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EVALUATING THE EFFECT OF NATURE-BASED SOLUTIONS ON URBAN RUNOFF USING HYDRAULIC MODELLING: A CASE STUDY IN SEKONDI-TAKORADI, GHANA

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SOURCE COVER PICTURE
From HKV lijn in water field visit to Sekondi-Takoradi in 2022.

PREFACE

This document contains the final thesis for my Master's degree, which represents the culmination of my studies in Civil Engineering and Management with a specialisation in 'Integrated Water Management & Engineering' at the University of Twente. The research topic focuses on the effect and implementation of Nature-Based Solutions (NBS) on rainfall runoff in urban areas in Ghana. The investigation was commissioned by HKV lijn in water, and I had the privilege of conducting this research in close cooperation with the University of Twente during my internship at HKV from February up and until July 2023.

I would like to seize this opportunity to express my heartfelt gratitude to the individuals who have played an integral role in shaping my journey and contributing to the completion of this Master's thesis. First and foremost, I would like to extend my appreciation to Alex Curran and Job Udo, my esteemed supervisors from HKV. Their expertise, guidance, feedback, and flexibility have been invaluable throughout this research. They provided me with the necessary resources, challenged my ideas, and helped me find my place at HKV. I am truly grateful for their unwavering support. Additionally, I would like to thank my two supervisors from the University of Twente, Suzanne Hulscher and Freek Huthoff. Your academic guidance has been indispensable, keeping me on track with valuable feedback and insightful suggestions that have greatly enhanced the quality of my work. Thank you for improving my research skills, fostering critical thinking abilities, and providing practical guidance. To my friends, fraternity and family, I express my deepest appreciation for your unwavering support, understanding, and encouragement throughout this journey. Your presence has helped me find moments of relaxation, diverting my mind from work, and providing useful insights that were worth exploring. The great memories we share have greatly motivated me during this journey. In particular, I would like to express my sincere gratitude to my girlfriend for your unwavering belief in my abilities, being a compassionate listener whenever I needed one, and offering unconditional support and involvement throughout the entire project.

Lastly, I would like to extend my gratitude to all the individuals who have contributed to this project in various ways, whether through collaboration, feedback, or encouragement. Each interaction has played a significant role in shaping the final outcome, and I am truly grateful for the collective involvement.

I sincerely hope that you will find this report interesting and enjoyable to read.

Ruben Borst
Enschede, 13th of July 2023

ABSTRACT

Rapid urbanization, combined with climate change, poses severe threats to future generations. The rapid development of built-up areas leads to a transformation of surface cover that disrupts the hydrological cycle and increases flood risk. Sub-Saharan African countries, in particular, are susceptible to hydro-meteorological risks associated with climate change due to their rapid urbanization rates. The implementation of Nature-Based Solutions (NBS) is still in its early stages. The application of NBS in urban areas has not been systematically explored yet, and its potential remains untapped.

The purpose of this research report is to investigate the effects of several urban Nature-Based Solutions (NBS) on the water system in a Sub-Saharan African urban environment. The case study focuses on Sekondi-Takoradi in Ghana. These regions are characterized by limited quantitative data and related NBS studies, mainly due to the complexity of NBS modelling. Parametrizing NBS is challenging, especially for hydraulic models, which are essential for simulating water flows and providing valuable insights into the functioning of the water system. Accurately assessing the hydraulic performance and effects of NBS requires addressing sub-questions related to NBS assessment, sensitivity analysis, hydraulic model development, individual and combined NBS effects, validation, and drawing generic lessons.

A basic hydraulic HEC-RAS model from the company HKV lijn in water was enhanced to improve accuracy, incorporating insights from literature review and expert input. The most influential model parameter was found to be roughness. To enhance land cover representation, satellite images were utilized to refine the model grid significantly. A sensitivity analysis of the five hydraulic parameters of HEC-RAS was performed to understand their impact on the model. The results of the sensitivity analysis were used to implement NBS in the model. It was found that considering different NBS effects, such as inundation depth, area, discharge, and surface runoff coefficient, is crucial for accurately simulating their impacts. Validation of the effects is only possible in terms of their magnitude and tendency due to spatial variability, lack of quantitative observations, and limited prior research on hydraulic implementation and combination of NBS. Nonetheless, the simulated NBS effects exhibited a significant reduction in the maximum discharge of hydrographs and surface runoff coefficient values. Combining NBS interventions could reduce these values by approximately 50%. Among the considered NBS, urban forest and bioretention areas demonstrated the largest absolute effects based on the given area characteristics, while check dams and stream renaturation NBS exhibited the largest unit effects.

In conclusion, this research report has demonstrated the implementation of Nature-Based Solutions in a hydraulic (HEC-RAS) model and the corresponding effects. The findings shed light on the relevance of NBS, the effects of different NBS implementations, and the influence of scale and spatial factors on their effectiveness. The next steps should include monitoring and local measurements to further refine the model. Ultimately, this research serves as a stepping stone for future (hydraulic) NBS studies and reveals a promising prospect of using urban NBS as a method to mitigate flood risk.

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1. INTRODUCTION

1.1 CONTEXT

Global human settlement patterns have been changing for the past decades, resulting in the phenomenon of urbanisation (X. Q. Zhang, 2016a). In 2014, 54% of the world's population lived in urban areas. It is expected to increase to 72% in 2050 (X. Q. Zhang, 2016b). This movement of people has a tremendous impact on the way we live. The United Nations consider urbanisation as the defining aspect of our time (UN, 2011). This development leads to transformation of the surface cover that disrupts the hydrological cycle in cities. The construction of impermeable surface layers and reduction of vegetation diminishes the ability to intercept, store and infiltrate rainwater (Zölch et al., 2017). Consequently, the risk of flooding and waterlogging events increases. The estimated effects of climate change, concerning larger rainfall frequencies and intensities, will amplify this risk even more. Thus, urban adaptation and mitigation strategies are necessary to reduce the impact of extreme rainfall events.

Management of urban stormwater has changed drastically from single objective approaches towards integrated sustainable approaches such as Nature-Based Solutions (NBS). NBS could be one of the most promising stormwater mitigation options. By mimicking natural processes NBS aim to control surface runoff in urban areas. This consists of the installation of NBS but also sustainable urban stormwater management technologies (Kõiv-Vainik et al., 2022). According to Somarakis et al. (2019): they are resource efficient by definition, can be adapted to diverse spatial areas and can assist cities in addressing various environmental and social challenges in a more cost-effective manner than grey infrastructure. Most NBS have not achieved wide-spread implementation worldwide since knowledge gaps exist regarding the quantification of designing, implementing and maintaining NBS. Moreover, the most effective NBS differ per region depending on the area's characteristics. This results in a lack of confidence of policy makers to invest in these types of projects.

The African continent experiences one of the largest urbanisation rates. In addition to that, Sub-Saharan Africa is the most vulnerable region to climate change and affiliated hydro-meteorological risks (Enu et al., 2022). This is a combination that could have devastating consequences. In Sekondi-Takoradi, Ghana, the planning system has endured intense criticism for failure to effectively control physical development to reduce flood risk in their major cities (C. Tasantab, 2019). Recurring flooding in cities like Accra, Kumasi, Tamale and Sekondi-Takoradi accentuate this fact. In contrast to Europe, the potential of NBS to mitigate hydro-meteorological risks such as waterlogging is not recognised (J. C. Tasantab, 2019). The application of NBS in urban areas is not systematically explored. Few studies have been conducted focussing on quantification of hydro-meteorological effects (Ruangpan et al., 2020). Even less research has looked into the potential impact of NBS on mitigating flood risks. Therefore, the proposed study aims at investigating the implementation of NBS in a hydraulic model and investigating the impact of NBS on the rainfall runoff during extreme rainfall events in Sekondi-Takoradi, Ghana, with use of a hydraulic model. The hydraulic model (HEC-RAS) from the Hydrologic Engineering Center is used to parametrise NBS and evaluate the impact of them in a selected study area (USACE Hydrologic Engineering Center, 2023b).

1.2 PROBLEM STATEMENT

The growing trend of rapid and unregulated urbanisation is largely responsible for changes in regional hydrology (Pabi et al., 2021). During the last decades the built environment strongly modified the urban hydrological cycle, resulting in fast runoff and waterlogging risks. Sub-Saharan African countries experience flood disasters with a high cost to environment, property and lives (Pabi et al., 2021). Nature-Based Solutions (NBS), that apply green infrastructure by mimicking natural elements, are considered to be a suitable sustainable approach to tackle problems related to urban storm water management (Qiu et al., 2021). However, studies about flood mitigation measures such as NBS are rare. Assessment of NBS is usually performed using a hydraulic or hydrological model. This still requires further research, due to the fact that the results strongly depend on the multiscale space variability of both rainfall and NBS distributions (Qiu et al., 2021). Additional challenges regarding understanding the impact of specific NBS strategies is difficult due to the large influence of specific conditions (e.g., soil type). Lack of field observations on effectiveness of NBS make it difficult for model-based-NBS-analysis to be validated. The usefulness and potential of NBS is addressed in research widely. However, very limited information is available regarding their effectiveness on flood mitigation. For Ghana a limited set of quantitative hydro-meteorological studies have been conducted concerning the effects of rainfall and human activities to runoff dynamics (Pabi et al., 2021). However, quantitative studies concerning the implementation and impact analysis of NBS in urban areas is missing, especially for Sub-Saharan African countries. The two main reasons are the lack of data and the complexity of modelling NBS. Parametrisation of NBS is difficult, especially for hydraulic models. The analysis of possible applications of NBS has just begun (Kvesić et al., 2022). Some assessment approaches have been developed focusing on effectiveness or impact and urban resilience. To promote the implementation of NBS to enhance urban resilience, accurate tools that demonstrate the value of these measures are necessary (Beceiro et al., 2022). This will boost resilient storm water management by helping with the mitigation of waterlogging events.

1.3 RESEARCH OBJECTIVE

From the problem statement it is clear that further research is necessary regarding the implementation and impact of NBS. Models are necessary to show the impact of NBS (Beceiro et al., 2022). To realise this, it is important to depict stream flow quantities (Huang et al., 2020). Consequently, a hydraulic model is selected as a suitable tool. *The aim of this master's thesis study is to quantitatively investigate the effect of NBS on urban runoff due to extreme rainfall and the implementation of NBS in a data scarce region in a hydraulic model*. As application area the city Sekondi-Takoradi (Ghana) is chosen. Previous research from the University of Twente in collaboration with HKV has investigated the implementation of NBS in ***hydrological*** models has been investigated (Van der Zaag, 2022). This research will investigate the implementation of NBS in a ***hydraulic*** model. Streamflow characteristics presented in a hydraulic model such as depth, width of water and flow velocity (and their relationship) are crucial variables for waterlogging events (Aksoy et al., 2016a). The existing HEC-RAS model of the Sekondi-Takoradi study area from HKV will be used because it is well-documented, has a high degree of reliability as well as flexibility for modelling complex scenarios (Huang et al., 2020).

1.3.1 Scope

To be able to effectively investigate the impacts and effects of NBS on runoff in urban areas a clear scope is necessary. This research will only look at the urban area of Sekondi-Takoradi in Ghana. The urban NBS defined in the catalogue of NBS for urban resilience by the World Bank (2021) will be used only. These urban NBS are specified in more detail in the NBS toolbox from Defacto (Defacto, 2022) for a similar area in Kigali. Furthermore, a hydraulic model 2D will be used to compute the effects of NBS. The flow values will be investigated (water depth, velocity, water surface elevation, rate, surface runoff coefficient and flood extent) to evaluate the outcome. Water quality and sediment transport is not considered. HEC-RAS (Windows version 6.3.1.) will be used to perform hydraulic model simulations to assess flood inundation under distinct return periods for current conditions (without NBS) and for several urban NBS scenarios. A network of NBS, rather than isolated strategies, will be analysed to efficiently manage flood-risks (Ferreira et al., 2020). The model will be run for single (extreme) rainfall events, typical for the Sub-Saharan continent. The effects of NBS are investigated for environmental responses to (extreme) rainfall events.

1.4 RESEARCH QUESTIONS

The problem statement leads to the aforementioned research objective. To achieve this objective a main research questions is constructed as follows:

- *"How can the impact of Nature-Based Solutions (NBS) on urban runoff caused by extreme rainfall be modelled for data scarce regions, and what are their effects on the Sekondi-Takoradi area in Ghana?"*

In order to structurally address the main research question a set of six sub questions is composed:

- *"Which NBS are relevant to consider for this study?"*
- *"What is the sensitivity of hydraulic parameters of NBS in a hydraulic model?"*
- *"How can the selected NBS be implemented in a hydraulic model?"*
- *"What are the individual and combined effects of NBS on urban runoff in a hydraulic model?"*
- *"Are there any observed effects available in literature to validate the results?"*
- *"Which generic lessons on NBS can be drawn from this case study?"*

1.5 READING GUIDE

In chapter two, the theoretical background is provided: NBS and the hydraulic model are explained. The third chapter presents the research methods, research model and limitations. Information about the study area is shown in chapter four. This advances to a detailed model description with all the model build-up steps. Chapter six provides the results of this study. It discusses the sensitivity analysis for the relevant urban NBS, which helped for implementing the NBS. Consequently, the individual effects are generated and validated. After this, the combined NBS effects are visualized. Chapter seven discusses the research (results) and provides recommendations for future research. Last but not least, the conclusion as well as the generic lessons are discussed in chapter eight. Appendices contain process related information, and general information.

2. THEORETICAL BACKGROUND

This chapter provides the background information for this research. Nature based solutions and the hydraulic model (HEC-RAS) are described.

2.1 NBS

The increase flood-risk from urban storms is closely linked to the previously described key factors: urbanisation and climate change (Lovejoy and Schertzer, 2013). Approximately 60% of the global population lives in water-scarce areas (Ozment et al., 2015). Climate adaptation and mitigation of urban floods is necessary. Impervious surfaces result in rapid transfer of rainfall into runoff. In urban areas this could quickly lead to watersheds. Expansion of the current grey infrastructure, i.e. drainage systems, is hardly feasible due to costs and its unsustainability in urban areas (Qiu et al., 2021). Studies have demonstrated that increase in urban area, high rainfall intensities and long return periods increase runoff and flow rate (Pabi et al., 2021). A solution is the implementation of so-called Nature-Based Solutions (NBS). To alleviate challenges regarding water supply, waterlogging and waterborne diseases, these NBS could be applied. NBS solutions such as restoration of river connectivity and morphology, creation of polders, drainage management through green infrastructure and modification of torrent controls at headwaters to mitigate hydropeaking are examples of adjustments that can enhance the function of ecosystems during heavy rainfall (Nyika & Dinka, 2022). Their complementary outcomes such as increasing biodiversity, contaminant retention, regulation of soil moisture and groundwater makes them nature-based. The conservation of these resources is essential to balance the hydrological cycle; recharge groundwater, enhance atmospheric recycling of water and regulate streamflow. Which reduces the flood-risk from urban storms.

NBS can be defined as "solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience" (Raymond et al., 2017). This type of solutions is especially efficient for storm water management (European Commission, 2015; Cohen-Shacham et al., 2016). In the past decades a large set of NBS has been identified and classified. In general, NBS are divided into ecosystem-based adaptation (e.g., mangroves or salt marshes) and green infrastructure (e.g., green roofs or permeable paving). Ecosystem services are a common thread for these two aspects, this is about benefits provided by natural environment and healthy ecosystems (e.g., drinking water or air purification). Pauleit et al. (2022) plotted these elements in terms of level of operationalisation (conceptual vs practical) vs breadth (i.e., width) of thematic scope, in figure 1 below.

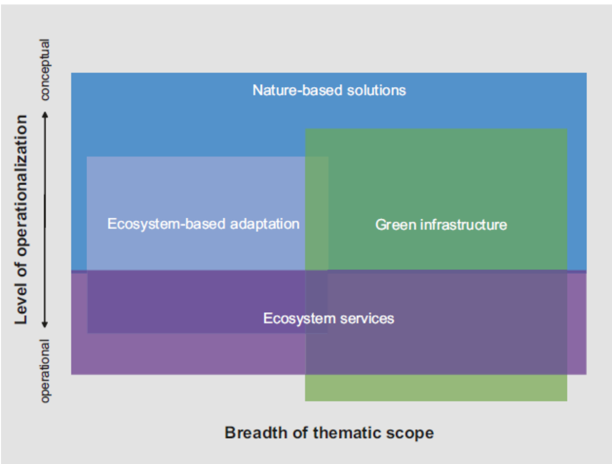


Figure 1 - Illustration of thematic scope and level of operationalisation of four concepts (Pauleit et al.,2022)

The conceptual idea of NBS can be implemented into practice in four ways (Nature Scot, 2023) leading to operational innovations:

- Ecological innovations: creation of new natural spaces, better management of existing spaces and restoration of functional ecosystems.
- Social innovations: changes in governance or culture, contributing to better methods for generating and sharing knowledge about nature in urban areas.
- Technological innovations: projects incorporating product, process and infrastructure innovations.
- System innovations: connecting the three aforementioned aspects to build resilient places by making use of multi-functional NBS applicable to the whole urban area and its inhabitants.

The four implementation strategies can be described in more detail in the form of 15 NBS for urban application according to the World Bank (2021). Figure 2 provides a detailed photographic explanation of the applicable nature-based solutions for urban areas. In practice, not every measure is used as often in urban areas. Bioretention systems, green roofs and constructed wetlands are primarily used for stormwater (heavy rainfall) management in urban environments (Biswal et al., 2022).

Figure 2 - Diversity of NBS for urban areas (World Bank, 2021)

These urban NBS are investigated intensively. NBS are commonly implemented where risks to the living environment occur (UNDRR, 2021). However, NBS are often not implemented at location where the risks are most severe. Most common practices are mangrove restoration, reforestation, urban forest, wetland restoration, agroforestry and conservation of agriculture. These methods are typically useful for floods, extreme heat and drought mitigation. The main applications of NBS are as follows:

Table 1 - Application of NBS according to published articles (Nyika & Dinka, 2022)

Application NBS	Publish Articles
Integrated management of environmental problems	53 (43.1%)
Water security enhancement	20 (16.3%)
Human health	20 (16.3%)
Climate change mitigation and adaptation	11 (8.9%)
Food security enhancement	10 (8.1%)
Disaster risk reduction	9 (7.3%)

In table 1 it can be seen that water related applications are a large share of focus of the total application range according to the published articles. Urban stormwater retention capacity is very important target of NBS. The most common methods are sustainable urban drainage systems (SUDS) (Kõiv-Vainik et al., 2022). The application differs per climate due to climate variability, depending on the conditions. In general, they target stormwater management through water retention and removal solutions such as overland flow, infiltration and evapotranspiration. Most studies focus on green roofs, bioretention systems (rain gardens), buffer and filter strips, vegetated swales, constructed wetland and water-pervious pavements (Kõiv-Vainik et al., 2022). There is a lack of decisive information about stormwater retention and removal capacity of these SUDS. Increasing frequency of extreme precipitation due to climate change leads to higher stormwater runoff. To get an overview of the location of most SUDS per climate the following Figure 3 is provided. The most information about water retention capacity increasing measures can be found about: green roofs, bioretention cells, buffers and vegetated filter strips (Kõiv-Vainik et al., 2022).

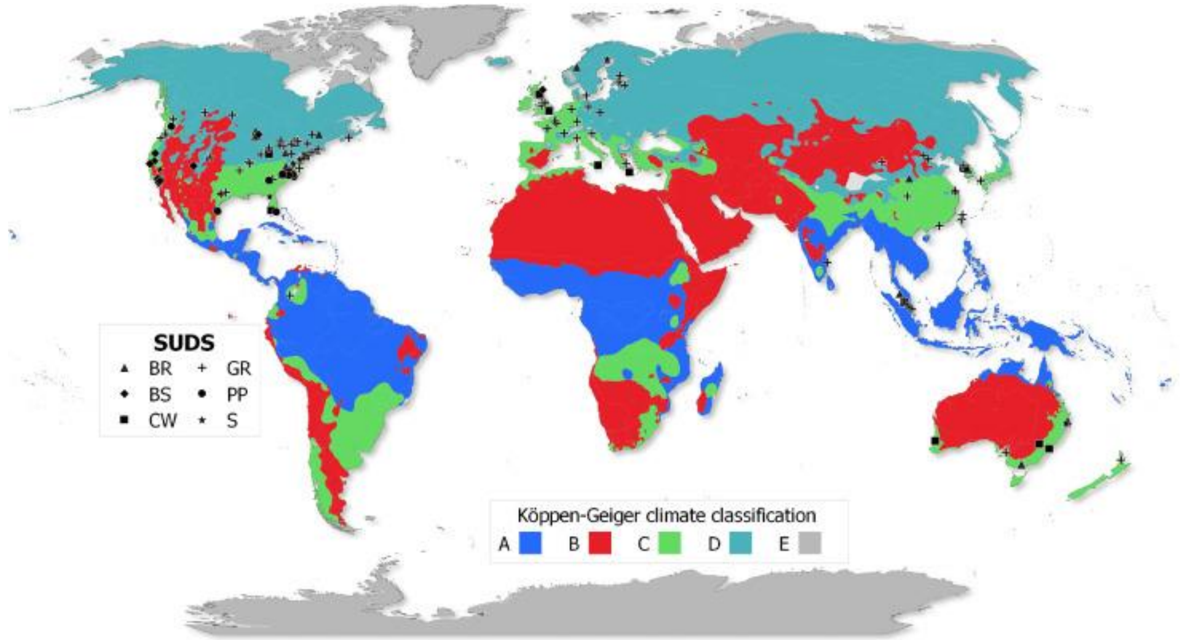


Figure 3 - Location of selected SUDS gathered in our database.

