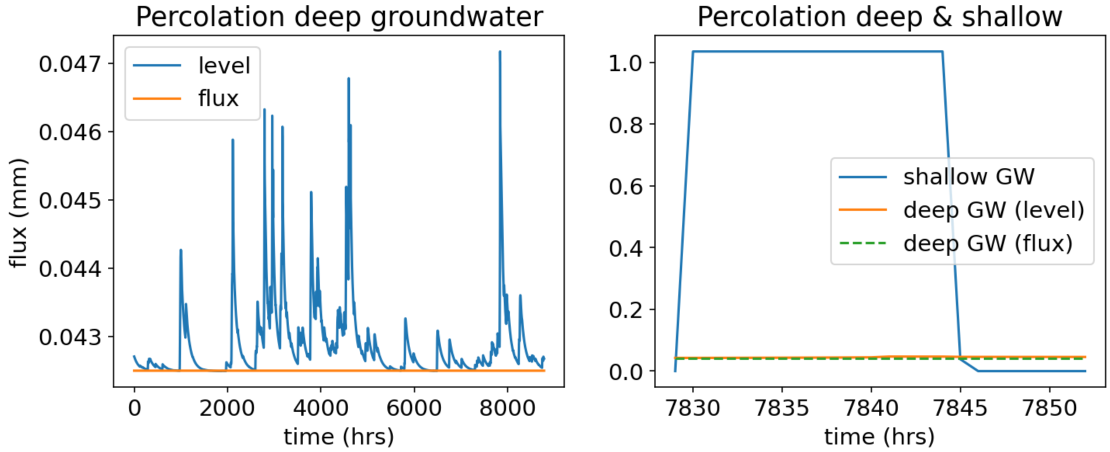


Figure 0-8 Differences between flux and level seepage (left) & contribution deep GW flow to total discharge (right)

A11. Stor_btm_meas_t0

'stor_btm_meas_t0' indicates how full the measure is at the start of the simulation. This could be used to simulate the standing water in a retention pond for example. It was found in this study that runs with this parameter produced higher runoff reduction values. It was found that 'stor_btm_meas_t0' is added to the effective depth during calculations, which also increases their effectiveness with this amount. An example is given for a retention pond, with a 'stor_btm_meas_t0' of 0 (a) and 100 (b). It shows that the effectiveness at an effective depth of 100 at (a) is equal to an effective depth of 5 mm (which is 105 mm) for (b).