Abbreviations: BR – bioretention cell; BS – buffer and filter strip; CW – constructed wetland; GR – green roof; PP – permeable pavement; S – swale. Köppen-Geiger climate classification: A (tropical, B (arid), C (temperate), D (continental) and E (polar). (Kõiv-Vainik et al., 2022)

When comparing the patterns of the SUDS and climatic conditions there is no straightforward pattern. However, it can be noted that the most quantifiable data is in the warm, wet areas. This probably indicates that they are more commonly implemented in warmer regions that experience a higher amount of precipitation. Consequently, solutions for these areas are important. It is interesting to see what the water retention potentials are all over the world. Figure 4 displays the median water retention capacity (%) for each area. As can be seen in Table 1, there is a large difference in the number of studied materials about SUDS. More studies are necessary to construct guidelines to mitigate climate change and retrieve quantitative data to successfully implement NBS.

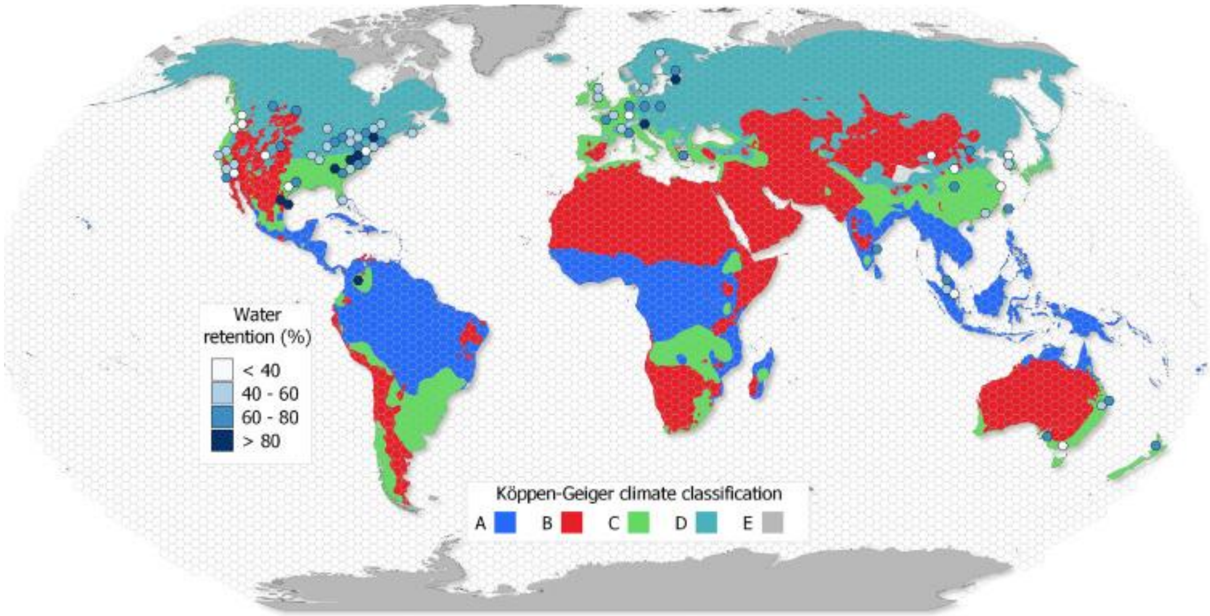


Figure 4 - Median water retention capacity (%) of different SUDS. Köppen-Geiger climate classification (Kõiv-Vainik et al., 2022)

The peak flow of urban runoff is heavily influenced by the spatial variability in rainfall. The more variable rainfall intensities are, the higher the difference in peak flow. The difference in total runoff volume for different NBS scenarios show that spatial variability in rainfall has much lower impact on the difference in total runoff volume (Qiu et al., 2021). To efficiently reduce uncertainty associated with spatial arrangement of NBS, it is advised to mix different NBS in one catchment (Qiu et al., 2021). Isolated implementation of NBS is primarily relevant for mitigation of local flood impacts (Ferreira et al., 2020). A whole network of NBS can be expected to be more effective in mitigating flood risk for a whole catchment. The need for this large scale implementation will grow in the future, given the increase in flood risk due to climate change and urbanisation (Ferreira et al., 2020).

2.2 HYDRAULIC MODEL

In general, numerical hydraulic models make simplifications of the characteristics of hydraulic systems. Some are obvious: 1D models average properties over the two remaining directions, and 2D(H) models must assume depth-average flow properties (Toombes & Chanson, 2011). In 1D models the geometry is primarily described by cross-sections. While in 1D/2D models the geometry is described by detailed bathymetry as well. There are also less obvious simplifications such as the inability of one-dimensional unsteady models to simulate supercritical flow, or the 'water-column' effects of two-dimensional models (Toombes & Chanson, 2011). These effects can cause significant differences between reality and the model. Hydraulic models are most of the time 1D, 1D/2D or 2D models. The water system is incorporated as a network of nodes and lines representing the water system's geometry. In general, 1D models are a lot faster and simpler. But it is harder to correctly simulate the flow through inundated areas. On the other hand, 2D models are more complex, have a higher computation time but show a more accurate simulation flow regarding inundation. Hydraulic models often consist of sub-grid channels on the floodplain that change inundation patterns, increase wave propagation speed, and inundation extent (Neal et al., 2012).

In models, knowledge about the flow path is necessary to accurately model water flow patterns. Most of the time this is not fully known, leading to simplified flow patterns. Fry and Maxwell (2017) indicated that the amount of NBS implemented is less critical than the spatial location of NBS along principal flow paths. Since these principal flow paths are relatively uncertain, effective implementation of NBS in models is hard. In addition, the geometry of the water system is simplified for modelling purposes (Zajkowski et al., 2022). Channel erosion and sedimentation is not considered, only static situations are modelled. Depending on the model, the flow conditions are set to be steady or unsteady which simplifies the real flood wave. In general, there is less density in nodes with information than in real life, causing the exact amount of water volume and flushing route to be less accurate. Despite the fact that input and output water streams influence the water distribution and runoff water volume in a region of interest, this is often not considered. Only a restricted area is modelled without full consideration of influences from the boundary area.

Next to the more general limitations and simplifications, there are more simplifications directly related to NBS. Since NBS are living systems (Mahmoud et al. 2021a), their influence and state change over time. This is not taken into account in hydraulic models. Next to that, seasonality dependency is not used. For example, the effect of forestation are different in the summer than in the winter; leaves have fallen off, influencing the hydraulic conductivity. Moreover, each cell has to have defined soil characteristics. These values consist of a lot of average values and often calculations are done with only one soil layer. Consequently, the hydraulic conductivity of the present soil layers is not represented correctly. The real storage volume is different than in hydraulic models since a simple retention function is used to calculate the duration and volume of the water that can be stored (Rezazadeh Helmi et al., 2019). In addition, the soil characteristics change over time (also during day and night, depending on the seasonality) and this is not incorporated in hydraulic models. NBS measures are implemented uniformly, but in reality, this is not the case since it concerns natural processes and implementations.

2.2.1 NBS effect analysis

There are several types and characteristics of design variables concerning NBS. These variables can be grouped into vegetation-related (e.g. leaf area index, plant species), soil-related (e.g. porosity, organic matter), and physical related variables (e.g. tree pit surface area) (Raymond et al., 2017). These parameters are used in a hydraulic model to model NBS as realistic as possible. In a hydraulic model the following set of variables is important (Ourloglou et al., 2020a):

- Critical depths: a flow characteristic which shows when the flow has a minimum specific energy. This helps determining if a flow is subcritical or supercritical.
- Water level: the height of the water in comparison with the bed level.
- Flow rate/discharge: the volume of water per unit of time.
- Energy line: a line representing the energy head (velocity head and piezoelectric head) of water.
- Froude number: a ratio of gravitational forces and inertia and flow rates, determining if a flow is supercritical, critical or subcritical.

The ecosystem service that is investigated would be the effect on the runoff mitigation. These listed variables are used to assess the most important effects of a flood wave: the inundation area, the total runoff volume and the peak flow. These three values are interdependent and show to what extent the area of investigation is affected by the extreme precipitation. Another important parameter is the friction coefficient since it impacts the discharge velocity and water level. Another point of view could be the water quality status; pollutant accumulated on urban surfaces move into water body’s (Ferreira et al., 2021).

2.2.2 NBS Modelling

In general the proposed approach to assess flood hazard has a two-step process, the first step involves the exploration of topography of the watershed and detection of flood-prone areas by using

GIS support (Aksoy et al., 2016b). Secondly, the flood risk areas are studied with more detail and in the different models which incorporated NBS. There are a lot of modelling methods for NBS, the following Figure 5 depicts the most frequently used models, their working principles, input data, advantages and limitations including some examples (Kumar et al., 2021).

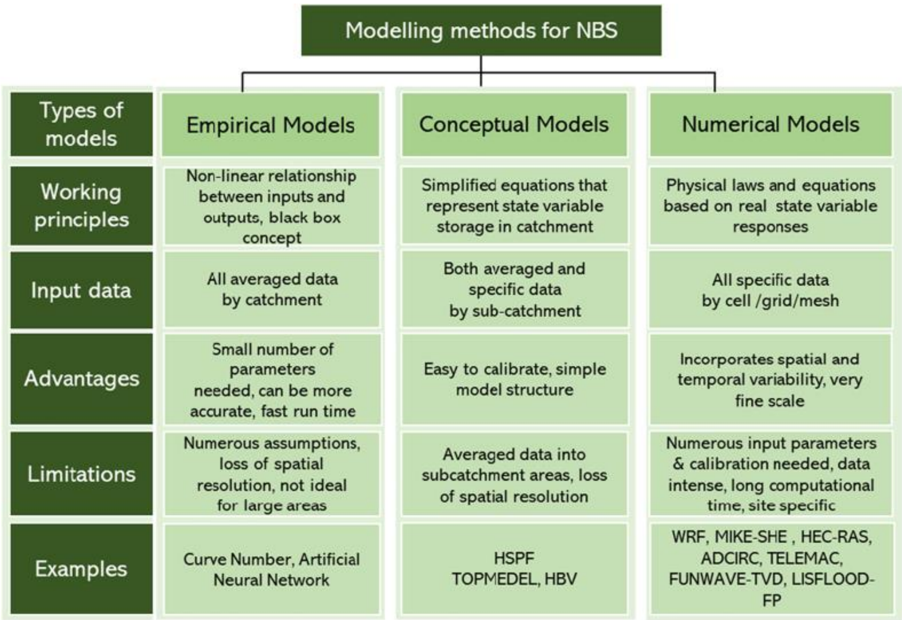


Figure 5 - Modelling methods for NBS with elaborate explanation and comparison (Kumar et al., 2021)

2.2.3 HEC-RAS

The HEC-RAS model of the Sekondi-Takoradi study area from HKV will be used. Because it is well-documented, has a high degree of reliability as well as flexibility for modelling complex scenarios(Huang et al., 2020). In addition, an existing model and modelling knowledge is present at HKV which boosts the initial progress in this research. Moreover, HEC-RAS is well-known for open channel modelling and sloped areas. Models such as SWMM are not able to cope correctly with slopes (Sun et al., 2017).

HEC-RAS explanation

The model consists of a certain file structure. A project file in HEC-RAS encompasses geometry data files, and flow files for a particular river system (USACE, 2001b). A project is broken down into various plans. Each plan represents a "specific set of geometric data and flow data" (USACE, 2001a). Channel geometry data such as survey information, channel lengths, Manning's n-values, contraction coefficients, and expansion coefficients are entered into a geometry file. Discharges and boundary conditions are entered into a steady flow file. Once the appropriate information is entered in the geometry file and steady flow file, the defined plan is run in a steady flow analysis. A diagram illustrating the HEC-RAS outline (Kristin E. Kasper et al., 2005) is shown in Figure 6.

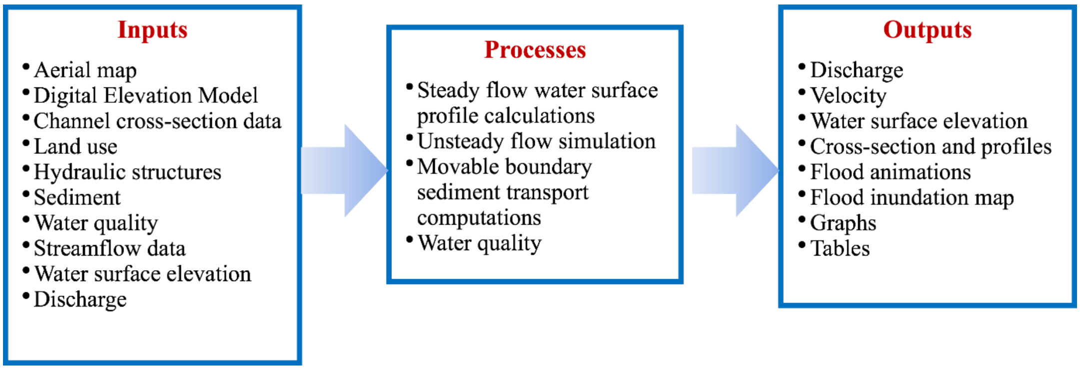


Figure 6 - HEC-RAS model outline

Computations HEC RAS

The basis of a HEC-RAS computation consists of a geometry file and a flow file (USACE Hydrologic Engineering Center, n.d.). Using the flow analysis tool, one can give simulation time windows and computation settings.

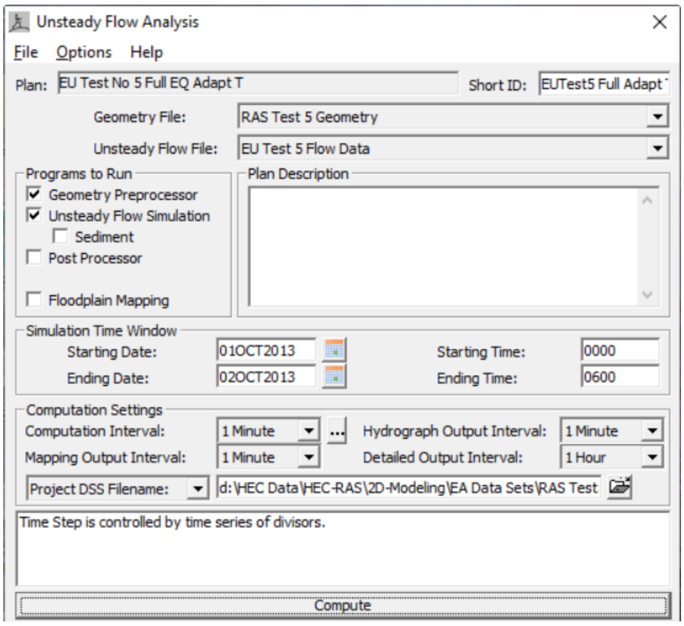


Figure 7 - Unsteady flow analysis figure of the simulation window in HEC-RAS version 6.3.1

The model uses (physical) field measurements of cross-sections of the stream and floodplain to calculate flow values (water depth, velocity, energy, water surface elevation, rate) based on the laws of energy conservation. After computing the results, they can be visualized using RAS mapper. This tool offers the opportunity to display the various outputs of figure 6. The areal data is loaded as well, one can shift through all the maps that are created, e.g. geometry maps such as land cover or soil classification.

3. RESEARCH METHODOLOGY

This chapter describes the used research methods, and visualises this with a research flow chart.

3.1 RESEARCH METHODS

This section elaborates about the research method per research question.

3.1.1 RQ1: relevant NBS

At first, a literature study is performed to obtain general information about NBS, (hydraulic) modelling practices and (similar) field observations. This descriptive research part is addressed in the chapter 'Theoretical Background'. With this obtained knowledge a more refined investigation can take place. The first step is to identify the environmental challenges in the area with help of simulations for rainfall scenarios with a 2 year, 10 year and 25 year return period (T), and reports about the area from HKV lijn in water. In addition, information about the study area is collected using literature and input from HKV professionals that visited the area. This helps in assessing the local context, including land use, topography, hydrology, and climate, so as to determine the feasibility and effectiveness of NBS. Using HEC-RAS (version 6.3.1) suitable locations for NBS and flood-prone areas will be identified by considering the topography of the watershed. This way the potential NBS options are identified with the local context and environmental challenge as input.

3.1.2 RQ2: sensitivity hydraulic parameters

For numerical analysis, the HEC-RAS programme software is downloaded from the official Hydrologic Engineering Centre. HEC-RAS does not have a built-in capability for implementing NBS, however it is possible to use it as a tool to evaluate the effectiveness of NBS. The hydraulic model from HKV is used as a basis for this study. This model covers a larger catchment area and consists of only a few land cover and soil characteristic values. By examining literature, satellite images, geographical information and HKV visit reports, the local context is analysed. The existing model from HKV is refined and upgraded with the information found about the local context. After increasing the accuracy and detail of the model, the influential parameters are determined. The most influential model parameters are evaluated for the study area catchment by changing them to the maximum and minimum value that is realistic in the study area. This is examined in order to see the maximum and minimum effects that can occur in the study area. By looking at the inundation maps (water depth and inundation area) for a first ranking is made. After that, a more detailed sensitivity analysis is performed by also looking at the hydrographs (discharge over time) in the area. With this information, more feeling for the model is developed and this is used as input for the implementation of NBS by adjusting model parameters. In the end, the sensitivity analysis also helps to check if simulated NBS effects are in proportion.

3.1.3 RQ3: NBS implementation

The list of relevant NBS is translated to hydraulic model parameters using literature. A visit to the Green Village and the sensitivity analysis help to assess if the effects are consistent with the known information about the effects and implementation. There are a lot of different sizes, scales and characteristics possible per NBS. A rather conservative approach is chosen as input for the parametrisation: average (or just below average) NBS characteristics are used to prevent overestimation of for example infiltration capacity. Information from literature helped to find logical model parameters, the characteristics of the study area determined what type of NBS is possible at which location. The information form the sensitivity analysis resulted in relevant locations for placement of the NBS.

3.1.4 RQ4: individual and combined effects of NBS

After implementation, the individual NBS are simulated with help of HEC-RAS for a short rainfall (3-hour) scenario with a 10 year return period. This return period is most common for evaluation of NBS (Hamers et al., 2023a), more information is provided in section 5.1. A short rainfall period is chosen since the impact on the catchment is larger for a shorter, intense rainfall period than for a longer, less intense rainfall period. In addition, this reduces computational time. Effects are measured in terms of the inundation area, inundation depth, surface runoff discharge, and surface runoff coefficient. Classification of effects is not considered since this study only quantifies the effects of NBS. After simulation of the individual NBS and assessing their effect on the aforementioned four characteristics, the NBS are combined. A set of combination scenarios is created based on the individual NBS results to prevent unnecessary simulations.

3.1.5 RQ5: observed effect in literature

The obtained quantitative data (e.g., depth-flow relationships) will be put into perspective. Earlier research from HKV gives a start for a literature search about the observed effects of NBS in literature. In addition, via connections from HKV additional parties are contacted which have some information. Since real-world measurements cannot validate the presented hydraulic results, research from other NBS studies is identified which help to give them some context.

3.1.6 RQ6: generic lessons

After addressing the previous research questions the specific outcomes are translated to generic outcomes. These are stated in the conclusion. Mainly results from the sensitivity analysis, implementation, individual and combined effects will generate generic lessons. This will help future research about NBS in urban areas. The generic lessons can be used as guidelines or starting principles.

3.2 RESEARCH MODEL

Figure 8 shows a comprehensive draft overview, made in draw.io, of all major steps included in the research process. The process is depicted using a flow chart. Some simplifications are done to make it a more coherent and understandable structure, and a legend is included to show the format of the various inputs, outputs and steps.

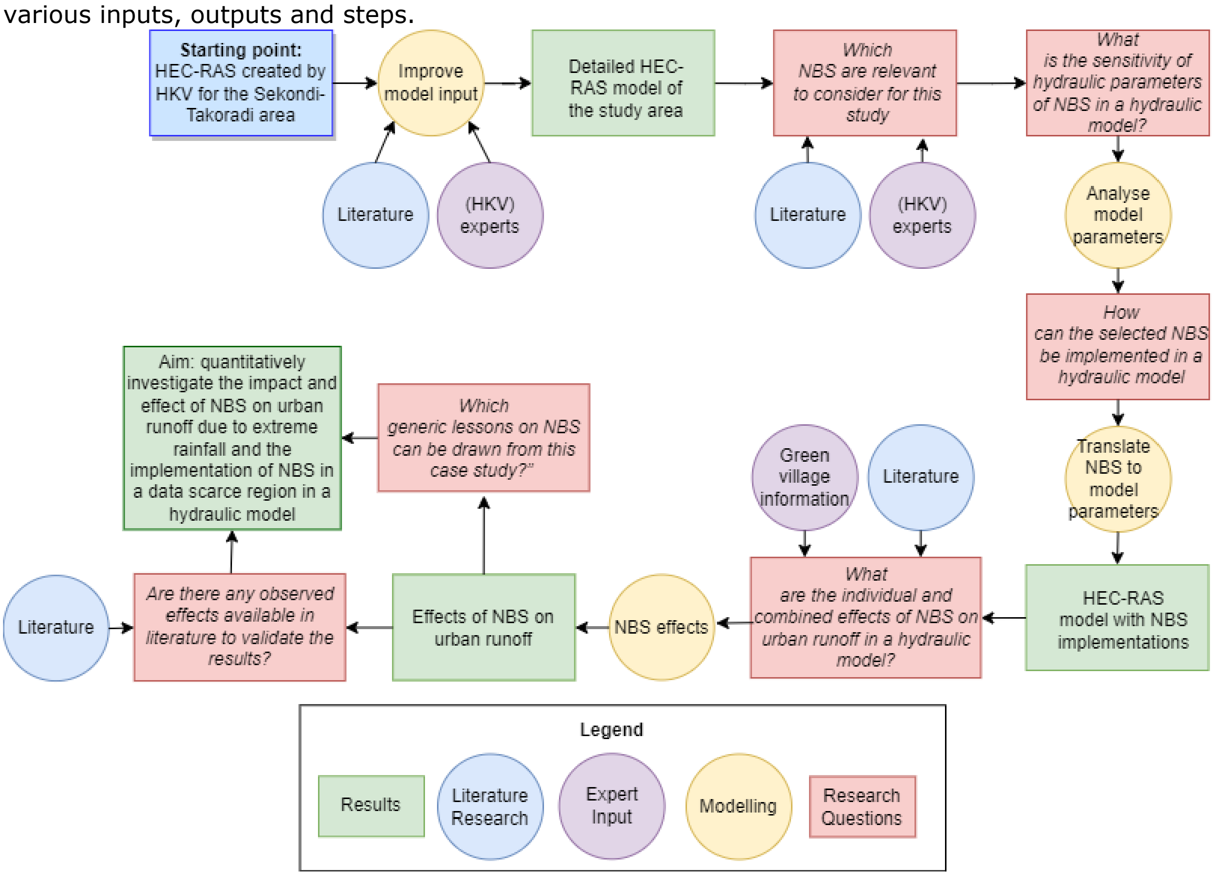


Figure 8 - Flow chart of the different major research steps

4. STUDY AREA

Before the HEC-RAS implementation and evaluation of NBS can take place, some background about the study area is provided to understand the area and problems. First the general information is discussed, thereafter the flood genesis of the study area.

4.1 GENERAL INFORMATION

This section will elaborate on the study area itself, a small-sized catchment in the city of Sekondi-Takordi. At first some information about Ghana itself is provided, secondly the city itself is described and finally the characteristics of the catchment are presented.

4.1.1 Ghana

Ghana is located in western Africa on the Gulf of Guinea. Bordered by Burkina Faso, Togo, and Cote d'Ivoire. Relief throughout the country is generally low; elevations do not exceed 900 metres. Most soils are formed from parent rock material that has been exposed to prolonged erosion and consequently has limited fertility (Boateng et al., 2023). The intrinsic poverty in nutrient of soils cause a heavy dependence of the vegetation cover (Boateng et al., 2023).

There are three major geographic regions; coastal, forest and northern savanna. The coastal zone is the smallest region but has more urban centres than any other region in Ghana. In 1980 around one-third of the population was located in urban areas. But a steady increase of migration toward urban centres results in the fact that currently more than half of the population resides in urban centres. Its population is about 29.6 million in 2018 (World Bank, 2022).

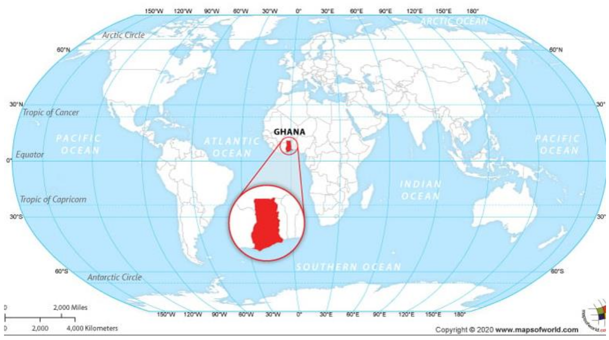


Figure 9 - Overview of the position of Ghana on the globe (Map, 2023)

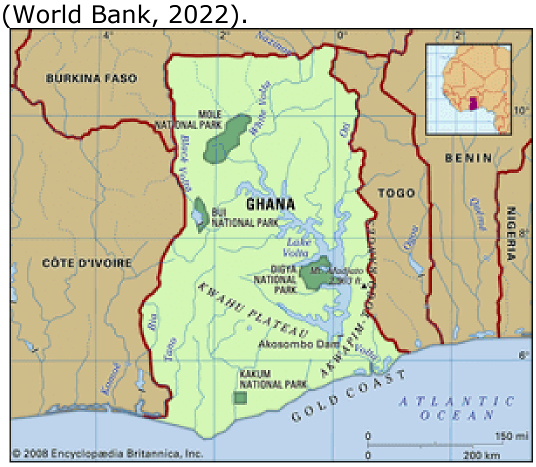


Figure 10 – Ghana in more detail (Boateng et al., 2023)

4.1.2 Sekondi-Takoradi

The Ghana Statistical Service (Ghana Statistical Service, 2014) describes the metropolitan area in more detail. The city is a mix of old and new buildings on a hilly site extending to the seashore where approximately living 260,635 inhabitants in the city in 2022. Two breakwaters enclose 90 hectares of sea with berths and loading facilities (Britannica, 2023). Discovery of oil led to substantial land-use change between 2007 and 2016. Farmlands, open forest and closed forest were converted into built-up areas (Adjei Mensah et al., 2019). In total, the metropolitan area is 191.7 km^2 in 2022. The Sekondi-Takoradi metropolis is located in the south-eastern part of the Western region, see Figure 11. The Atlantic Ocean is at south of the metropolis.

The landscape varies a lot. The coast has capes and bays which have been eroded largely. The central portion of the area is low lying and has an altitude of about 6 metres below sea level covered with ridges and hills. The faulted shale and sandstone resting on a foundation of granite, schist and gneiss is characteristic for the area. The faulting system clearly marked the area, especially the coastline which follows the direction of Northeast. The two main rivers flowing through the area are the Whin and Kansawora, coming from the Essei and Butre lagoons above the metropolis. The drainage pattern consists of different networks in nature in the form of small 'tree' or 'dendrite' branches.

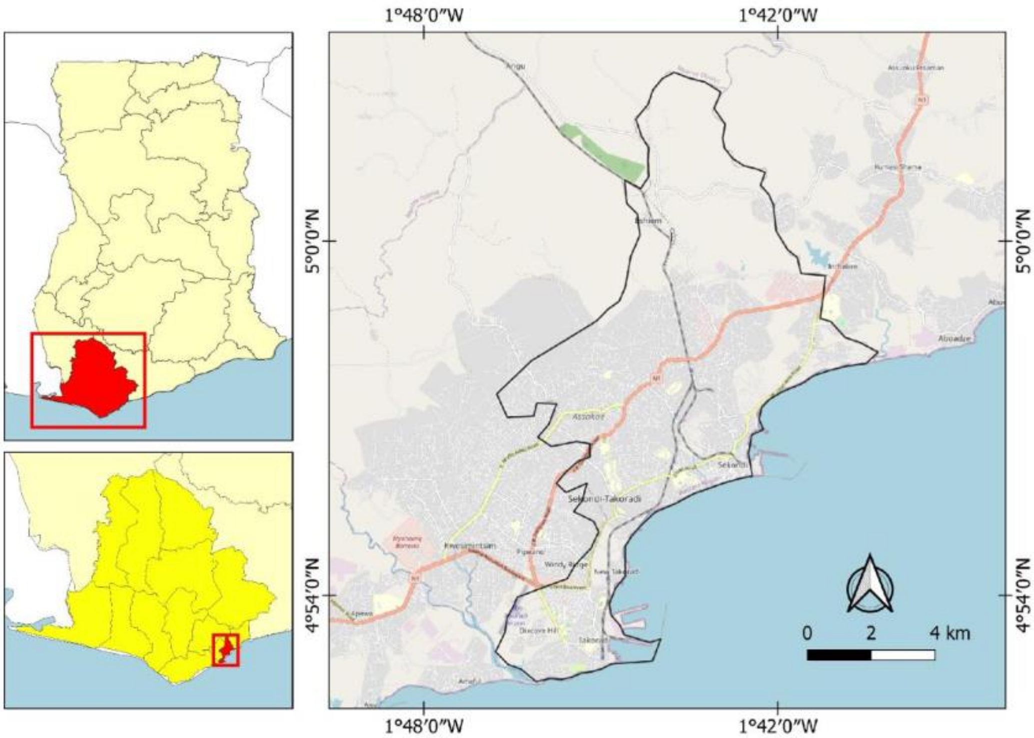


Figure 11 - Sekondi-Takoradi metropolitan area (Kussaana & Mabe, 2016)

4.1.3 Climate Problems

African cities deal with acute water flooding problems (Oiro et al., 2020). Recurring floods in cities in Ghana (e.g., Accra, Tamale and Sekondi-Takoradi) underline the necessity of mitigating floods. In Ghana, 80% of the disasters are climate-related (Pelicaric et al., 2013). These hazards are expected to increase in frequency and magnitude (Forzieri et al., 2018). Studies recommend creation of NBS awareness and better financing of these projects to supplement research in these countries (Nyika & Dinka, 2022). The national government is searching for solutions by establishing measures to protect livelihoods of vulnerable areas to climate-related risks (Echendu & Georgeou, 2021). Still, risks are continuing to be created by land use practices (Echendu & Georgeou, 2021). Different coping strategies are evaluated. Most of them focus on adaptive measures. While preventive measures are better. Human activities such as dumping waste in the river, dumping ponds and river streams, obstruct the drainage capacity of the urban environment (Danso & Addo, 2017a). The city of Sekondi-Takoradi is expecting more and more problems in the near future. Therefore, they are investing in coping strategies to avoid risky situations (Danso & Addo, 2017a). Lack of capacity in institutional organisations results in delays in permits approvals, non-compliance with regulations, uncontrolled conversion of vegetated land, lax monitoring of physical development and poor enforcement (J. C. Tasantab, 2019). Land owners evade building and lands use regulations, creating flood risk since they build in swamps, waterways and other flood prone locations (J. C. Tasantab, 2019). It is necessary to address this policy but also make the current situation safe.

4.1.4 Land cover

The study are has experienced extensive land cover changes with an annual rate of land cover change of 1.77%. From the study it was realised that, for the past 17 years, the Sekondi-Takoradi metropolis has seen dramatic urban expansion and this has resulted in the loss of non-urban lands such as farmland and forestland, hence altering the characteristics of the land surface in the metropolis. Urban expansion was identified as the main cause of the Land use/Land Cover (LULC) changes in the metropolis.

An urban development model showed that in the next 50 years if the trend of land use change continues, there will be complete removal of natural surfaces. These could lead to increased incidence and severity of flash floods and droughts. Therefore the data produced in this study can be used to guide effective urban planning to mitigate the combined effects of land use changes due to urbanisation and climate change (Aduah & Baffoe, 2013).

4.1.5 Geographical aspects catchment

In the city of Sekondi-Takoradi there is one particular area of interest for this study. A small-sized catchment in the Sekondi region. This area is selected due to a few reasons:

- **Comprehensive size**. The surface area is 1.16 km^2, which makes it relatively easy to model and to oversee
- **Confined area.** All rainwater in this region will stay in this region and end up in the sea or soil. There is no inflow from other catchments; the region is hydrologically isolated.
- **Dense urban environment.** This is a typical African city that has to deal with extremely urbanized areas.
- **Various geographical aspects.** The area has different elevation levels, land covers, geometry.
- **Waterlogging problems**. In this area excessive water results in severe waterlogging events.

The catchment is displayed in the following Figure 12. The black rimmed polygon indicates the catchment on a satellite map of Sekondi-Takoradi in Ghana.

Figure 12 - Satellite map of Sekondi-Takoradi with the catchment location

To get a glimpse of the characteristics of the area itself, the following Figure 13 displays a hybrid map with the catchment indicated by black lines. It is visible that especially the southern part is more densely populated than the northern part.

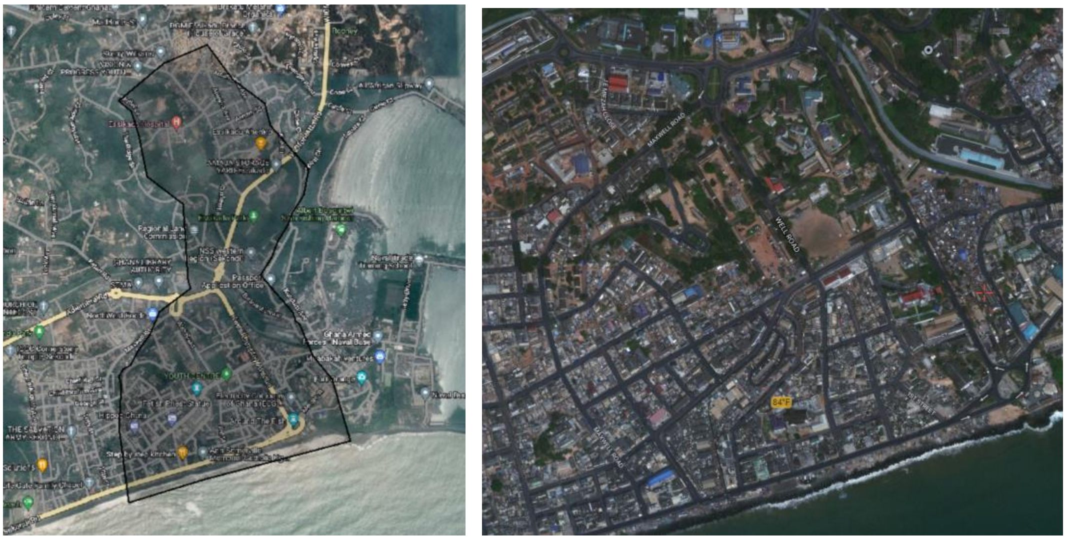


Figure 13 - Urban characteristics of the catchment

In addition, the following map shows the elevation of the catchment. The northern part has the highest elevation levels. There are areas which are located 35m above +NAP. From North to South the terrain slopes towards the sea. The terrain in the bottom part of the catchment is located a lot lower, with terrain levels between 0.5m and 10m above +NAP.

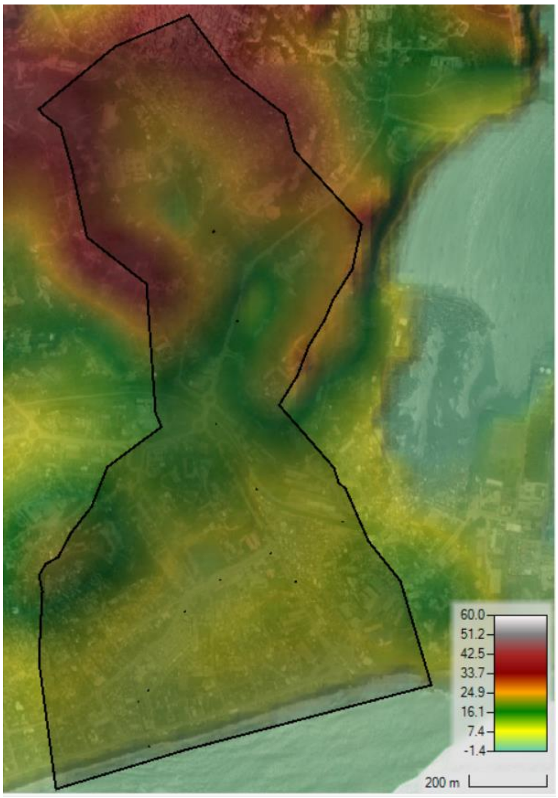


Figure 14 - Elevation map of the urban catchment in Sekondi-Takoradi

4.1.6 Land Cover

The catchment consists of urban area for the largest part. In figure 17 six main land covers are depicted. It can be seen that more than 75% consists of urban area. The remaining percentages consist of vegetation or bare area. Noteworthy, this figure is from 2013. Almost ten years later the urbanization has increased even more, reducing the presence of vegetation and bare area. The expansion possibilities near the coast were limited to bare areas and vegetation. In other words, these land use types experienced deficits and were converted mainly to built-up area. This change is implemented in the model based on satellite info, as will be explained in section 5.2.

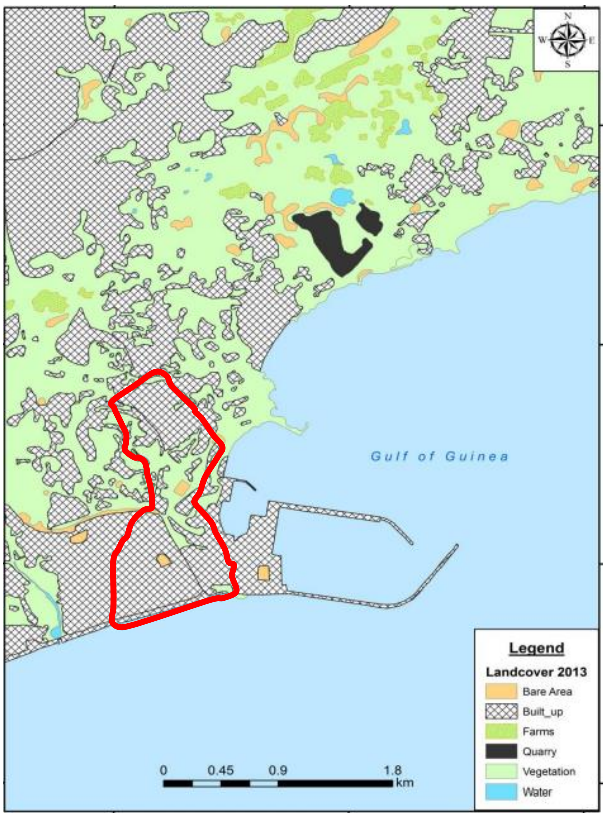


Figure 15 - Land cover map of the Sekondi-Takoradi region

4.2 FLOOD GENESIS

This section addresses the meteorological status of Sekondi-Takoradi and some details of flood history to provide background of study area. In addition, it underlines the necessity of change (for example by NBS) in the study area and other similar urban environments.

4.2.1 Meteorological

The climate is largely determined by the hot, dry continental air from the Sahara and the humid, maritime, tropical air mass that forms above the South Atlantic. Continental air moves southward to the coast; the Harmattan, and maritime air moves northward. The convergence zone is characterised by seasonal patterns. Rain occurs when the dominant air mass is the maritime air and vice versa. The climate is equatorial with an average temperature of 22°C. The mean annual rainfall is 1380mm per year, on average there are 122 rainy days (Kussaana & Mabe, 2016). Rainfall is bi-modal, with the largest wet season occurring between March and July and the smaller wet season between August and November (Dadzie-Paintsil & Mensah, 2022). During the first rain season the most severe precipitation events occur, as can be seen in Figure 74 in appendix 10.1.3. There are events where in a short period of time 50-100mm will fall. These events will lead to flood events because the current environment is not able to cope with these amounts of water.

4.2.2 Flood history

Despite the availability of the state policies to curb flooding, the country is struggling to lessen flood related hazards, especially in the urban zones (Ahadzie, 2011). Suburbs within Accra, Kumasi, Cape Coast and Sekondi-Takoradi get flooded during the rainy seasons (Yeboah and Aklorbortu, 2009) (Danso & Addo, 2017b). The following rainfall events affected the area:

- Flash floods affect the capital Sekondi-Takoradi on 01-06-2019 (Ina-Thalia Quansah, 2021).
- Parts of Sekondi-Takoradi flooded after downpour on 23-04-2020 (Ghana Guardian News, 2020)
- Several hours of downpour leave part of Sekondi-Takoradi flooded on 30-06-2021 and 25-02-2023 (Antwi, 2020).
- Residents are worried over perennial floods on 12-06-2021 (Opera News, 2021).

In appendix 10.5 some floodmarks in the catchment area can still be seen. They are indicated as black marks on the buildings.

4.3 FLOOD IMPACT

As seen in section 4.1.2 the terrain elevation varies severely across the catchment. There are a few low-laying spots to which the water drains. The water from the higher altitude areas will flow towards the lower elevations. Most of the water will end up in the bottom part of the catchment. In Figure 16 the arrival time of water with a threshold of 0.1m inundation depth can be seen. It appears that there are three spots, in relatively flat areas surrounded by steeper slopes, which experience the fastest arrival time. As can be seen in a T=10 situation, especially these areas show the largest water depths. It is clear that the flood impacts a large urban area in this case study.

Figure 16 - Duration before water depths exceed 10 cm per location

Figure 17 - Maximum water depth after a T = 10 rainfall event

In 2022 the company HKV lijn in water investigated the damage due to the presence of excessive water in this area with use of a damage model. They modelled a rainfall event with a return period of 10 years, which resulted in an inundation map for the area depicted in Figure 17. By applying a damage formula, estimates of the impact of such an event could be made. The results are visualized in Figure 18.

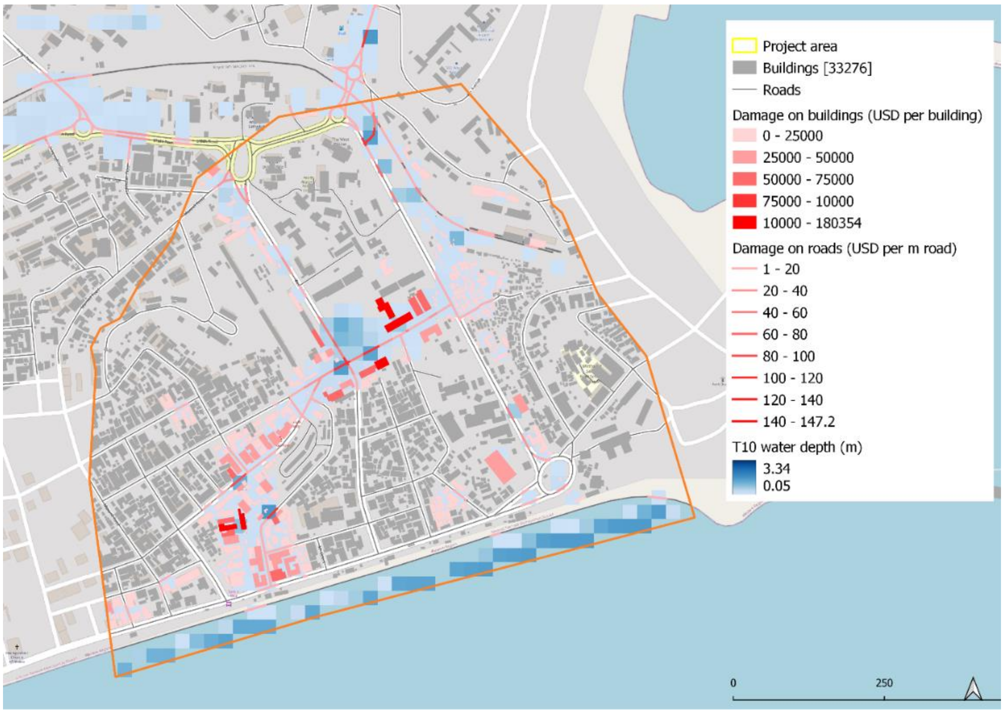


Figure 18 - Damage map for the southern part of the catchment (Sharma et al., 2023)

The largest damage occurs in the centre of the lower part of the catchment. This is the lowest area of the whole catchment, and the most urbanised area. In appendix 10.1 one can see the impact of the waterlogging events on the houses. The floodmarks indicate how high the water has risen during earlier flood events (see also the section 4.2 about flood genesis).