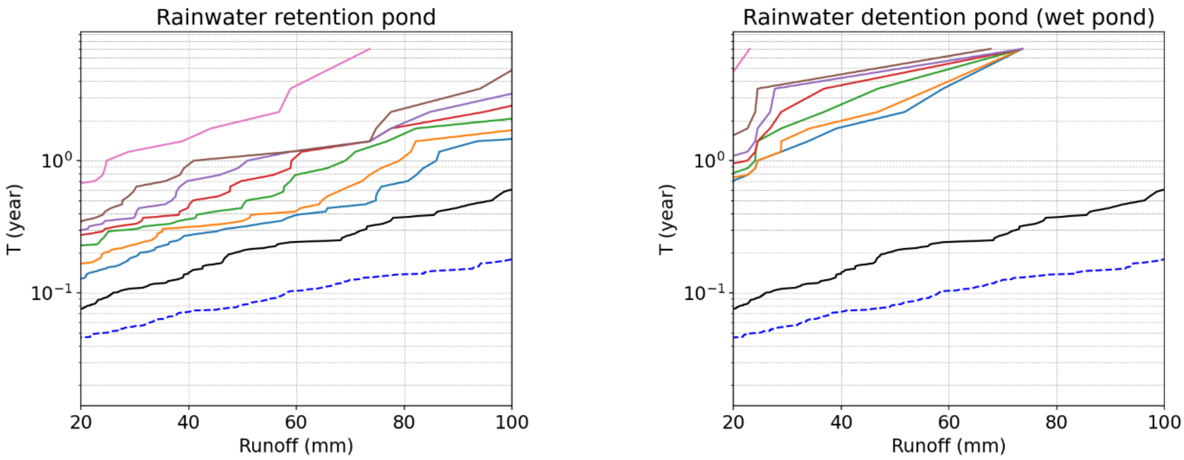


Figure 0-9

A12. Measure effectiveness per measure inflow area

Table 0-3 Measure effectiveness per measure inflow area for all measures

id	Measure	5	10	20	30	40	50	100
6	Vegetative swale	3.44	5.29	10.4	17.57	25.39	32.73	54.09
15	Extensive green roofs	1.77	2.07	2.6	3.1	3.54	3.98	5.85
22	Rain garden	6.16	7.78	10.81	12.89	14.25	14.76	17.69
23	Infiltration trench	3.82	5.57	7.67	9.21	9.78	10.01	10.01
28	Rainwater retention pond	2.73	5.24	14.27	38.21	67.91	133.31	1000
29	Rain barrel	1.33	1.82	3.55	7.38	16.11	35.07	1000
72	Bioretention cell	3.35	5.62	12.05	21.77	35.9	47.15	50.77
90	Permeable parking	5.88	11.01	30.46	76.22	121.59	136.33	143.75

A13. List of stakeholder participation

Table 0-4 Participants of design workshop CRCTool

Participant	Background	Participant	Background
Participant 1	Meteorology	Participant 9	Hydraulic engineering
Participant 2	Meteorology	Participant 10	Fieldworker
Participant 3	Drainage systems	Participant 11	Planning
Participant 4	Drainage systems	Participant 12	Environmental science
Participant 5	Hydrology	Participant 13	Civil engineering
Participant 6	Hydrology	Participant 14	Civil engineering
Participant 7	Subdivision	Participant 15	Civil engineering
Participant 8	Subdivision	Participant 16	Civil engineering