5. MODEL DESCRIPTION

As a basis, a HEC-RAS model of Sekondi-Takoradi from HKV was used (HKV lijn in water, 2023). This model consisted of a DTM, and limited land cover and soil characteristic data. Output is validated by field visits. This model was upgraded with use of more detailed information to get results close to reality for a smaller catchment of the original model. In this section this upgrade of the model is described. HEC-RAS version 6.3.1 was used for all modelling steps. In general the main handicap for the improvement of flood management in developing countries, especially Africa, is the lack of hydrological and meteorological data (Cea et al., 2022). However, the increasing satellite remote sensing data made available by NASA, ESA and JAX helps. This data includes digital terrain models, quantitative precipitation estimations, land use and soil types. The land cover and terrain can be derived from GDEMs and land cover maps. Hydrological soil groups can be obtained from the Global Hydrological Soil Groups 250m global data set (Ross et al., 2018) provided by the Food and Agriculture Organisation (FAO) harmonized World Soil Database.

5.1 INPUT

HEC-RAS uses different model inputs which are discussed in this section.

5.1.1 Geometry

As digital terrain model (DTM) the Airbus WorldDEM with 24m resolution is used. ALOS DTM, JAXA and FABDEM from Fathom were investigated but did not significantly improve the quality (HKV lijn in water, 2023). The basic HKV model consisted of a larger catchment of part of the Sekondi-Takoradi agglomeration and a smaller catchment (Figure 19). For this study the smaller (blue) part of the DTM is used, indicated in Figure 20. To this grid the known drainage channels were added (Figure 21). As input the measurements from the HKV field trip in 2022 were used. Moreover, 2021 Google Satellite data and the Sekondi-Takoradi Metropolitan Assembly (STMA) report were used. The depths below the DTM were estimated based on the drain size obtained from field visits by HKV (HKV lijn in water, 2023). At locations where the terrain rises in the opposite direction of the drain flow, a straight line was assumed by HKV (HKV lijn in water, 2023). Noteworthy, the last 20 meters of the drainage near the sea (bottom) are located underground in reality. Due to model limitations this underground drainage part is represented by a deep slit in the DTM since a workaround such as pipe drainage is not directly implementable. The DTM is sloping towards the sea at those locations, so no additional water is pouring in those slits. Therefore this representation of reality is suitable enough to pursue modelling. Structures such as housing are not considered in this DTM. Explanation about how these structures are incorporated can be found in section 5.2.1.

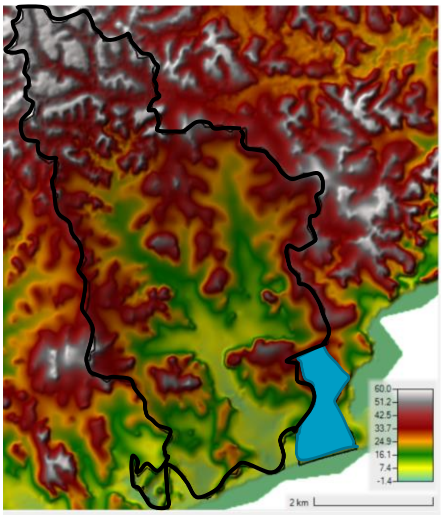


Figure 19 - Original DTM, with blue indication of the used catchment area

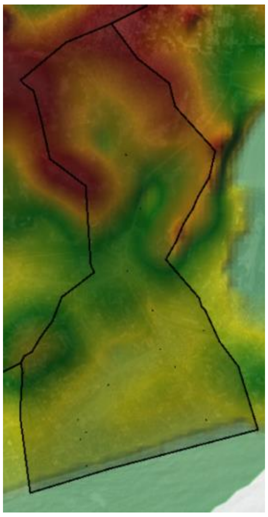


Figure 20 - DTM of the used catchment for this study


Figure 21 - DTM with drainage systems incorporated

5.1.2 Refinement

The computational mesh is generated for a larger area than the catchment itself. This is to ensure that if there is a small mistake in perimeter of the catchment this will not result in false results. Every drop of water will now flow in the catchment. Break lines are added as well since they play an important role during flood propagation, positively enhancing the model performance (Ongdas et al., 2020). To improve accuracy, a refinement grid (red area) is applied around the centre of the catchment. This is a computational mesh with a 10m resolution (red coloured area in Figure 23) which ensures more accurate calculations.

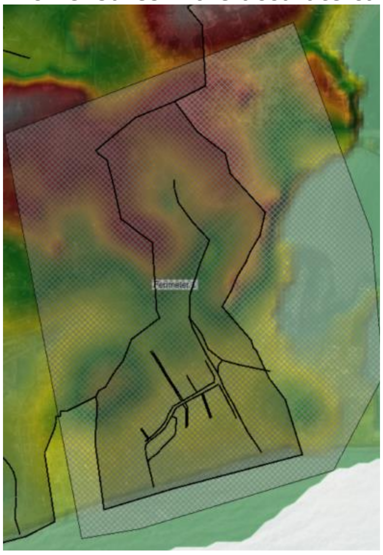


Figure 22 - DTM with computational mesh (grid size 24m)

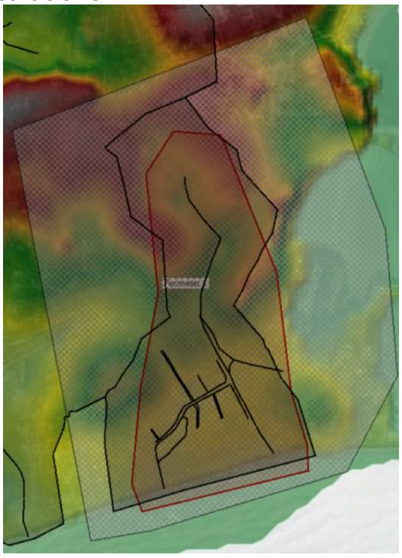


Figure 23 - Addition of the refinement grid (red)

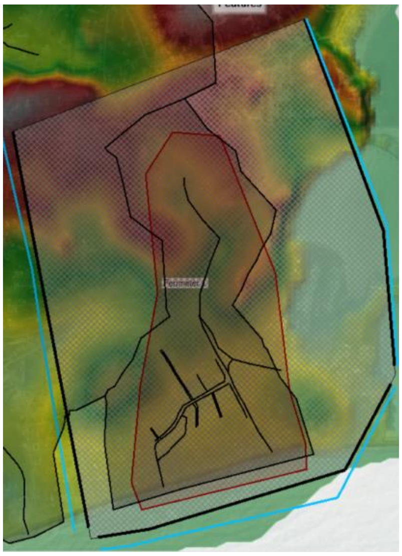


Figure 24 - Addition of the boundary conditions (blue)

5.1.3 Boundary conditions

In addition, three boundary lines (blue) are inserted in the model (Figure 24). The left and right boundary condition are a normal depth boundary. It represents the energy slope to calculate the normal depth with manning's equation. These values are mostly unknown and are approximated by using the channel slope or water surface slope. The lower the slope, the less backwater concave effects (Vadyman, n.d.). The friction slope value for both boundaries is set to 0. This assumes that the water surface elevation at the boundary is the same elevation as the downstream boundary. There is no change in water surface elevation due to frictional resistance along the boundary. This value is typically used at the end of a water surface catchment. Because the slope changes at every point along the BC line, so there is no obvious value to use. The borders are generally far away enough from the region of interest so that they do not have an effect on it. And the these locations are not the most important BC, that is the downstream/outflow boundary condition at the sea.

The bottom boundary line is related to the sea level. The tides of the sea will have little effect on the catchment since it lays lower than the catchment (Cleaner Seas Group, 2023). Water levels vary, for the worst conditions: high sea level = GMT+1.6m and for the best conditions the low sea level = GMT-0.06m (Cleaner Seas Group, 2023). To be safe, a boundary value of 1.6m is taken for the bottom boundary condition at the border of land and sea. The last 'boundary' condition is the rainfall distribution, described in the next paragraph.

5.1.4 Rainfall distributions

A hyetograph is a graphical representation of the distribution of rainfall over time. It is usually represented by a bar graph showing rainfall amount versus time. In this area, there are only daily rainfall records available from STMA. These datasets do not provide enough information about the short rainfall durations for which the catchment is vulnerable. Therefore the following design storm hyetographs are used, which are constructed by HKV (HKV lijn in water, 2023) for analysis of the Sekondi-Takoradi region.

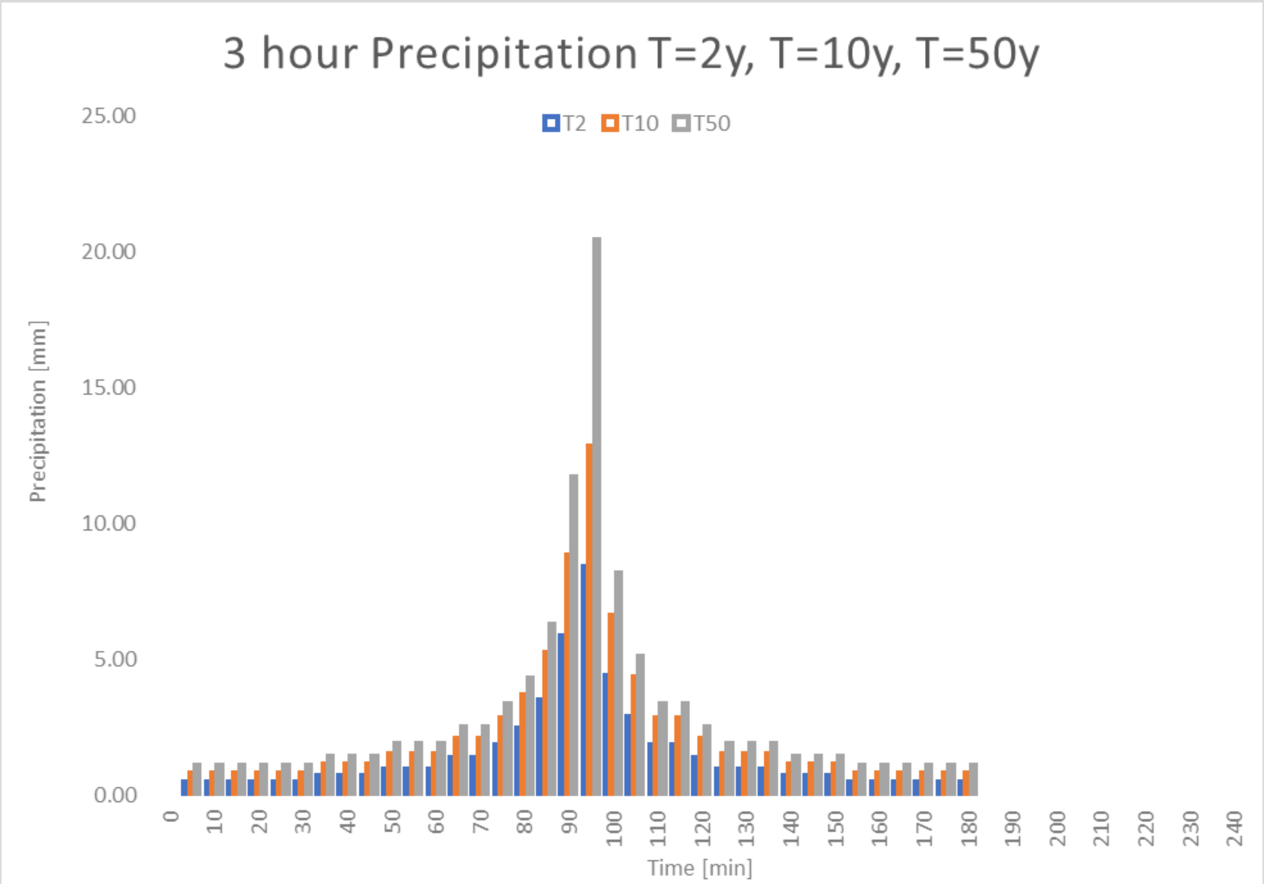


Figure 25 - Precipitation events of 3 hours for T = 2, T = 10 and T = 50

From literature, it is observed that spatial variability in rainfall has very low impact on the difference in total runoff volume (Qiu et al., 2021). Moreover, there were no rain gauges in the area present to distinguish spatial rainfall variability. In addition, the catchment is small (1.16 km^2). Consequently, a uniform rainfall distribution is assumed. By applying the alternating block method to measured intensity duration frequency (IDF) curves the hyetographs were made. This provides a design storm event for an event of a given return period. The presented hyetographs are incorporated in the model for the modelled catchment using rain-on-grid (ROG) modelling. In particular, the T = 10 situation is useful for comparison later on since this is the most common return period that is used for NBS simulations (Hamers et al., 2023b). Short duration rainfall distributions are used since the catchment is vulnerable to these types of events (HKV lijn in water, 2023).

5.1.5 Necessary layers

For 2D HEC-RAS rain-on-grid (ROG) modelling (Krest Engineers, 2021) there are three necessary layers listed below. These individual layers and the incorporated parameters are discussed in more detail in the next sections.

- Land Cover layer: mostly created from National Land Cover Database (NLCD) land cover raster files, providing manning's n value and impervious percentage. No infiltration occurs on a impervious surface.
- Soil Layer: defines soil textures or hydrologic soil groups from a Soil Survey Geographic Database (SSURGO).
- Infiltration Layer: created by intersecting the land cover layer and soil layer with an infiltration method.

5.2 LAND COVER

In the basic model there were only five land covers in area of the catchment: open water, mixed-use, residential, building footprint, and industrial. By studying the satellite images, aerial photos and urban development reports (Stemn & Agyapong, 2014) several land covers were added and implemented in the model. The final result can be seen in Figure 27.


Figure 26 - Original land cover layer from HKV in HEC-RAS


Figure 27 - Updated land cover layer

The list of land covers is specified by two classification parameters: the manning's n value and the impervious percentage. These are described in the next two sections. All the land covers included in the model are:

Table 2 - Land cover table with manning's n values and impervious percentage

Nr.	Land cover	Manning's n values [$\mathbf{m^{-1/3}\ s}$]	Impervious [%]
1	Drain	0.020	100
2	Building footprint	0.30	100
3	Asphalt road	0.016	90
4	Concrete	0.017	90
5	Bare	0.018	25
6	Mixed forest	0.120	15
7	Bushes	0.060	10
8	Grass	0.040	5
9	Artificial pitch	0.027	100
10	Open water	0.035	100
11	Breakwater dam	0.100	40
12	Residential	0.030	65
13	Mixed land use	0.038	50
14	Industrial	0.030	75

5.2.1 Manning's n values

The manning's n values are a value that represent the roughness of a land cover layer. Most of the values are generic values taken from the HEC-RAS manual or from Chow (1959). The different values are changed due to the characteristics of the region. Drains in this area are not finished with a trowel and consist of a relatively rough surface (Kalyanapu et al., 2009). In addition, there is a lot of debris and waste in the drains which also increases the roughness, as can be seen in appendix 10.1. So a n value of 0.013 or 0.015 is not realistic, the value of n = 0.020 is closer to reality (The Engineering Toolbox, 2004). For the artificial pitch, the average pitch grass is taken as a roughness value (Graf & Chhun, 1976). The bare area consists mostly of hard material (rock underneath) which is not very permeable, so a value of 0.018 is taken (Krest Engineers, 2021).

Building incorporation

There are a few methods to incorporate buildings and structures in a hydraulic model (Schubert & Sanders, 2012):

1) Building-resistance (BR) method. Where a larger resistance parameter value is assigned to building footprints cells.
2) Building-block (BB) method. Elevation data are raised at building footprints to the height of the rooftops. Buildings appear as blocks.
3) Building-hole (BH) method. Holes in the computational mesh are aligned with building walls, and the free-slip boundary conditions is enforced.
4) Building-porosity (BP) method. Spatially distributed parameters including porosity and building drag coefficient are introduced to model the impact of buildings.

For the HEC-RAS model the first method is selected since no detailed building geometry data is available. BB, BH and BP methods require detailed grids (< 5x5m), BR can be used with any type of computational grid(Schubert & Sanders, 2012). On top of that, it is relatively the easiest method to implement and it is capable of a fast execution. Especially in urban areas this method is reliable according to a studies of Beretta et al. in 2018. Simulating flow depth and flood inundation extent with the BR method provided no significance difference with the other methods. Downside of the BR method is that it is still a bit less accurate. However, this is particularly the case with respect to velocity prediction. Which is not most essential for this study. A powerful aspect of BR is that the predictions of flood extent, depths, velocity and stream flow are not very sensitive to the manning's n values (Schubert & Sanders, 2012). Moreover, the inside of the buildings can still be flooded in this case so this gives a better inundation map than the BB method for example. Consequently, the BR method is used. These literature findings support use of n_m = 0.3 $m^{-1/3}$ s as recommended the US Army Corps of Engineers (McMahon, 1981). Figure 28 displays the building footprints.

Figure 28 - Building footprints (in red) of the whole catchment

Accuracy
One method to increase the accuracy of your maps in a data scarce region is the implementation of roughness coefficients with smaller grid size than the grid itself. Adjusted roughness coefficients help compensating for inaccuracies due to an undetailed geometry (Berreta et al., 2018). Consequently, the implementation of the manning's n values is a good step towards a more accurate results.

5.2.2 Impervious percentage

The impervious percentage is the percentual part of a land cover that is not penetrable for water. Precipitation and infiltration features are used so this parameter is necessary because it largely determines the runoff (USACE Hydrologic Engineering Center, 2023a). When the impervious percentage parameter is increased, the effective infiltration capacity of the soil is reduced. Impervious percentage values are taken from a open file report about quantification of impervious surfaces (Tilley & Slonecker, 2007). The impervious percentage of an area is only included here, not in the Curve Number. This gives more accurate, physically based results (USACE Hydrologic Engineering Center, 2023a).

5.3 INFILTRATION METHOD

The infiltration method is one of the most important features of the model. Infiltration is a measure of how much rainfall can be absorbed by the ground without running off. There are two other options in HEC-RAS: the Green-Ampt (GA) method and Deficit and, Constant Loss (DCL) method (D. L. Ficklin & M. Zhang, 2013). The last two options require far more detailed data sets regarding hydraulic properties, soil moisture content, etc. (Bouvier et al., 2018). This data is not available in these data-scarce regions which makes them unsuitable. The GA method and DCL method are more focussing on the infiltration rate estimation, while SCS CN is focussing on estimating the runoff. The latter is more important for this study because it focuses on runoff volume and peak flow rates. Many hydrological and hydraulic studies use SCS CN method for simulating surface runoff volumes (USACE Hydrologic Engineering Center, 2023a). For comparable studies, SCS model performed better than the GA model

(Bouvier et al., 2018). A great advantage of the GA model is the temporal variation of rainfall excess intensity, but with this small sized catchment that is not considered. The SCS method is valuable for computing direct runoff and not for describing its evolution over time. Since this study only looks at short term effects (within a few hours), this suits perfectly.

Consequently, this study uses the SCS (Soil Conservation Service) method. It is an empirical method used for determining direct runoff generated by a rainfall event. It considers the effect of rainfall on the soil, vegetation and other surface conditions. It uses a combination of the Curve Number (CN) and the abstraction ratio to estimate the amount of runoff. It assumes that the amount of runoff from a precipitation event is a function of the amount of rainfall that exceeds the infiltration capacity of the soil (D.L. Ficklin & M. Zhang, 2013). HEC-RAS uses the CN method to estimate the runoff from each catchment in a watershed. The water is routed through the stream network using hydraulic properties of the watershed.

In HEC-RAS infiltration works according to these steps:

1. The input is the land cover, soil type and hydrologic conditions.
2. The abstraction ratio determines which part of rainfall becomes runoff immediately
3. The minimum infiltration rate represents the amount of water that passes through the soil profile during saturated conditions.
4. The Curve Number is a numerical value assigned to a particular land cover, representing the watershed's response to rainfall.
5. Once CN is calculated, a mathematical equation takes into account the rainfall intensity, curve number and soil moisture condition to calculate infiltration. The soil moisture condition is assumed to be constant throughout the simulation period.
6. The amount of infiltration is subtracted from the total rainfall, the resulting volume becomes direct runoff that routes through the stream network in HEC-RAS.

5.4 SOIL LAYER

The following Table 3 displays all the values of the soil layer necessary for the SCS infiltration method: CN value, abstraction ration and minimum infiltration rate (USACE Hydrologic Engineering Center, n.d.-a). The parameters itself, and the justification for the values is provided in the next paragraph.

Table 3 - Land cover table with CN value, minimum infiltration rate and abstraction ratio

Nr.	Land cover	CN value [-]	Min. infilt. Rate [mm/h]	AR [-]
1	Drain	95	3.8	0.05
2	Building footprint	92	3.8	0.05
3	Asphalt road	95	3.8	0.05
4	Concrete	98	3.8	0.05
5	Bare	72	3.8	0.2
6	Mixed forest	52	3.8	0.2
7	Bushes	67	3.8	0.2
8	Grass	49	3.8	0.2
9	Artificial pitch	90	3.8	0.05
10	Open water	100	3.8	0.2
11	Breakwater dam	60	3.8	0.05
12	Residential	85	3.8	0.05
13	Mixed land use	85	3.8	0.05
14	Industrial	85	3.8	0.05

The original model had three soil layers that were incorporated as can be seen in following Figure 29. However, the original values were general soil values in terms of CN, AR and the minimum infiltration rate were all the same. After closer examination of the hydrological soil groups in the region, new values are assigned. That resulted in more specific values in terms of CN, AR and minimum infiltration rate for the whole catchment as can be seen in Figure 30.

Figure 29 - Original soil layer and characteristics of the catchment

Figure 30 - Improved soil layer with soil characteristics

5.4.1 Minimum infiltration rate

The soil in Sekondi-Takoradi can be characterized according to the following geological map in Figure 31. Sekondi consists of Sekondi Sandstone (thickness: 200m) and Essikado Sandstone (thickness: 105m). The soils are reddish in color, and have an almost clay consistency . They classify as aeolian type or loess soil type. This is an unstratified soil deposit that is composed of small, yellowish brown in color, particles mixed with clay (Cain, 2000). Belonging to ferric acrisols, which classify as sandy loam soils.

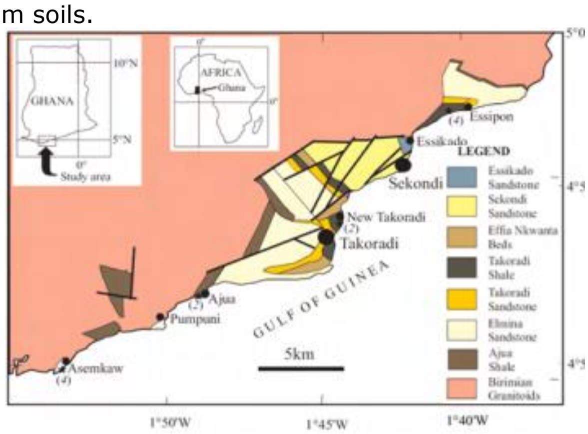


Figure 31 - Simplified geological map of the Sekondi-Takoradi Area, Ghana (Atta-Peters, 2000)

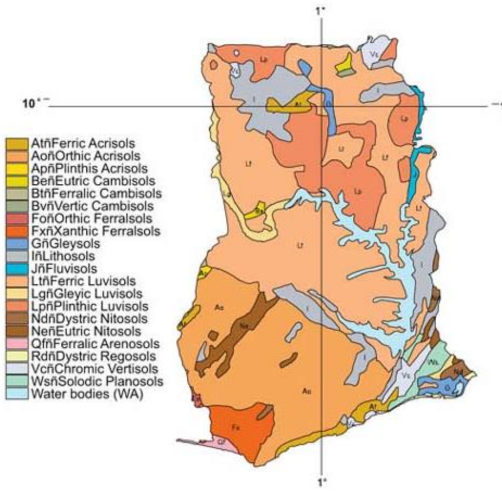


Figure 32 - Dominant soils in Ghana

According to hydrologic soil property tables classified by soil texture at the HEC-RAS site these types of soil have a minimum infiltration rate around 0.15 – 0.30 in/hr = 3.8 mm/h (Shallow loess close to clay loams) (Maryland, 2009). Consequently, the minimum infiltration rate is set to 3.8 mm/h for the whole catchment.

5.4.2 Abstraction Ratio

The CN method assumes an initial abstraction before the surface runoff. In HEC-RAS, the abstraction ratio (AR) is a parameter used to estimate the amount of rainfall that is lost or intercepted before it becomes runoff (Baltas et al., 2007). The abstraction ratio represents the portion of rainfall that is lost due to evaporation, interception, or infiltration, and is therefore not available to contribute to runoff. The abstraction ratio is defined as the ratio of the amount of rainfall lost to the total amount of rainfall that falls on a particular area. It is typically expressed as a fraction, with values ranging from 0 to 1. A value of 0 means that no rainfall is lost, while a value of 1 means that all rainfall is lost before it becomes runoff. For the land use parameters the AR is assigned to better simulate the amount of rainfall that is lost, and therefore improve the accuracy of hydraulic modelling results in HEC-RAS.

The default AR in HEC-RAS is 0.2 (USACE Hydrologic Engineering Center, n.d.-a), however, recent research has indicated that this is not correct for urban environments. Human intervention results in decrease of initial abstraction ratio in the watershed (Baltas et al., 2007). Impervious areas leads to runoff reaching the outlets of a waterway faster. AR of 0.05 was tested for different studies and circumstances (Noori et al., 2012). Several studies have found that the standard SCS-CN AR value of 0.2 does not suffice and provides a poor performance of runoff prediction in urban areas (Noori et al., 2012). Therefore, AR = 0.05 is used in this model for urban areas, and AR = 0.2 is used for non-urban areas. Impervious area will be treated at 100% runoff with almost no initial abstraction: AR = 0.05. This is important for urban area especially, since the impervious area is directly connected to the storm runoff system.

5.4.3 Curve Number

The curve number is a dimensionless number that indicates the runoff potential in a specific area. They range from approximately 30 (for permeable soils with high infiltration rates) up to 100 (for impervious areas such as waterbodies) (Acheampong et al., 2023). The higher the number the greater the potential, and vice versa. With the CN estimation the amount of rainfall that infiltrates is determined and the amount of rainfall that becomes surface runoff. The FAO soil database is very suitable for the estimation of CN values (Cea et al., 2022). The CN values have been determined by looking at the soil in the area and the type of land cover. The CN table at the HEC-RAS site (USACE Hydrologic Engineering Center, 2023a) presents the corresponding CN value that is used for this study. These CN values apply for the pervious area that is left when the impervious area is subtracted from the land cover. Otherwise the model would account double for the impervious area (CN = 100) and the pervious area that would be included in the CN value (USACE Hydrologic Engineering Center, 2023a).

6. RESEARCH RESULTS

After the further development of the original HEC-RAS model, simulations have been performed. This chapter will start with the definition of input and output parameters, followed by the analysis of the water system. At first, inundation patterns are visualised. Thereafter, the sub catchments are defined together with pour points of each catchment to obtain hydrographs. The global sensitivity analysis shows the most influential model parameters for the catchment. Local sensitivity analysis shows the effects of a change in the most effective model parameters. In addition, it examines the effect of slopes and type of catchment on the hydrograph and inundation maps. After understanding the water system in the study area, a subset of suitable NBS given the local urban situation are determined. The influential input parameters in the HEC-RAS model concerning NBS implementation are evaluated with help of a sensitivity analysis. This information, in combination with literature, results in the model schematisation and parametrisation of each relevant NBS. Definition of output parameters help to analyse individual effects; inundation depth, inundation area (extent), discharge wave (hydrograph) and surface runoff coefficient. These effects are validated using available literature. Last but not least, the combination of multiple NBS is investigated see how NBS influence each other in relation to the size of implementation, unit effect and spatial characteristics. Consequently, conclusions for the specific study area and generic lessons are drawn.

6.1 INPUT & OUTPUT

The whole research results section uses the following input and output parameters. They are indicated below as a basis for further reading.

6.1.1 Input parameters

In the model there are three influential layers with accompanying input parameters:

- land cover layer: impervious percentage + Manning's n coefficient.
- infiltration layer: abstraction ratio + curve number + minimum infiltration rate.
- Elevation layer: the height of cells in the DTM of the study area.

The 5 model parameters of HEC-RAS are displayed below. The accompanying theoretical value range is stated in the second column. The last column consists of the physical values of the parameters in areas such as this case study. This set of values is considered relevant for the sensitivity analysis and is used to obtain the sensitivity of the parameters. For each land classification area only 1 parameter is varying per simulation. This way, the effect of an individual parameter can be obtained.

Table 4 - HEC-RAS (realistic) model parameter values and explanation

Parameter	Values	Physical values	Explanation
Curve Number [-]	0-100	39-100	The HEC-RAS manual describes the possible values. (USACE Hydrologic Engineering Center, 2023b)
Manning's n [$s/m^{1/3}$]	0-1	0.01 – 0.3	The HEC-RAS manual describes these values as well as a manning's definition document (The Engineering Toolbox, 2004).
Impervious percentage [%]	0-100	2-100	Estimation of residential impervious areas follow from two documents. (Yancey et al., 2008) (Majid et al., 2013)

Minimum infiltration rate [mm/hr]	0-∞	0.5-10	According to the hydrological soil group and SCS soil group: B – C soils (0.30inc/hr – 0.05inch/h) = (7.62 mm/h 1.27mm/h) (USACE Hydrologic Engineering Center, 2023b)
Abstraction ratio [-]	0-1	0.01-0.2	Literature states the correct values (Noori et al., 2012)

Dependency parameters

It is good to note that the CN value and the impervious percentage value are dependent on each other. If the impervious percentage is high, the percentage of the land cover that is pervious and characterized by the CN value is low. In that case, a change in CN value does not have as much impact as the same change for an area with a much lower impervious percentage. The other parameters are not dependent.

6.1.2 Output parameters

Four (model) parameters are chosen for evaluation of the sensitivity analysis, the implementation of NBS and evaluation of individual and combined effects of NBS.

- Water inundation depth: the maximum water depth in the catchment per grid cell [m].
- Water inundation area (extent): the maximum surface area of the catchment covered by water [m^2].
- Water flow (discharge): the amount of water flowing out of a (sub) catchment [m^3].
- (Surface) runoff coefficient: A dimensionless number indicating the ratio between the total runoff (mm) and the precipitation (mm) (Ferreira et al., 2022). The surface area under the hydrograph results in the total amount of rain (mm) that will fall in the catchment. The surface area under the discharge graph results in the total volume of water that passes a certain point after some time. Dividing the volume by the area of the catchment results in the total runoff (mm). Consequently, the runoff coefficient can be calculated.

Constraints

It is good to note that all outputs are calculated for a 4 hour period. This value is chosen since most of the rainfall (>95%) has left the catchment by then for all simulations. For all water to leave the catchment a simulation of 11 hours is necessary. Simulating a period this long costs a lot of additional computation time. The current model takes around 15 minutes to run, and increasing the simulation time by a factor 3 results in a computation time around 40 minutes. Due to the large number of necessary computations the simulation time of 4 hours is chosen. In addition, another input parameter is the rainfall distribution. One method often used to demonstrate the effect of (NBS) measures is to correct or alter the rainfall distribution in the region of the measure. This is often applied, but requires a significant amount of assumptions and does not model the actual system closely. Therefore, this method is not used.

Area classifications

The shapefile of the case-study area in HEC RAS is subtracted and implemented in QGIS. With help of QGIS the sizes of each land classification polygon were determined. For the sensitivity analysis only the 5 largest land classification areas are selected. The other land classification areas are assumed to have too little influence on the model parameters. This results in the following list of land classification area sizes:

Table 5 - Top 6 largest land classification sizes in the catchment

Top 6	Area [m2]	Area [%]
Residential	577216	49.8
Asphalt Road	164437	14.2
Mixed forest	115777	10.0
Bushes	113061	9.7
Building footprint	95234	8.2
Bare	52703	4.5

6.1.3 Spatial variability

Implementing all NBS for the whole catchment is very difficult and time consuming. A delineation of sub catchments is made based on hydrological properties, as described below in section 6.2.2. Since spatial dependency is the most determining factor in terms of the effects of NBS, this delineation is used to identify 2 sub catchments that have different spatial characteristics which can be used for comparison. To test the effect on the water system two totally different sub catchments are evaluated to see the effect for different conditions on the discharge wave at the pour point, and the inundated depth in the whole catchment. The chosen catchments are all different in shape, size, location, elevation and land cover. But all have a distinct pour point where all the water of the catchments (that is runoff) ends up. In Figure 33 - Overview of the catchments that are evaluated the chosen catchments can be seen (1 and 8). Next to the figure, the characteristics of the chose sub catchments are shown.

Figure 33 - Overview of the catchments that are evaluated

Table 6 - characteristics of sub catchment 1

Sub catchment 1	
Residential	47%
Size	300479 m2
Elevation	Steep slopes, 9% on average

Table 7 - characteristics of sub catchment 8

Sub catchment 8	
Residential	71%
Size	50085 m2
Elevation	Mild slopes, 3.3% on average

6.2 WATER SYSTEM ANALYSIS

A set of urban NBS has been retrieved from literature, which can be found in section 2.1. Not all NBS can be implemented everywhere in the whole catchment area due to its characteristics. To get more insight about the local context, a water system analysis is provided in this section. At first the inundation characteristics are discussed. Although it is a small catchment, there is still spatial variability as can be seen in chapter 4.1. To get more insight in the water system characteristics of the area and the influence of spatial variability on different urban NBS, the catchment is delineated into sub catchments. This way, the results can be analysed more thoroughly.

6.2.1 Inundation characteristics

In section 4.1 the environmental challenges are described aforehand. After construction of the detailed model the following results are obtained for three scenario's with rainfall return period T = 2, T = 10 and T = 25. Which add to the visual inspection of environmental challenges.

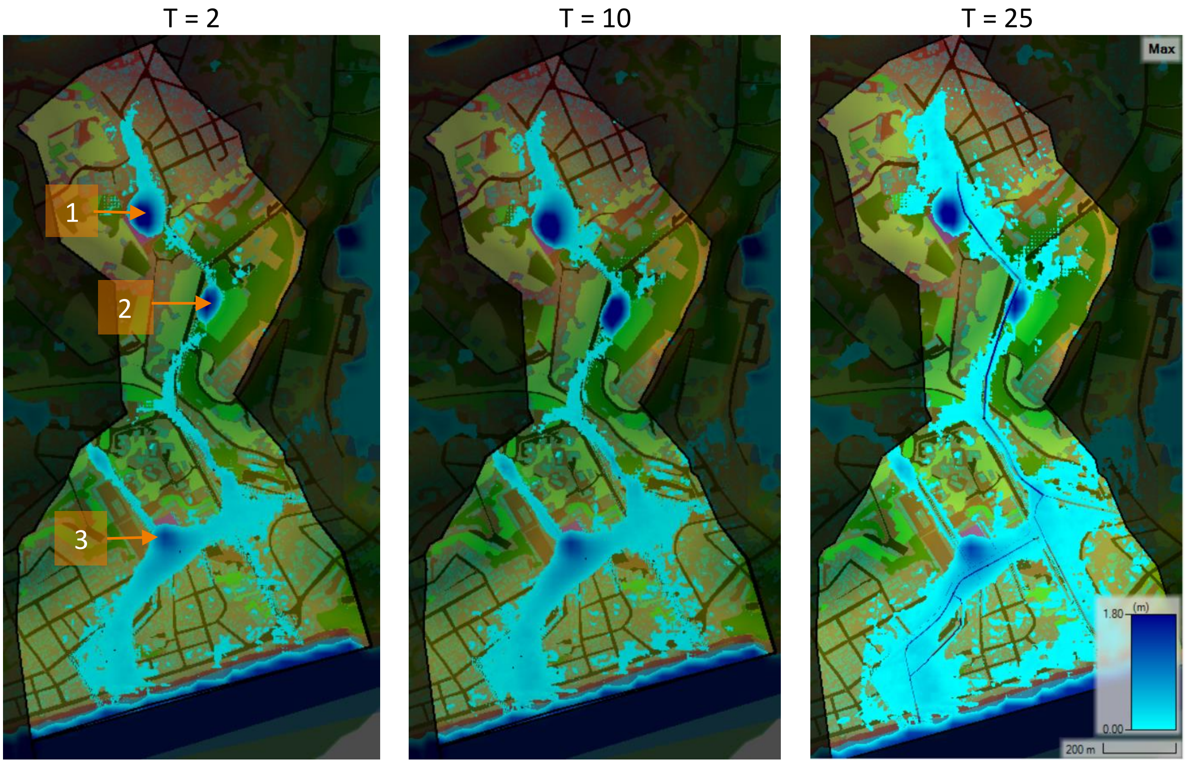


Figure 34 - Inundation maps for T = 2, T = 10, T = 25 for a 4 hour rainfall event

The inundation pattern is almost the same, but the difference is the water depth at the critical points and the surface area of the inundated area. The heavier the rainfall the larger the water depth and inundation spreading pattern. For critical point 1 the inundation surface increases more than the water depth for larger rainfall events. This is caused by the flatness of the area. Due to the steeper areas at critical point 2 and 3 the effect is vice versa; the water depth increases more than the inundation surface. The main environmental challenge lays at the three main critical points. The next table displays the maximum water depth for each scenario for the three critical points.

Table 8 - Water depths per critical point

Critical point	1	2	3
T = 2y	1.27m	1.81m	2.24m
T = 10y	1.36m	2.55m	2.63m
T = 25y	1.89m	3.39m	2.97m

6.2.2 Sub catchment delineation

Using QGIS method 'delineate sub-catchments', the following set of sub catchments are determined using the DTM. At first the stream network is converted to a polygon. Secondly, the pour points have been determined. Per cell a check is performed to which other cells the cell drains (or vice versa). Doing this for all cells results in a drainage pattern with a few so called 'pour points', a whole area drains to this point. The sub-catchments are displayed below in Figure 35 including the pour points.

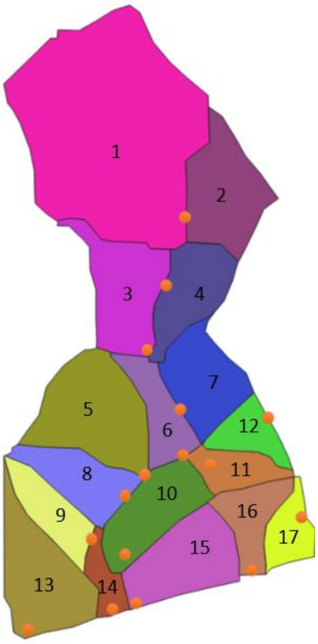


Figure 35 - Catchments and numbered sub catchments with pour points

In Figure 35 the drainage points are mapped on the DTM of the sub catchments and pour points. This clearly visualizes that the pour points are located at drains, which is logical. The pour points near the edges, (catchment number 13, 15 and 17) that do not effect the drains are left out since the water in the corresponding catchment flows out to the sea without interacting with other catchments or drainage systems. This results in 14 pour points that are used for examination of the water system.

6.2.3 Drainage systems

In general, the area can be divided in 4 area's, as can be seen in Figure 37. The drainage catchments are merged according to the location of the pour points. There are two drainage systems, one in the grey drainage catchment and one in the green drainage catchment. The blue areas are not interesting for this study since they drain directly to the sea and do not influence the problem area's. It is worth noting that pour point 11 and pour point 13 are located underground in reality. Due to model limitations this underground drainage part is represented by a deep slit in the DTM. Since the DTM is sloping towards the sea at those locations, a neglible amount of water is pouring in those slits. Therefore this representation of reality is suitable to pursue modelling.

Figure 36 - Elevation map with the drainage systems and location of pour points on the drainage system

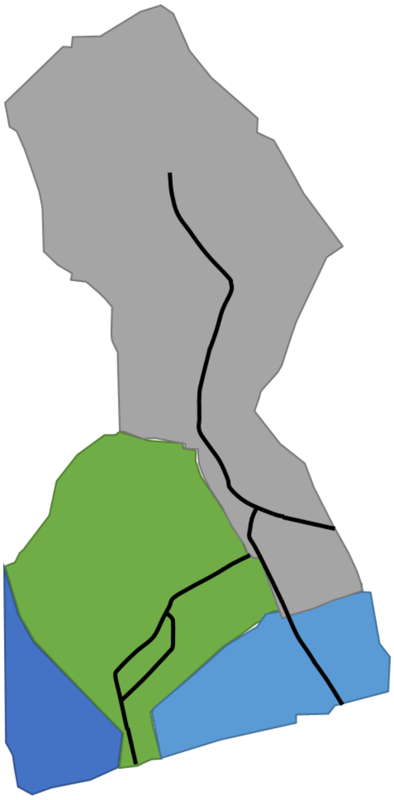


Figure 37 - Catchment divided in four different sub areas depending on the connection of pour points

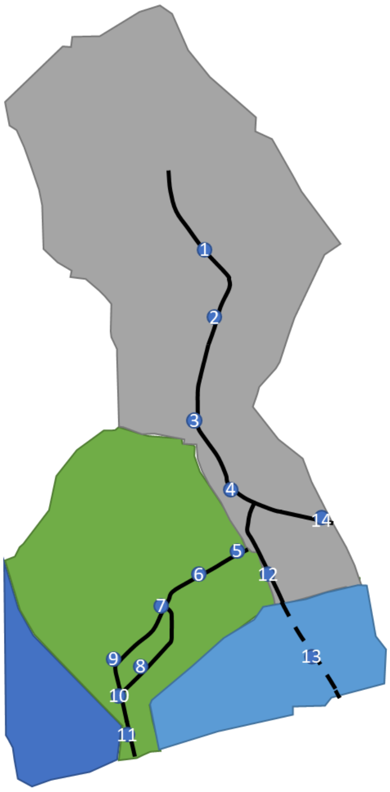


Figure 38 - Catchment with pour points added per sub area

For the overview, the pour points and their location in the catchment are visualized in Figure 36. The outflow of each catchment can be measured in these pour points. This results in a hydrograph for each sub catchment. For later analyses, it is interesting to see what amount of water will leave or stay in the whole catchment. Consequently, a line is drawn around the bottom of the whole catchment. All water that flows out of the catchment is caught this way, representing the catchment outflow.

Figure 39 - Measurement location of the total outflux of the catchment

6.2.4 Discharge characteristics

The hydrographs of the study area are visualized below per drainage system area for all pour points. A T=10 situation is simulated under the basic circumstances of the catchment (as described in section 5). The colour of the curves match with the areas in .

Northern drainage system

To get better insight, the two drainage systems are evaluated separately. The first, northern, drainage system (grey area in Figure 38Figure 40) is shown below. Pour points 1, 2, 3, 4, 12, 13 and 14 belong to this drainage system. It can be seen that that water accumulates when going downstream from point 1 to 4. The discharge wave keeps increasing up to point four. The discharge at point 14 and 12 added together does not come close to the discharge at point 4, which indicates that water is disappearing from the drains. The total area under the graphs, the total water volume, is significantly less. When looking at the inundation maps in section 6.2.1 this is correct. Near the junction of the drain coming from the north, a lot of water is flowing over land. The simulated discharge wave at point 13 displays a larger water flow than at point 12. This is due to some additional inflow from the sub catchment around point 12. The general shape of the discharge waves is quite similar, especially for the first four points. Due to the steep areas the discharge wave quickly grows, resulting in a large gradient. After the peak, the water slowly drains, resulting in a more gentle slope. Around 70 min, there is a sharp decrease visible, this is in line with the rainfall event that is almost to an end.