A14. Map of infiltration values D-HYDRO

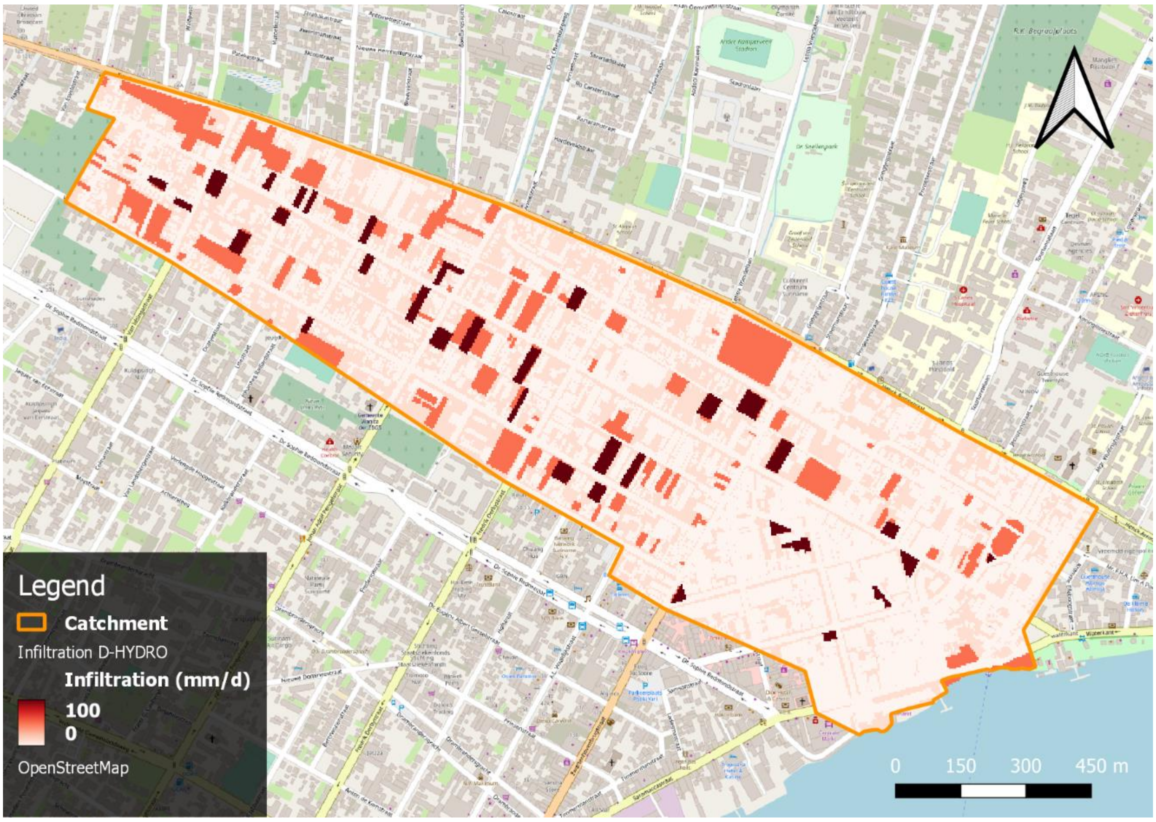
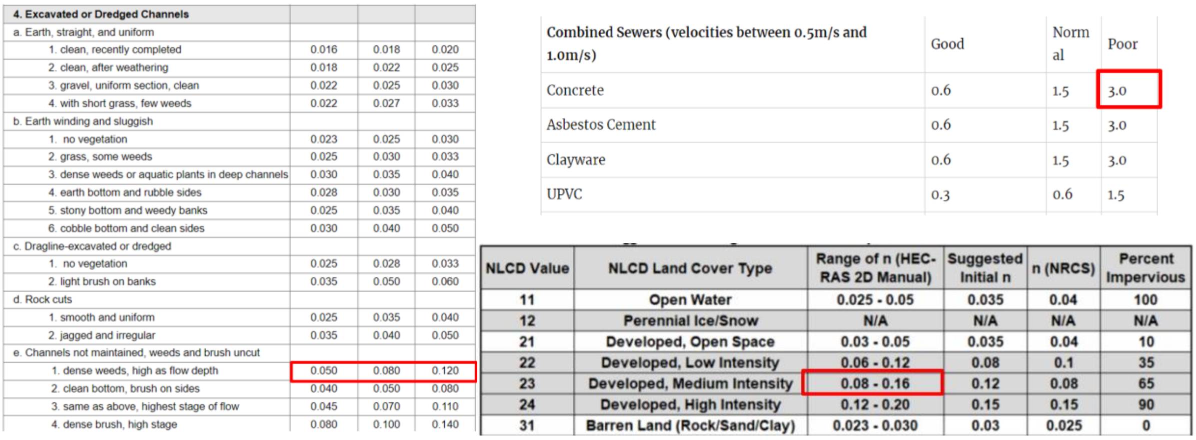


Figure 0-10 Infiltration values for D-HYDRO input with all potential measures

A15. Design tables for roughness factors



4. Excavated or Dredged Channels			
a. Earth, straight, and uniform			
1. clean, recently completed	0.016	0.018	0.020
2. clean, after weathering	0.018	0.022	0.025
3. gravel, uniform section, clean	0.022	0.025	0.030
4. with short grass, few weeds	0.022	0.027	0.033
b. Earth winding and sluggish			
1. no vegetation	0.023	0.025	0.030
2. grass, some weeds	0.025	0.030	0.033
3. dense weeds or aquatic plants in deep channels	0.030	0.035	0.040
4. earth bottom and rubble sides	0.028	0.030	0.035
5. stony bottom and weedy banks	0.025	0.035	0.040
6. cobble bottom and clean sides	0.030	0.040	0.050
c. Dragline-excavated or dredged			
1. no vegetation	0.025	0.028	0.033
2. light brush on banks	0.035	0.050	0.060
d. Rock cuts			
1. smooth and uniform	0.025	0.035	0.040
2. jagged and irregular	0.035	0.040	0.050
e. Channels not maintained, weeds and brush uncut			
1. dense weeds, high as flow depth	0.050	0.080	0.120
2. clean bottom, brush on sides	0.040	0.050	0.080
3. same as above, highest stage of flow	0.045	0.070	0.110
4. dense brush, high stage	0.080	0.100	0.140