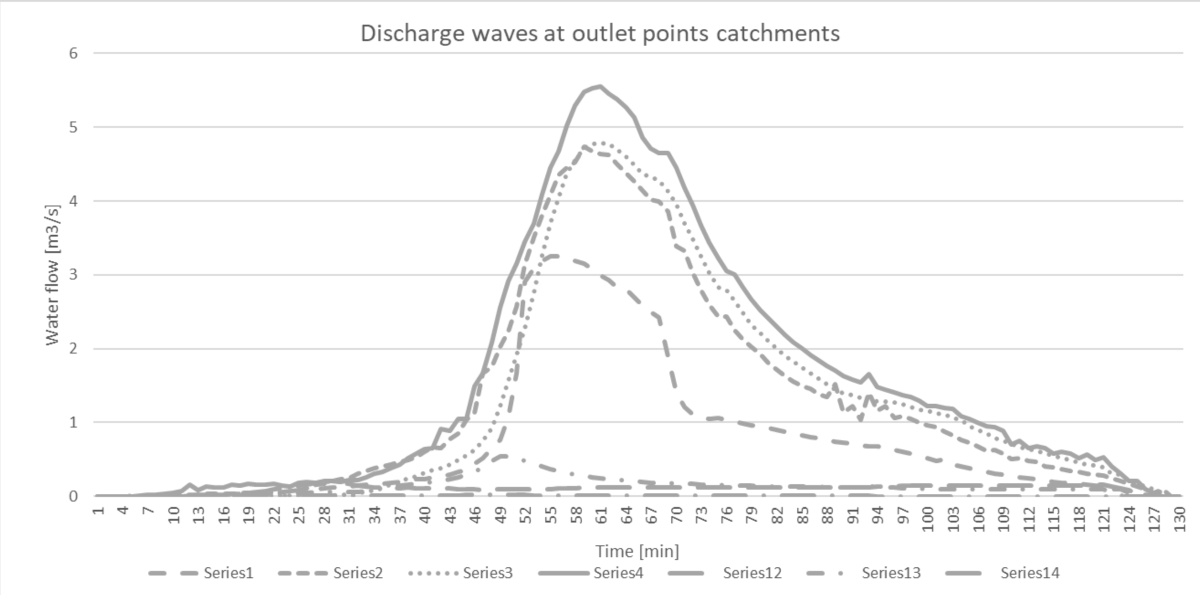


Figure 40 - Discharge waves at outlet points in the northern catchment (grey area)

Southern drainage system

The second drainage system area, the green one in Figure 41, is shown below (points 5 up and till 11). This drainage system has a less high peak discharge (2.6 m^3/s at max vs 5.6m^3/s at max). The general shape is more flat, there is not sharp peak visible. For almost all measurement points the first part of the graph has a large gradient. Thereafter the peak discharge persists and starts decreasing slowly, resulting in a mild slope. The increase in discharge waves follows a natural pattern, the further downstream the drain the larger the discharge due to additional inflow from sub catchments.

The highest discharge is measured at location 7, just before the junction in the drainage system. Input from earlier sub catchments accumulates, as well as some water from the northern drainage system due to overflow. The water bifurcates and additional water enters the drains from the surrounding sub catchments. The total water volume (area beneath the graphs) of point 7 and 11 is almost the same. However, the water volume at point 11 should be higher than the water volume at point 7 due to the sub catchments. Consequently, not all water leaves the area. The excess water results in inundated area as can be seen in Table 7.

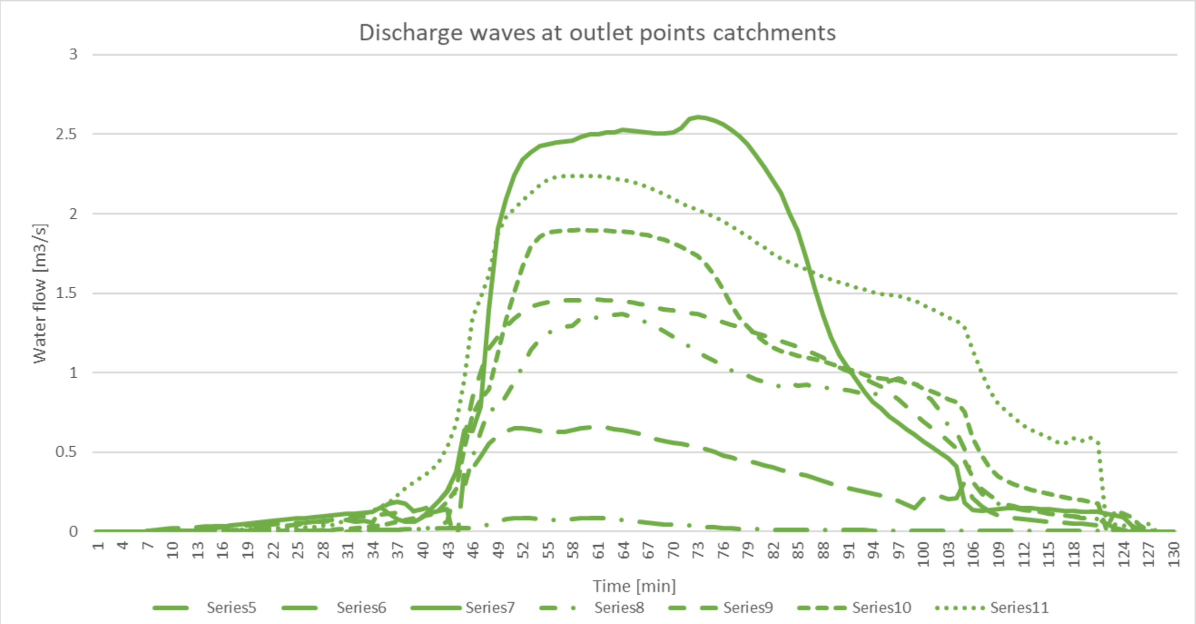


Figure 41 - Discharge wave at the outlet points in the southern catchment (green area)

Separation drainage systems

To see what the extra inflow from the northern drainage system into the southern drainage system is, the northern (grey are in Figure 40) area has been cut off by a large drain (20m x 5m) to ensure no water will enter the bottom area. The inundation patterns changes drastically. Reduction of 40cm of the maximum water depth occurs in the southern part of the study area. Also, large reduction in the northern part occurs, this is due to the fact that all the water can disappear out of the area via the drain that disconnects the both areas.

6.3 RELEVANT URBAN NBS

In section 2.1 NBS are explained and a set of urban NBS defined by the World Bank (2021) is given. This set is used as the basis for determining the relevant urban NBS for this study area that can be investigated. *"Which NBS are relevant to consider for this study?".* The set of steps introduced in section 3.1.1. are followed to determine the relevant urban NBS for this study area. A short insight in the topographical challenges followed from the water system analysis. This section discusses the outcomes and selection of suitable NBS given the characteristics of the study area catchment.

6.3.1 Local context

Section 4.1.5 already elaborated on the geographical context of the study area. In addition it can be seen from the above Figure 34 that the topography facilitates this inundation pattern for different rainfall events. The high altitude areas in the northern part of the catchment in combination with hard soils and urban impervious areas quickly dispatch the water to the southern part. Most of the water flows through the existing drains. However, with these more extreme weather circumstances, the drainage capacity is not enough. There is too much water in the drains, leading to inundation. The urban characteristics leave little room for large scale NBS implementations such as floodplains, or large wetlands areas. Rainfall events have a short duration but are heavy, a lot of water needs to be drained. The existing infrastructure is rigid and deteriorated, increasing the roughness at the drainage channels.

6.3.2 Potential NBS

Considering the topographical challenges and the local context, a sub selection of the urban NBS has been made. Some NBS are not suitable due to the limited space in this urban catchment (e.g. constructed inland wetlands). Others are not possible due to the geographical aspects, such as salt marshes or sandy shores. A few NBS also have very similar characteristics, such as green corridors and urban forests, only their spatial allocation differs. Consequently, both families are merged into urban forest. Since one challenge is to store the water, a few measures focus therefore on water storage by introducing bioretention areas. Delaying water in the current water system, from the hills and in the drains is also considered in the NBS selection by introducing urban forests, terraces and slopes, and river and stream renaturation. To summarize: the NBS families that are worth investigating in this region, and accompanying individual NBS, are displayed below:

1. Urban forests
    a. Forest transition
    b. Contour planting
2. Terraces and slopes
    a. check dams
3. River and stream renaturation
    a. Green drains
    b. Drain floodplains
4. Bioretention areas
    a. Bioswales
    b. Green roofs
    c. Permeable pavement

6.4 SENSITIVITY

The NBS listed in the previous paragraph are schematised in the hydraulic model. In this section a sensitivity analysis is carried out to analyse the NBS model input parameters and their effect on the model results. Moreover, it helps to understand the behaviour of the water system and it gives a good indication of the effects of possible NBS (Bharath et al., 2021). Especially for data-scarce regions it is important to do a sensitivity analysis (Ballinas-González et al., 2020). This is important because it can be used for validation of the effects of NBS implementation (section 6.5) and expansion of the knowledge about behaviour of the water system. This section answers the research sub question: *"What is the sensitivity of hydraulic parameters of NBS in a hydraulic model?".* In this analysis, one precipitation condition is evaluated; a 3 hour precipitation event with a return period of 10 years. The sensitivity analysis is carried out by changing one of the five mentioned model parameters (section 6.1.2) at the time while keeping the other parameters constant to understand their impact on the following output parameters: *water inundation depth, inundation area (extent) and water flow* (Alipour et al., 2022). Different parameters and effects are assessed with the global and local sensitivity analysis.

6.4.1 Method global sensitivity

The general goal is to see the effect of different parameters on the water depth and inundation area water depth in the whole catchment. This way, the effect of different values can be translated in change of water depth. It can be noted which parameters have the most influence on the water depth. This is used as input for the NBS implementation. Moreover, if it becomes apparent that wrong parameter values are used for land classification areas, it is clear what this would do with the water depth due to this global analysis.

To see what the influence of the five model parameters is on the inundation depth and inundation area, the model parameters are changed individually for the top 5 land covers (Table 5) for a T=10 scenario. Since NBS are most commonly designed for a T=10 scenario this part of the sensitivity analysis is only performed for a T=10 situation (Hamers et al., 2023). The following model scenarios are simulated for the residential land cover, see Figure 42. It is noteworthy that for each scenario the minimum and maximum possible value for a parameter is chosen. The difference is not a fixed percentage of the basis scenario. This because it is most interesting to see what possible changes to the current largest land cover (residential) would do to the inundation map for a T = 10 scenario. If a change in the model parameter leads to either a large increase or decrease in the effect, it is defined as an impactful parameter.

Residential\Scenarios	Basis	1	2	3	4	5	6	7	8	9	10
CN	**90**	**39**	**100**	90	90	90	90	90	90	90	90
AR	0.05	0.05	0.05	**0.01**	**0.2**	0.05	0.05	0.05	0.05	0.05	0.05
min. Infil. Rate	3.8	3.8	3.8	3.8	3.8	**0.1**	**20**	3.8	3.8	3.8	3.8
Manning's n	0.03	0.03	0.03	0.03	0.03	0.03	0.03	**0.018**	**0.12**	0.03	0.03
Impervious %	85	85	85	85	85	85	85	85	85	**10**	**100**

Figure 42 - global analysis model scenarios for the 5 model parameters varying from minimum value to maximum value

6.4.2 Outcomes global sensitivity

Results are displayed using maps of the maximum inundation pattern (water depth). This is a measure for the impact of water. For each scenario the difference map is calculated. This is the result of subtracting the original situation (basis) from the new situation. Only the most extreme difference maps are shown below. The other difference maps can be found in appendix 0. Hydrograph results for the 13 pour points are not generated here since this takes a lot of computational time and this is more efficient to do after the most effective parameters have been found. The change in water depth was the largest for the largest land cover: *residential*. Hence only the four results with the most significant change in inundation map for this land cover are shown.

Table 9 - Largest visible effects of the inundation map for four different scenario's

<table>
<tr><th>CN = 39 instead 90 (s1)</th><th>N value = 0.018 vs 0.03 (s7)</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><th>N value = 0.12 vs 0.03 (s8)</th><th>Impv % = 10 vs 85 (s9)</th></tr>
<tr><td>
</td><td>
</td></tr>
</table>

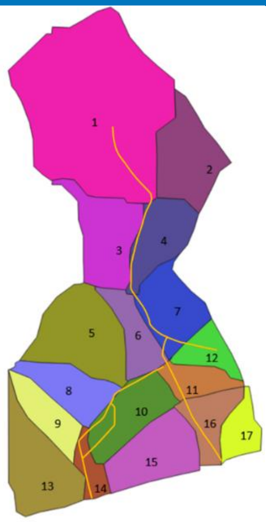
The largest effect is visible for the manning's n value, which corresponds with literature (Bharath et al., 2021). This works for both the increase and decrease, which makes sense since the parameter can be changed quite a lot in both directions. This is corresponding with literature where is stated that for flood extent mapping the roughness coefficient is the most important factor (Cappato et al., 2022). Next to that, the impervious percentage has significant impact. Only a decrease in impervious percentage shows a significant difference. This is due to the fact that the parameter cannot be increased as much as it can be decreased. Last but not least, the Curve Number values shows some impact. The same reasoning for displaying only one difference maps applies here.

The goal of the global sensitivity analysis was to find which model parameters have most significant influence on the water depth. The result is as follows: *1) Manning's n value, 2) Impervious percentage* and *3) CN value.* The minimum infiltration rate and the abstraction ratio have the least influence. This is understandable since this only affects a small part of the total rainfall. In addition, the extent of the effects of changing the model parameters is examined. This is used as input for parametrization of NBS for implementation.

6.4.3 Method local sensitivity

The roughness parameter is the most influential parameter, so this is systematically changed. The roughness value is related to the CN value and impervious percentage (which are dependent) due to the land cover characteristics. Consequently these values are altered at the same time. For the application of NBS later on, it is useful if realistic values are applied which could be related to NBS. In this analysis the land cover with the largest water storing ability (CN value) and water velocity reduction ability (roughness value) is used, which is the mixed forest. For all the catchments, and combinations, the roughness is set to 0.012, CN value to 50 and impervious percentage is set to 15% of the specific area. The following set of scenarios have been modelled to see the effects. Some sub catchments are grouped since they fall in the same drainage catchment (described in section 6.2.3.), or their elevation is similar. Grouping gives a clearer distinction between the base situation and new scenario.

Table 10 - local sensitivity analysis model scenarios

Catchment overview	Nr.	Area
	1	northern drains
	2	southern drains
	3	Sub catchment 1
	4	Sub catchment 2
	5	Sub catchment 3
	6	Sub catchment 4
	7	Sub catchment 5
	8	Sub catchment 6
	9	Sub catchment 7
	10	Sub catchment 8
	11	Sub catchment 9
	12	Sub catchment 10
	13	Sub catchment 11
	14	Sub catchment 12
	15	Sub catchment 14
	16	Sub catchment 1,2,3,4,7,11,12
	18	Sub catchment 5,6,8,9,10,14
	19	Sub catchment 1,2
	20	Sub catchment 5,6,8,9

The main results of the above scenario sensitivity analysis are displayed and explained in this paragraphs. While all scenarios were evaluated, only scenario 1, 19 and 16 are shown below. First the noteworthy findings from changing the area in the northern catchments (upstream) are discussed. Thereafter, the changes in the southern catchment (downstream) are discussed.

6.4.4 Outcomes local sensitivity

After obtaining the results from the global sensitivity analysis a more thorough analysis is needed. To obtain results for specific regions of the study area the hydrographs for all the sub catchments are evaluated.

Upstream changes

Changing sub catchment 1 and 2 (scenario 19) results in a large decrease of peak discharge as can be seen in the following Figure 43. This hold for both the northern and southern drainage system, although the northern drainage system experiences a larger drop. The discharge waves at the measurement points in the northern area are delayed in comparison to the original situation. The former steep shape becomes more bell-shaped. The width is larger. Also, measurement point 5 experiences a less increase in discharge due to the delayed water from the upstream area.

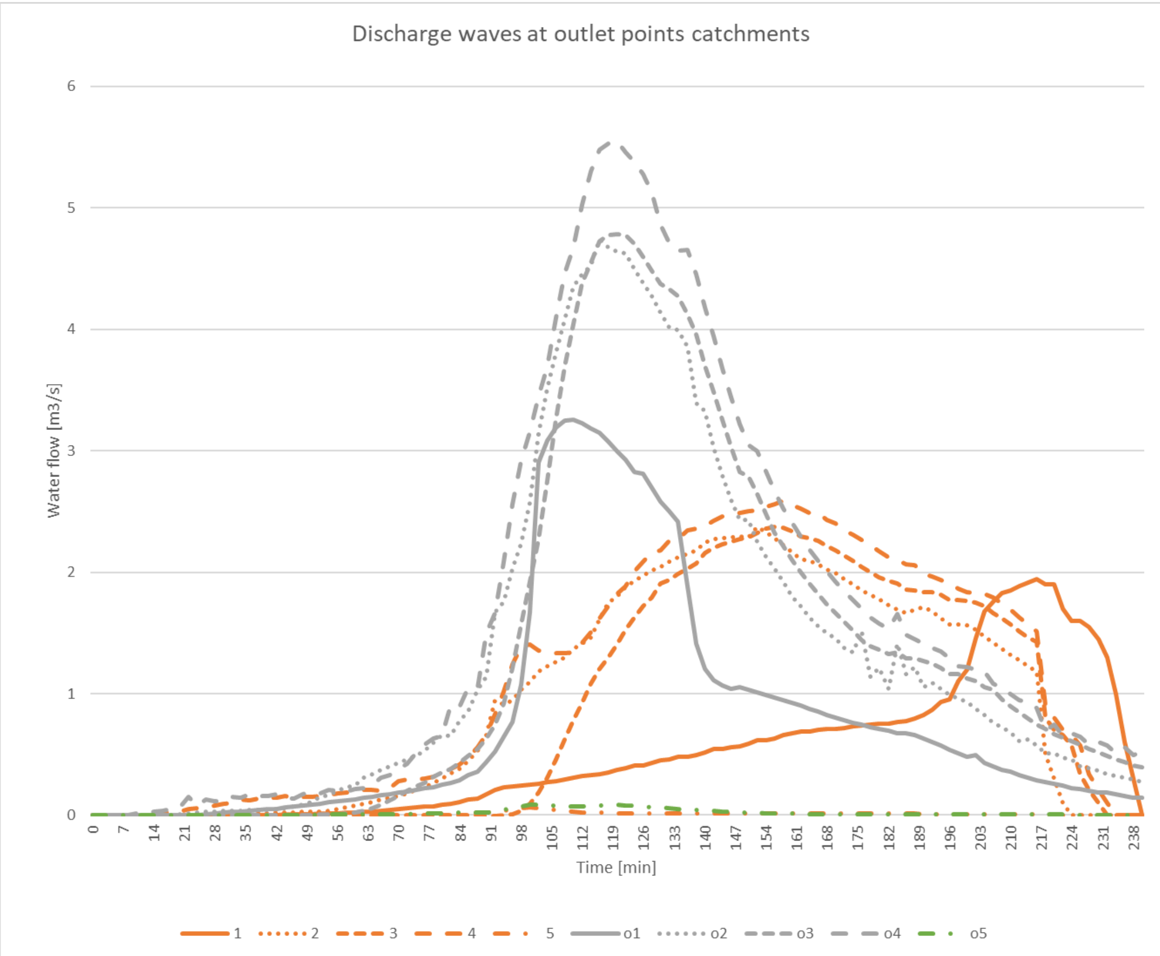


Figure 43: discharge waves of scenario 19 (sensitivity of northern 2 sub catchments). Green curves show sub catchments related to drainage area 1, while grey curves relate to drainage area 2 (see figure 39). Orange curves show the new discharge curve.

If the sub catchments 3, 4 and 7 are also changed (scenario 16), the same observations can be made. But the discharge waves becomes a bit less high and a bit wider (see *Figure 44*). Now the discharge wave at point 5 is back to normal due to the general delay. Another difference is the trend of the discharge wave at point 4. This curve increases very gradual.

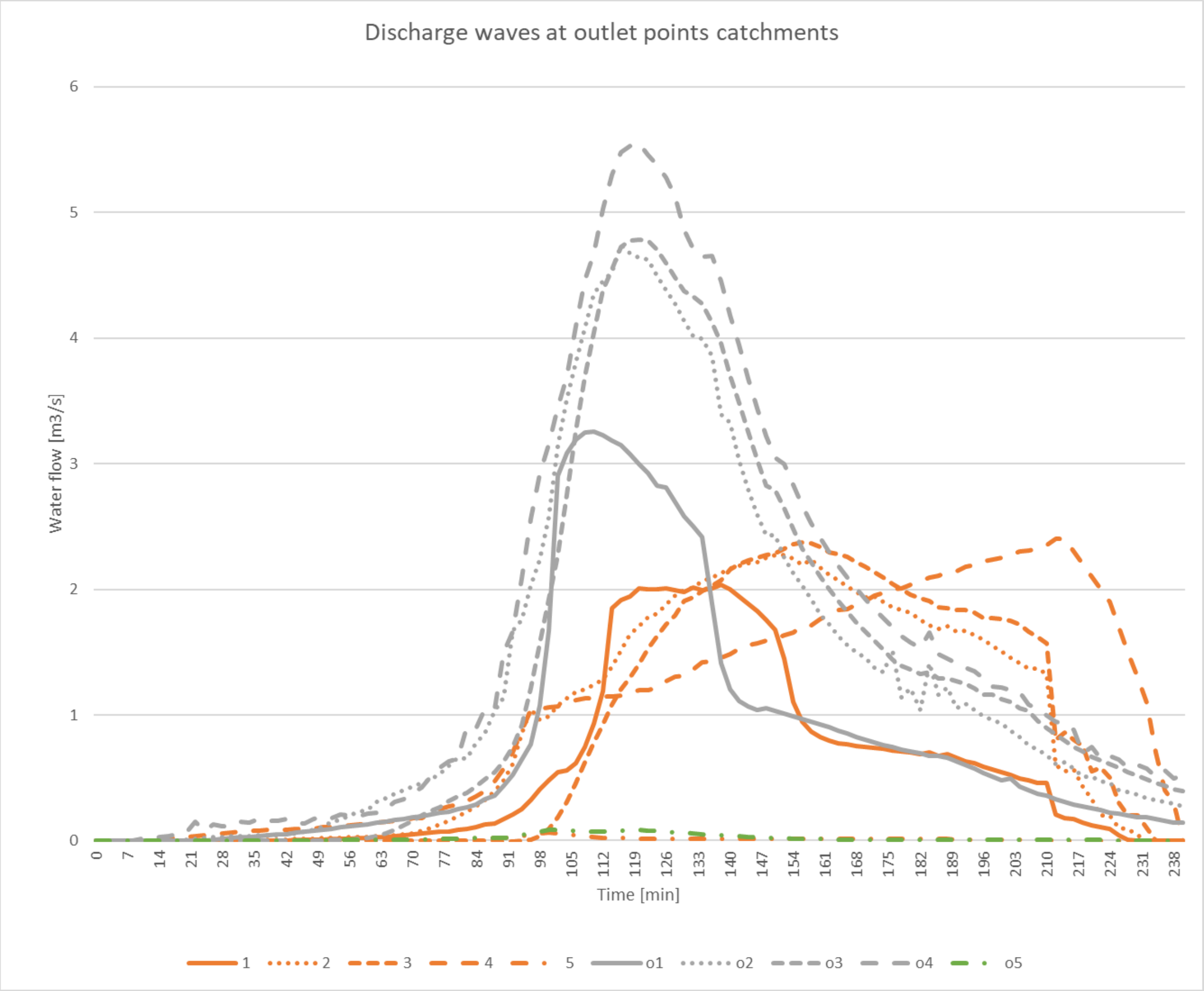


Figure 44 - Discharge waves for scenario 16 (sensitivity of northern 5 sub catchments). Green curves show sub catchments related to drainage area 1, while grey curves relate to drainage area 2 (see figure 39). Orange curves show the new discharge curve.

Interesting to see, if only the roughness and curve number of the drains in the drainage system in the northern part are changed (scenario 1) almost the same effects occur as for the two scenarios above. The maximum values exhibit a slight increase, but the discharge waves generally demonstrates a tendency towards increased width, reduced steepness, and lower peak values.

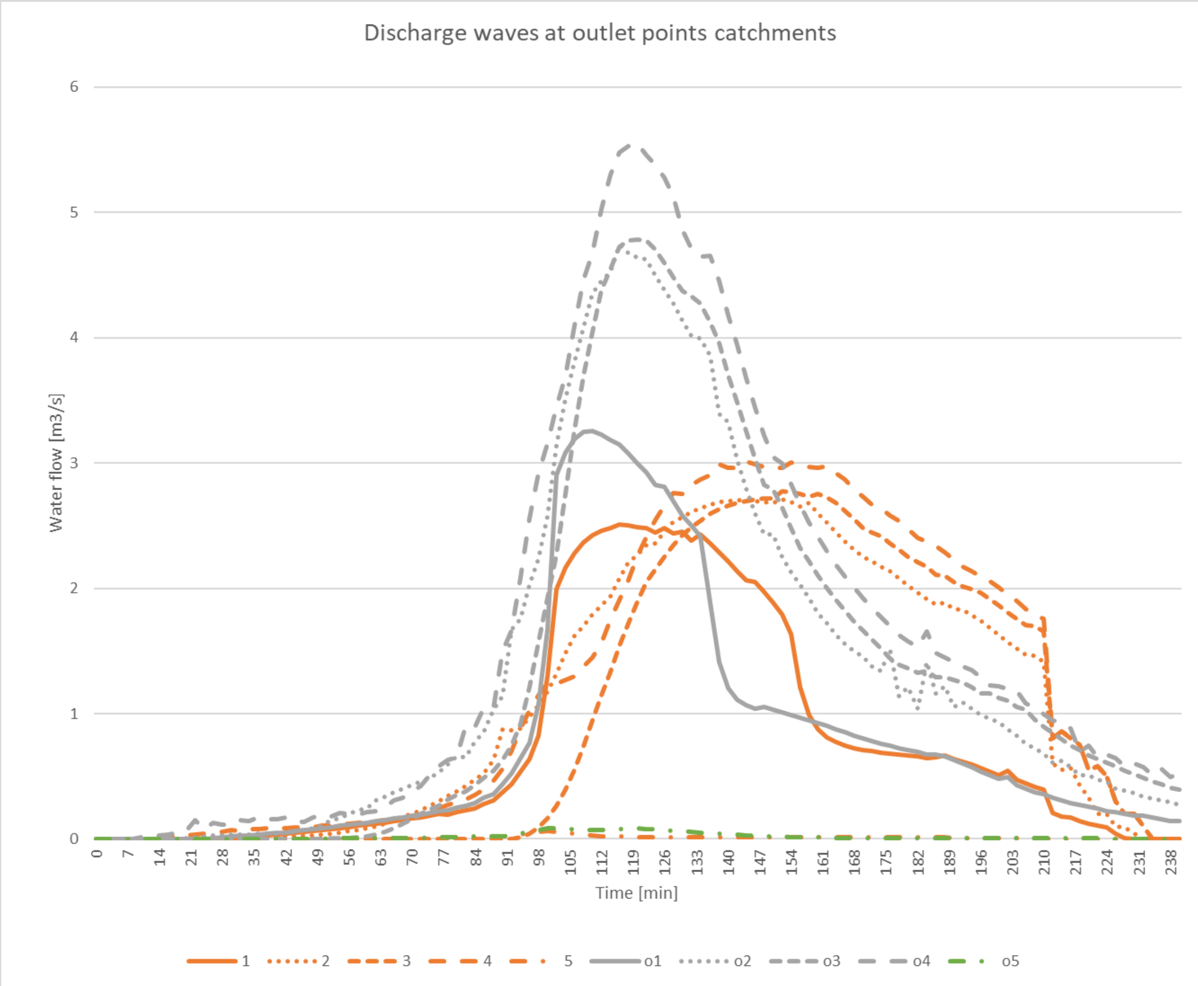


Figure 45 - Discharge waves for scenario 1 (sensitivity of drainage channels). Green curves show sub catchments related to drainage area 1, while grey curves relate to drainage area 2 (see figure 39). Orange curves show the new discharge curve.

It can also be seen that the discharge at point 5 becomes less high than in the original situation. Less water flows from the northern drainage to the southern drainage system around point 5. This can be noticed from the inundation map as well:

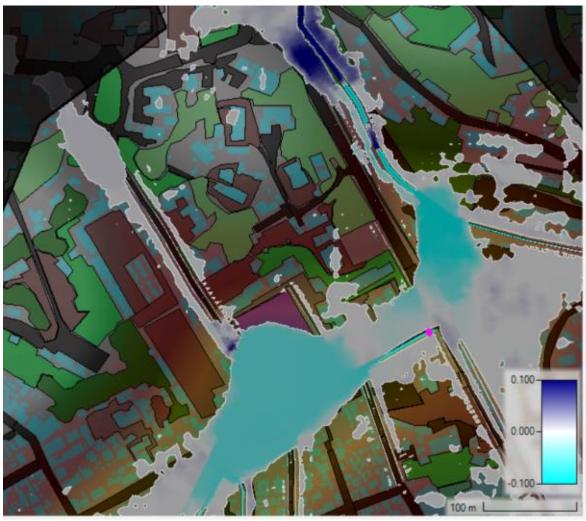


Figure 46 - Inundation difference map in comparison to the original situation.

The other inundation maps show the same tendency. Water depths downstream decrease, but the water depths upstream increase, only the extent differs. At the three most extreme points the differences are noted in the following table:

Table 11 - Water depths per scenario per extreme point from the inundation map

Scenario\Location	1	2	3
1: northern drains	*1.83m*	2.67m	2.38m
16: sub catchment 1,2,3,4,7,11,12	*1.94m*	2.77m	2.23m
19: sub catchment 1,2	*1.72m*	2.39m	2.45m

In addition, slopes impact the amount of surface area that is necessary to achieve the same results. In the northern part it could be seen that introducing a very rough drainage channel had almost the same effect as changing the whole land cover in the northern region. Without slopes this could not have been the case since the flow path would not be that clear. The steep slopes force the water in one way regardless of the water depth. In the lower areas one can see that the water can flow in many directions due to the flatness or that above a certain water depth a new area can be reached. The latter is also the cause of the connection between the two drainage systems.

Downstream changes

When changing the characteristics from all the sub catchments in the southern part of the study area (scenario 18) it is found that with a change of land cover for the whole southern area the water depth will increase but the discharge will decrease. This is visible in the following graph of the southern drainage system. The discharge waves are wider and have a less high peak. There is no change in upstream discharge of the northern catchment due to the disconnection of the drainage systems.

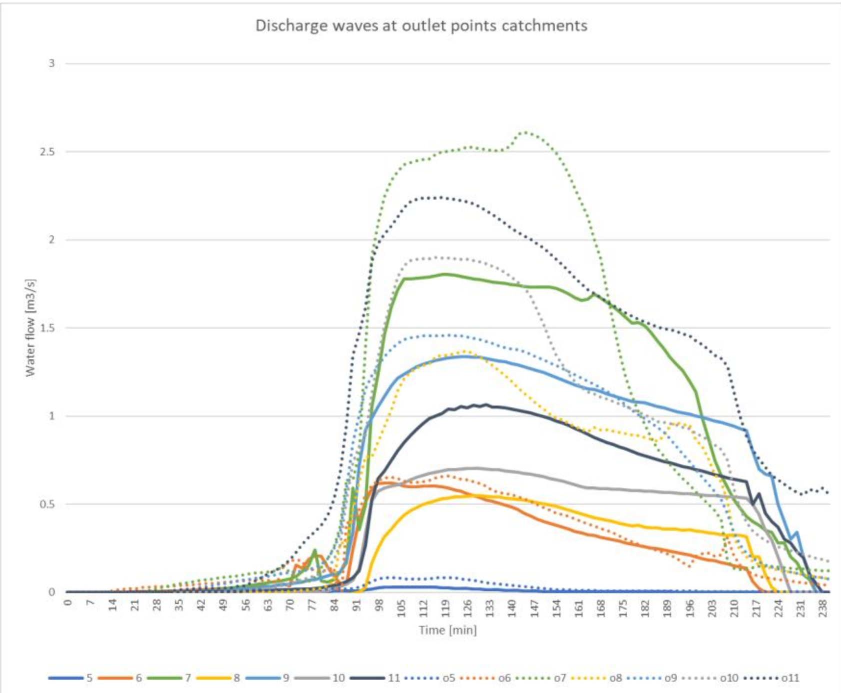


Figure 47 - Downstream changes when changing the land cover for the whole southern area

The comparison inundation map, where the new situation is compared with the basis situation, shows that there is an increase in water depth downstream for scenario 18. In appendix 10.2 Figure 75 the colour scheme of Figure 47 is adjusted to see the difference of all old hydrographs compared to the new hydrographs even better. There are no upstream effects visible in the inundation map as well.

This is due to the disconnection between the drainage systems. The increase of inundation depth could lead to increase in inundation depth of the northern drainage system but then the increase should be extreme which is not the case now.

Figure 48 – Inundation difference map of the southern drainage system for scenario 18

If only a few sub catchments in the southern drainage system, which do not lay in the inundated zone, are converted to the mixed forest land cover the results are a bit different (scenario 20). In that case one can see that the water depth is decreasing a bit and the discharge wave as well. This corresponds with literature, coarsening the environment and increasing storage results in less volume of water downstream (Lane et al., 2022). In this case in the drainage channels itself. The main conclusion here is that the change in land cover should not take place in or near the lowest points of a catchment if one would decrease the inundation depth and inundation area. Delaying and storing the water a bit more upstream will help reducing the water depth and inundation area downstream at the lowest points in the catchment.

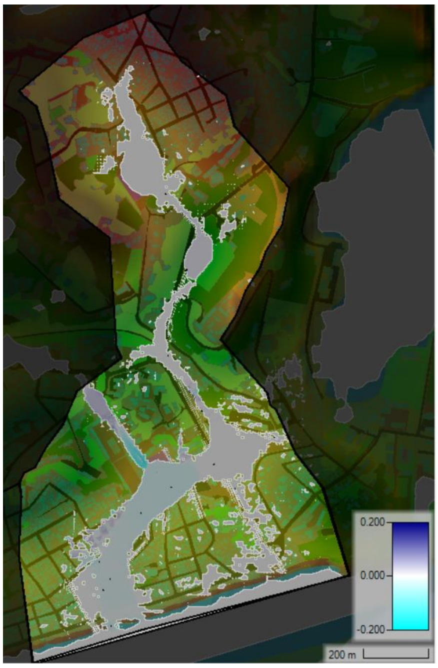


Figure 49 - Inundation difference map for scenario 20

6.4.5 General results sensitivity analysis

The manning's n value is the most sensitive model parameters, followed by the CN value and impervious percentage. Changing land covers related to these three parameters gives an indication what the effects are for specific implementation locations. In the southern area it has been found that the most impact by changing only the land cover in the sub catchments downstream can be made on mild slopes (slope between 5 and 10%). Almost flat areas have already a low discharge levels and high water depths, the water in this area should not be delayed but stored to generate a positive impact at the water depths downstream in the drainage channels. In the northern part it became clear that due the steepness of the slopes not enough water could be stored or slowed down. When cutting off the whole top region by implementing a large channel (10x10m) almost 40 cm water depth reduction could be achieved (see Figure 76 in appendix 10.2.1). When changing the whole top area to the roughest land cover possible in practice, only 15 cm water depth reduction could be achieved. Due to the steepness the water cannot be retained in the northern area with measure only focussing on increase soil retention capacity or roughness. One should think of retention basis or other elevation related measures.

6.5 IMPLEMENTATION NBS

After the sensitivity analysis, the selection of relevant urban nature-based solutions can be implemented. Implementation requires a strict definition of how the urban NBS should be implemented. This section answers the question: *"How can the selected NBS be implemented in a hydraulic model?".*

As mentioned, five model parameters were defined in HEC-RAS that can be used to implement the NBS: manning's n value, impervious percentage, minimum infiltration rate, CN value, and abstraction ratio. The sixth input parameter is the grid (elevation data) which can be altered to create storage areas. The sensitivity analysis helped to find the parameters that have most influence and gave an indication of the possible effects and their magnitude. It became clear that manning's n value is the most important parameter that has most effect on the water depth and inundation area. The curve number is the second most important model parameter. And because of the dependency the impervious area is closely linked to the CN value. In this section the implementation of the NBS will be discussed.

In section 5.4.3 a possible set of urban NBS families and examples was given: urban forests (1), terraces and slopes (2), river and stream renaturation(3), and bioretention areas (4). The idea of this research is to gather insight in the possible effects of implementing NBS. Therefore only this selected set of urban NBS, which in theory are most applicable, are applied to the case study area. The analysis of the study area resulted in the potential locations. The sensitivity analysis helped looking at the relevant locations. In this section the placement and implementation of the NBS is addressed. Per NBS the implementation is discussed:

6.5.1 Urban forest

The Urban forest NBS family concerns the transition from an urban area to a forest. Going from urban areas to a forest area mostly effects the roughness and infiltration capacity in the model. From the sensitivity analysis it could be seen that increasing the roughness has most effect in the upstream area. Improving the retention capacity of the soil upstream in the catchments helps reducing the water depth and inundated are. In the inundated area itself the opposite occurs since the water will be held even longer in this area than originally. This can be done in two ways, the whole area can be changed to a forest (a) or contour planting is applied (b). The implementation of both methods is discussed below.

a – forest transition

Figure 50 - Visual example of urban forest transition

b – contour planting

Figure 51 - Visual example of contour planting

To test the effect on the water system two different sub catchments are evaluated to see the effect for different conditions on the discharge wave at the pour point, and the inundated depth in the whole catchment. These two sub catchments are evaluated for two situations:

- Situation a: complete forest transition. All the land that is bare, bushes, grass, or concrete (which is not used as a road or parking lot) is transformed to mixed forest. In HEC-RAS the land cover of a specific region is changed to the 'mixed forest' land cover. This is the most occurring type of forest in this region and can be applied in the model. The following values are applied:

Table 12 - Urban forest model parameter characteristics

Parameter	Value	Literature
Manning's n	0.120	(Chow, 1959), (Kalyanapu et al., 2009)
Impervious percentage [%]	15	(USACE Hydrologic Engineering Center, 2023b)
Minimum infiltration rate [mm/h]	3.8	(Cain, 2000)
Curve number [-]	52	(Chow, 1959)
Abstraction ratio [-]	0.05	(Baltas et al., 2007)

- Situation b: contour planting. Perpendicular to the flow direction (downwards the slope) lines of 'mixed forest' are created in the model. The same parameter characteristics as in table x are implemented.

6.5.2 Terraces and slopes

This NBS contains a whole set of options. The whole are can be changed by decreasing or increasing the elevation, platforms (think of rice fields) can be created, or small dams can be created on the slopes. Since the study area is an urban area, it is difficult to change the whole elevation in an area. Creating platforms is also difficult due to this reason. Therefore, another option is investigated: small dams are created (a) perpendicular to the water flow. This method is a bit similar to creating platforms but then on a smaller scale which can be applied in urban area. In the model the small dams are implemented as small, impenetrable, structures.

Figure 52 - Example of small dams on a slope

To test the effect on the water system the same two different sub catchments are evaluated for the same reasons as stated in section 6.5.1. In Figure 33 the chosen catchments can be seen (1 and 8). Next to the figure, the characteristics of the chose sub catchments are shown. The sub catchments are tested for the following implementation: small dams are applied perpendicular to the flow of the water in the catchment. Since the area is an urban area the dams cannot be too high since whole buildings would flood. Consequently, smaller but more dams are placed in urban areas. The dams are 10 cm heigh and the width is 10 cm. According to literature this is a common size (Lucas-Borja et al., 2021).

6.5.3 River and stream renaturation

Regarding this NBS there are two main methods possible. Make a drain green by creating a rough bed by adding vegetation (a), and create floodplains next to each drain with vegetation (b). For the first method, the drain obtains the following values (Chow, 1959) and retains its original U-shape. The size of the U-shape differs per location. At largest, the current drains have a cross-sectional area of 1.5m^2 (Figure 60).

Table 13 - Model parameters for the renaturation of drains

Parameter	Value
Manning's n	0.100
Impervious percentage [%]	30
Minimum infiltration rate [mm/h]	3.8
Curve number [-]	60
Abstraction ratio [-]	0.05

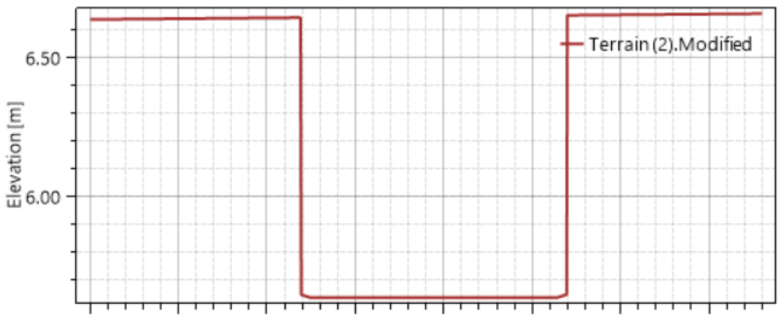


Figure 53 - Cross-section of drains for NBS 3a where only the vegetation is implemented in the drains

The second method cannot be applied everywhere since there is limited space to incorporate floodplains everywhere. This would merely lead to an increase in capacity and not an increase in vegetated perimeter. To account for this limited space but still maintain the effects of a vegetated floodplain, the drains are given a more natural cross-section with sloping sides which function as floodplains. The drain gets the same values as above but the shape is changed, see Figure 54. This increase the cross-sectional area with 1.1m^2, making a total of 2.6m^2 (73% increase). The smaller drains are also increased with 73% to make it consistent.

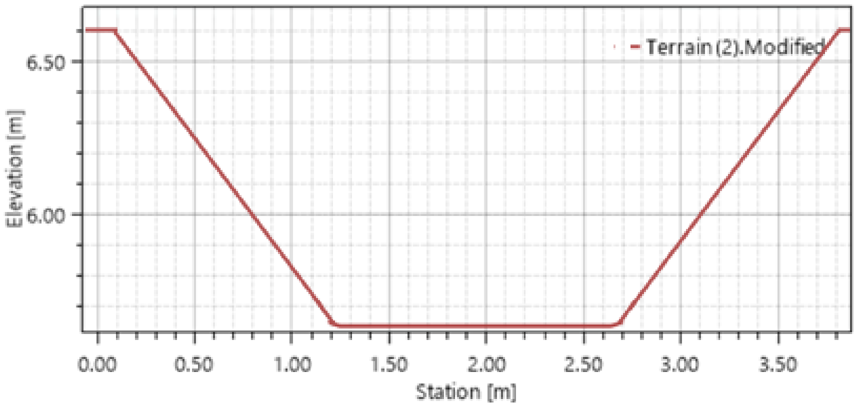


Figure 54 - Cross-section of drains according to NBS 3a where the capacity is increased and vegetation is implemented

The two drainage systems (orange lines) are investigated, displayed in Figure 55. For both drainage systems only the upstream parts are used for analysis (yellow areas). Since the sensitivity analysis already showed that downstream increase of roughness of the drainage channels does not reduce water depth and inundated area. The downstream area is defined as the 50% of the drainage system that has the highest elevation.