Combined Sewers (velocities between 0.5m/s and 1.0m/s)	Good	Normal	Poor
Concrete	0.6	1.5	3.0
Asbestos Cement	0.6	1.5	3.0
Clayware	0.6	1.5	3.0
UPVC	0.3	0.6	1.5

NLCD Value	NLCD Land Cover Type	Range of n (HEC-RAS 2D Manual)	Suggested Initial n	n (NRCS)	Percent Impervious
11	Open Water	0.025 - 0.05	0.035	0.04	100
12	Perennial Ice/Snow	N/A	N/A	N/A	N/A
21	Developed, Open Space	0.03 - 0.05	0.035	0.04	10
22	Developed, Low Intensity	0.06 - 0.12	0.08	0.1	35
23	Developed, Medium Intensity	0.08 - 0.16	0.12	0.08	65
24	Developed, High Intensity	0.12 - 0.20	0.15	0.15	90
31	Barren Land (Rock/Sand/Clay)	0.023 - 0.030	0.03	0.025	0

Figure 0-11 Roughness factors for channels (left)[1], sewer system (upper right)[2] & 2D roughness (bottom right)[3]

A16. Event separation of top 10 storage events for different baseline discharges

Table 0-5 Ten highest ranked storage events (in meters) based on different baseline discharges (in mm/day)

	RANK	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Baseline q = 6	**6**	**9.7**	**9.4**	**6.1**	**5.3**	**4.0**	**3.8**	**3.2**	**2.4**	**2.2**	**2.1**
	12	*5.7*	*4.7*	*5.3*	*4.2*	*3.6*	*3.2*	*2.6*	*2.4*	*2.0*	*1.6*
Baseline q = 12	**12**	**5.7**	**4.7**	**5.3**	**4.2**	**4.1**	**3.6**	**3.6**	**3.2**	**2.6**	**2.4**
	24	*5.2*	*5.2*	*4.1*	*3.7*	*3.2*	*3.2*	*2.6*	*2.4*	*2.3*	*2.2*
Baseline q = 24	**24**	**5.2**	**5.2**	**4.1**	**3.8**	**3.7**	**3.2**	**3.2**	**2.6**	**2.4**	**2.3**
	48	*5.0*	*4.4*	*3.6*	*3.6*	*2.7*	*2.7*	*2.5*	*2.3*	*2.1*	*1.9*
Baseline q = 48	**48**	**5.0**	**4.4**	**3.6**	**3.6**	**2.7**	**2.7**	**2.5**	**2.3**	**2.1**	**1.9**
	96	4.6	3.3	3.0	2.8	1.8	1.7	1.7	1.6	1.6	1.6
Baseline q = 96	96	4.6	3.3	3.0	2.8	1.8	1.7	1.7	1.6	1.6	1.6

1) https://www.fsl.orst.edu/geowater/FX3/help/FX3_Help.html#8_Hydraulic_Reference/Mannings_n_Tables.htm
2) https://rashms.com/blog/mannings-n-roughness-coefficient-for-hec-ras-2d-modeling/
3) https://civilweb-spreadsheets.com/drainage-design-spreadsheets/pipe-flow-calculator/colebrook-white-roughness-coefficient/

B. DESCRIPTION OF PYTHON CODE

In this appendix the functions created to analyse and process the data in this research are given. The corresponding python code can be found in the supplementary materials.

B1. Description code for rainfall analysis

1. **incomplete_years(dataframe):** filters incomplete years from rainfall dataset

2. **hourly_data(file, start, end):** makes hourly rainfall dataset compatible for further analysis

3. **daily_to_hourly(dataframe, hyetograph):** upsamples a daily rainfall dataset to hourly based on a general hyetograph
4. **mevpy(dataframe, time sequence):** makes the dataframe compatible for Generalized Extreme Value (GEV) analysis for a given time sequence (hourly or daily)
5. **GEV(dataframe):** performs GEV analysis for mevpy() output and returns GEV function in x and y values
6. **IDF(dataframe):** defines max rainfall rates for different return periods for mevpy() output

7. **plotIDF(dataframe):** plots IDF curves from IDF() output

8. **timeperiod(dataframe, start, end):** define a specific time period for a rainfall dataset

9. **peaks_over_threshold(dataframe, time sequence, thresholds):** gives all points above a certain threshold for a rainfall dataset
10. **Extract_individual_storms(dataframe):** Locates daily rainfall event based on the output from peaks_over_threshold() and plots the events with date and total rainfall amount

B2. Description code for processing UrbanWB output

1. **Runoff_return_period(dataframe):** Ranked baseline runoff and runoff for different measure depths is plotted against the corresponding return period
2. **Runoff_reduction_factors(dataframe):** Runoff reduction factor is plotted for baseline runoff and different measure depths
3. **Baseline_discharge(dataframe):** plot open water level (storage) from UrbanWB output, make marks at the start of every storage event and count these marks
4. **plotSDFparamaribo(dataframe):** plots an SDF curve specifically for study area characteristics

B3. Description code for processing D-HYDRO output

1. **Validation(dictionary):** plots water depth for observation points and total water storage in the system for provided validation input (D-HYDRO output (netCDF file))
2. **Water_depth_obs_point(dictionary):** plots water depth at observation points for multiple netCDF files (D-HYDRO output)
3. **Flooding_properties(dictionary):** plots total water storage and system outflow for multiple netCDF files (D-HYDRO output)

C. SUPPLEMENTARY MATERIAL

This list contains the materials used to perform this study with a short description. The required software used is given in table (Table 3-1)**.** The supplementary material can be found at **link**.

1. **CRCTool Paramaribo**
    - Input: neighbourhood parameters/ measure parameters/ rainfall input data
    - Model run: all model output (pysol)/ python files for running model/ figures
2. **CRCTool Documents**
    - CRCTool project files: Project files from paramaribo.crctool.org
    - CRCTool backend files: python files for webinterface calculations
    - CRCTool parameters: explanation of all CRCTool parameters
    - Preliminary parameter sensitivity tests: all tests done with CRCTool
    - Nature-Based Solutions data: all collected data on NBS parameters
    - Runoff reduction factor calculation sheet: manual calculation of runoff reduction factor
3. **DHYDRO Data**
    - DIMR config files: run different measures for a specific rainfall event
    - FlowFM models: D-HYDRO model file for different NBS
    - NBS: adjusted DEM and infiltration rasters
    - Rainfall events: rainfall events in D-HYDRO input format
4. **DHYDRO Projects**
    - base_v5_DIMR: All D-HYDRO projects in a single DIMR configuration
5. **QGIS project**
    - Catchments: Shapefiles of Greater Paramaribo, catchment & pilot area
    - DEM: DEM of Greater Paramaribo & catchment area
    - Drainage system: Drainage system exported from SOBEK
    - Excel export: NBS and land use fractions
    - Flooding areas: Flooded areas from D-HYDRO output
    - Grids: Raster files for unstructured grid and infiltration layer
    - Land Use Area: Land use areas of catchment/pilot for CRCTool
    - Land Use OSM: Land use areas from OpenStreetMap
    - Measures: Potential measure locations
6. **UrbanWB-master**
    - Urban Water Balance Model: UrbanWB from Deltares
    - UrbanWB functions: Explanation of functions in UrbanWB