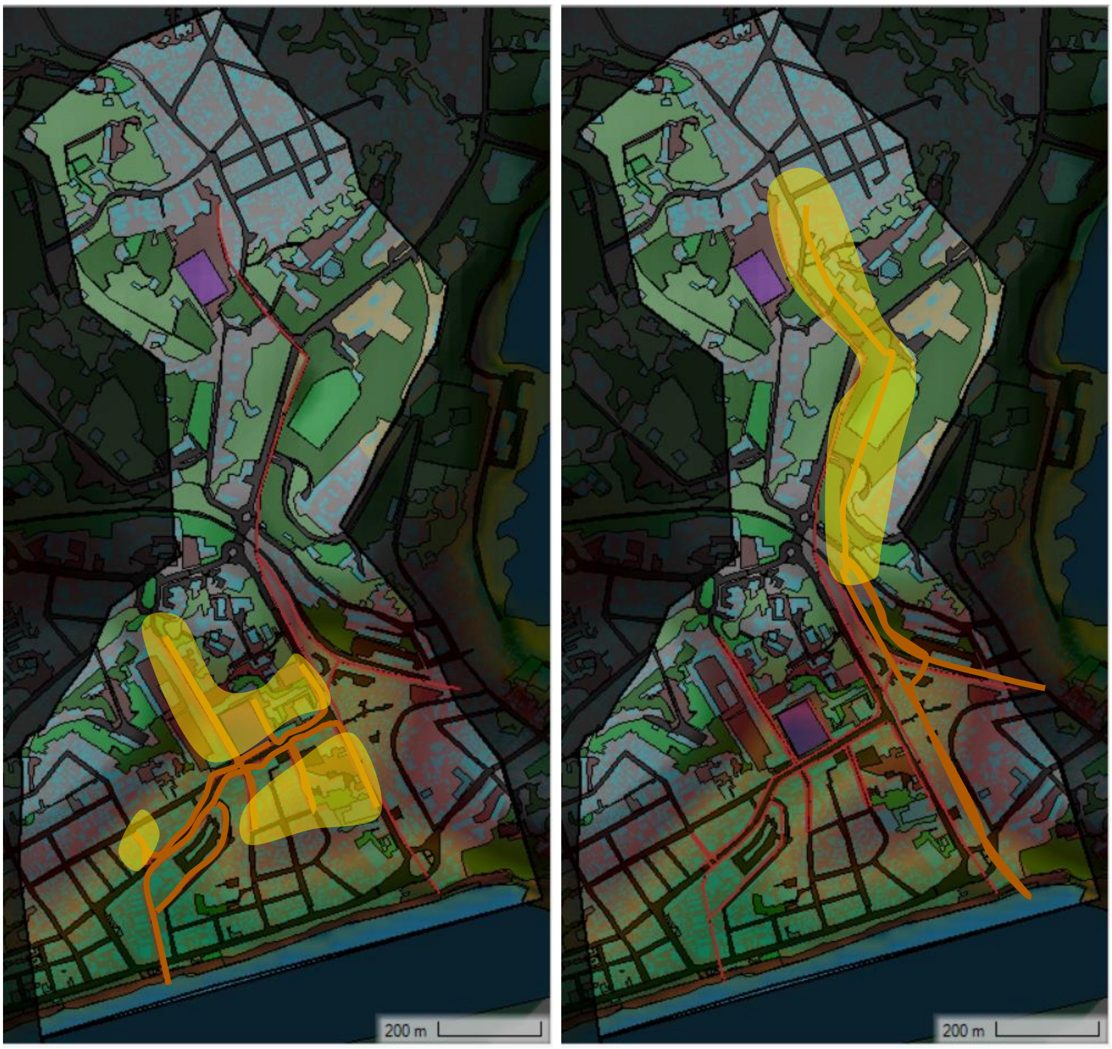


Figure 55 - Drainage systems (orange/red) in the catchment and upstream locations of drains in each system

6.5.4 Bioretention areas

Regarding bioretention areas there are a lot of options (Ourloglou et al., 2020b). One can think of bioswales (a), green roofs (b) or permeable pavement (c). Each option has the characteristic that is creates a natural storage area for the water.

a

b

c


Figure 56 - Three different bioretention pictures (source:)

Bioswales (a) are implemented according to the parameter options that are stated above. They are constructed at several locations to see their effect. These locations are indicated in the following Figure 57. The locations are chosen because there is room for implementation: an artificial soccer pitch, grassland or bare area. Moreover, they are located near the core of the water system (around the drains) where most of the water flows. From the sensitivity analysis it could be seen in the inundation maps that water accumulates in the local minima, these locations are chosen for implementation. Literature stated that upstream implementation (near the edge of the catchment or uphill) would not work since most of the water would enter the system after the retention area.

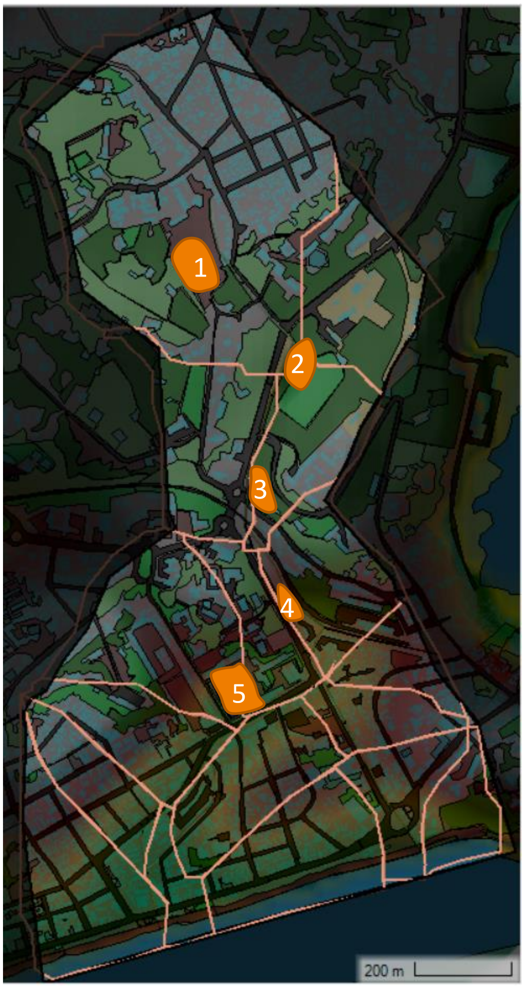


Figure 57 - Catchment and implementation locations of bioswales

In addition their slopes are 4:1 since this is the ideal slope according to literature (Nacto, n.d.). The maximum depth in comparison to the adjacent ground level is 1m. The surface area and volume depends on the location, but the following table summarizes the dimensions:

Table 14 - Overview of the dimensions of the bioswales

Bioswale nr.	Surface area [m²]	Perimeter [m]	Volume [m³]
1	10294	392	10245
2	5578	309	5539
3	3798	260	3765
4	2231	203	2206
5	8138	349	8094

Green roofs (b) can be modelled by using the parameters in Table 15 below or by applying a rainfall correction (Liu et al., 2021a). A commonly used method is adjustment of the rainfall distribution by estimating the effect of the green roofs and reducing this from the modelled rainfall (Q. Zhang et al., 2015). This reduction factor is obtained from the green roof characteristics, and is applied to the rainfall. However, this impacts the whole rainfall distribution, creating an unreal situation since not the whole area consists of a building footprint which is normally the case when using this method. In this study, the abstraction ratio is changed together with the CN value. This way initial abstraction takes place which accounts for the storage of green roofs. The AR is increased with the reduction factor that is obtained from literature for general green roofs and the CN value is decreased according to literature value (Liu et al., 2021a).

All the options are incorporated by adjusting the five model parameters. For bioswales also the elevation is adjusted. The model parameters are displayed in the following table. The values are obtained from literature (Chow, 1959).

Table 15 - Overview of the characteristics of bioswale and permeable pavement model parameters

Parameter\Options	a	b	c
Manning's n [-]	0.090	0.040	0.030
Impervious percentage [%]	0	0	45
Minimum infiltration rate [mm/h]	3.8	3.8	3.8
Curve number [-]	54	92	68
Abstraction ratio [-]	0.05	0.58	0.05

Green roofs (b) are applied to each building footprint since this is easy to do in HEC-RAS and gives a good indication what would happen to the whole catchment. This is not realistic but should give an general idea of the effects. Since some buildings are not suitable, and others extremely well suitable, the assumption of applying the smallest possible green roof to the whole catchment should level out. There are a few types of green roofs: extensive, semi-intensive and intensive green roofs (Vegetal, 2014).

CRITERIA	Extensive green roofs	Semi-extensive green roofs	Intensive green roofs [roof garden]
Load-bearing component	CONCRETE WOOD TANBARK	CONCRETE	CONCRETE Maximum pitch 5%
Plant choice	Sedums, mosses, perennials	Perennials, smalll shrubs, lawns	Shrubs, trees, lawns
Thickness of growing medium	4 to 15 cm	12 to 30 cm	30 and over cm
Weight of complete system (kg/m²)	75 to 180	200 to 500	500 to 2000
Irrigation	No*	✓	✓
Maintenance			
Cost of roofing	€	€€€	€€€€

Figure 58 - Three types of green roofs and characteristics (Vegetal, 2014)

Due to the relatively light weight buildings in the urban area, extensive green roofs are used. In addition, the thickness of the growing medium is little, as well as the costs and maintenance. These factors need to be considered for this type of urban areas in Africa such as the catchment. For extensive green roofs the lightest version is chosen. For green roof type GR-5, the substrate (S1) has a thickness of 5 cm, with an average CN value of 92 (Liu et al., 2020). The impervious percentage is set to 0 because the CN value applies to the whole region. This type of green roof could store on average (considering wet and dry situations) 25.7% of the thickness, which is 12.85mm (Liu et al., 2020). In HEC-RAS this value is used as the initial abstraction. The abstraction ratio = initial abstraction divided by soil potential maximum retention. Leading to an abstraction ratio of 12.85/22.1 = 0.58. The manning's n value (n and the min. infiltration rate are the same as for a grass land cover.

Permeable pavement (c) is applied to all the side-walks, public parking spaces and residential parking spaces for the whole catchment in the first scenario. The values in for scenario c are used in the

HEC-RAS model. However, the spatial variability of land cover and elevation makes it difficult to retrieve a sound conclusion on this analysis alone. Therefore permeable pavement is also applied in a more defined and regulated area; sub catchment 1.

6.6 INDIVIDUAL EFFECTS URBAN NBS

The effects of the implemented urban NBS are presented and explained in this section. The effects are discussed according to the implementation sequence of the relevant urban NBS. This section answers the first part of the question: *"What are the individual and combined effects of NBS on urban runoff in a hydraulic model?".*

Up and till now the effects of changing the basis model are evaluated by looking at inundation depth, inundation extent and hydrographs. In addition, the surface runoff coefficients are calculated to capture all information. The runoff coefficient is calculated as the ratio between the total runoff (mm) and the precipitation (mm) (Ferreira et al., 2022). The surface area under the hydrograph results in the total amount of rain (mm) that will fall in the catchment. The surface area under the discharge graph results in the total volume of water that passes a certain point after some time. Dividing the volume by the area of the catchment results in the total runoff (mm). Consequently, the runoff coefficient could be calculated. It is good to note that this is calculated for a 4 hour period. This value is chosen since most of the surface runoff volume(>95%) left the catchment by then for all simulations. Before all water left the catchment a simulation of 12 hours is necessary. Simulating a period this long costs a lot of additional computation time. The current model takes around 15 minutes to run, increase the simulation time by a factor 3 results in a computation time around 40 minutes. Due to the large number of necessary computations the simulation time of 4 hours is chosen. After showing the results, a set of observations and conclusions is presented. In general, only the hydrographs (discharge curves) and the runoff coefficients are shown per implementation. This due to the fact that the effects of NBS are best visible in the hydrographs and runoff coefficients. In appendix 10.3 the inundation maps of each NBS implementation can be inspected for additional information about the NBS effect on the (maximum) spatial distribution of water.

6.6.1 Urban forest

There are three implementation options possible for sub catchment 1 and 8. Planting the whole area where possible (a), planting the whole are ((a) extreme), and contour planting (b). First, the discharge curves and runoff coefficients are shown for sub catchment 1.

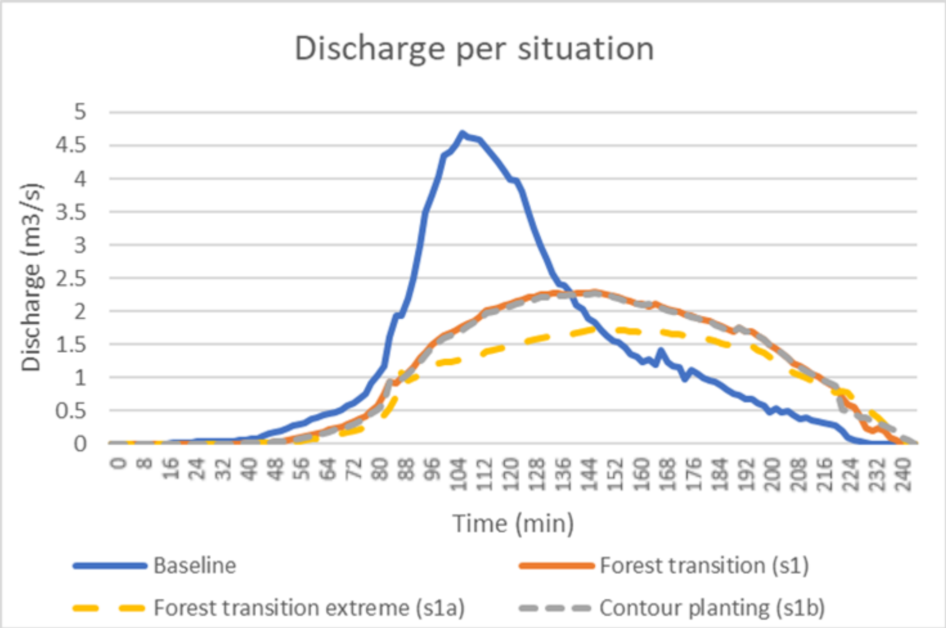


Figure 59 - Discharge curves at the pour point of the sub catchment for different urban forest situations

Table 16 - Runoff coefficients of sub catchment 1 for different scenarios of urban forest NBS

Situation	Runoff Coefficient
Base	0.78
1a	0.74
1a extreme	0.56
1b	0.75

For sub catchment 8, following results are obtained:

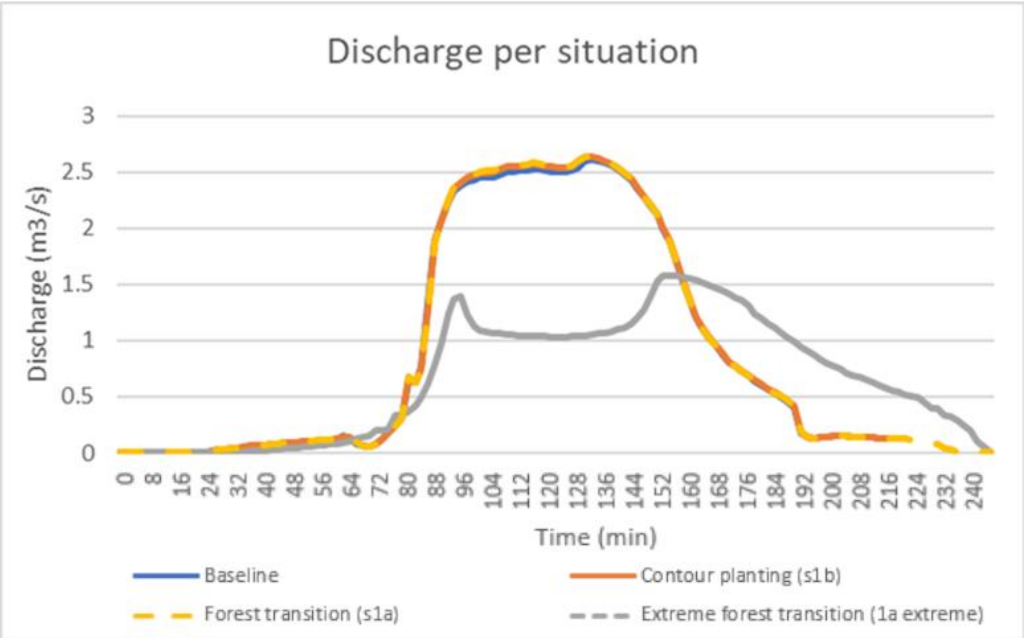


Figure 60 - Discharge curves at the pour point of the sub catchment 8 for different urban forest situations

Table 17 - Runoff coefficients of sub catchment 8 for different scenarios of urban forest NBS

Situation	Runoff Coefficient
Base	0.87
1a	0.84
1a extreme	0.65
1b	0.85

From the different results maps and numbers, some observations can be made. As can be seen in Table 16 and Table 17, the runoff coefficient is almost not influenced by the difference in implementation of contour planting or normal planting. This could be caused by the catchments characteristics: flat and a lot of residential area. Consequently, water is flowing slowly and the difference between contour planting and normal planting is not that extreme. The same holds for the discharge wave. This effect is also visible in the runoff coefficients. The second location has mild slopes, here the effect of forestation is better visible and reduces runoff coefficients with 26% whereas there is only a reduction of 5.2% in sub catchment 1. This could be caused by the steepness. In terms of runoff coefficient and the inundation map, there is a large difference between the extreme scenario and the other scenarios for both catchments. This could be due to the structure of the land cover of the area.

In sub catchment 1 the inundation map (appendix 10.3.1) does not display a significant change for contour planting or normal planting. The inundation maps show that if forestation takes places near the lowest elevation point in the sub catchment, the water depth locally rises. But reduces downstream, this can especially be seen for all scenarios in sub catchment 1 or the extreme scenario in sub catchment 9. The closer to the lowest point of elevation in a catchment, the more visible this effect is.

In sub catchment 8, the difference between the normal NBS implementations and the extreme scenario is much larger in terms of discharge wave, inundation depth and runoff coefficient. It can be seen that for a catchment with large elevation differences, urban forests help reducing the peak discharge wave, reduce water depths, but the total runoff will not decrease that much. For an area with milder slopes, the opposite is true.

6.6.2 Terraces and slopes

The small dams which create terraces are 10 cm heigh and placed according to the following map. They are placed in sub catchment 1 and in the whole area. In catchment 1, a total length of 3203m of small dams are placed. In the whole catchment a total of 11235m of dams are placed.

Sub catchment 1

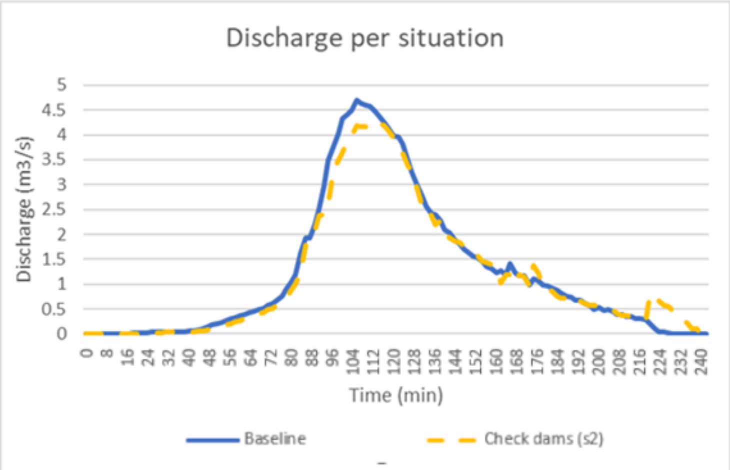


Figure 61 - Discharge comparison of the implementation of the check dams for sub catchment 1

Whole catchment

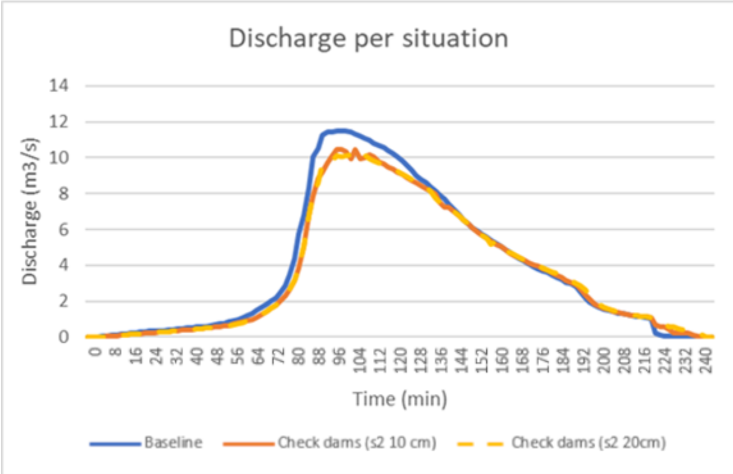


Figure 62 - Discharge comparison of the implementation of the check dams for the whole catchment

Table 18 - Runoff coefficients of implementation of check dams in the whole catchment and sub catchment 1

Situation\ Runoff coefficient	(a) Sub catchment 1 (h=10cm)	Whole catchment (h=10cm)	Whole catchment (h= 20cm)
Base	0.78	0.64	0.64
2	0.72	0.59	0.58

From the inundation maps (appendix 10.3.2) it can be seen that introducing check dams results in small reduction of water depth. In the northern part of the catchment this effect is most visible, as well as in the southern part of the catchment in the centre of the urban area. Interesting to see, that near the middle of the catchment small increase in water depth is visible in Figure 85. This could be caused by delay of upstream water that now confluences with water near these locations, their discharge waves are aligned.

For both discharge graphs the general shape remains the same, but with a lower peak discharge and a small shift to the right. Peak discharge drops with 0.5 m^3/s (11%) for sub catchment 1, and with 1.7 m^3/s (15%) for the whole catchment. is delayed due to the check dams. Increase of the height of check dams (20 cm instead of 10 cm), but leaving the dams at the same location, did not lead to significant difference. The runoff coefficients did decrease with 7.7% for the sub catchment 1 and with 7.9% for the whole catchment. Consequently, check dams have more influence on reducing the discharge peak than decreasing the total runoff. In addition, the magnitude of influence is larger for the discharge curve than the runoff coefficient.

6.6.3 River and stream renaturation.

The methods of increasing the permeability and roughness of the current upstream drainage channels is applied in HEC-RAS (a), in addition the storage volume is also increased of the drainage channels by creating small floodplains(b). This results in the following results for the northern drainage system.

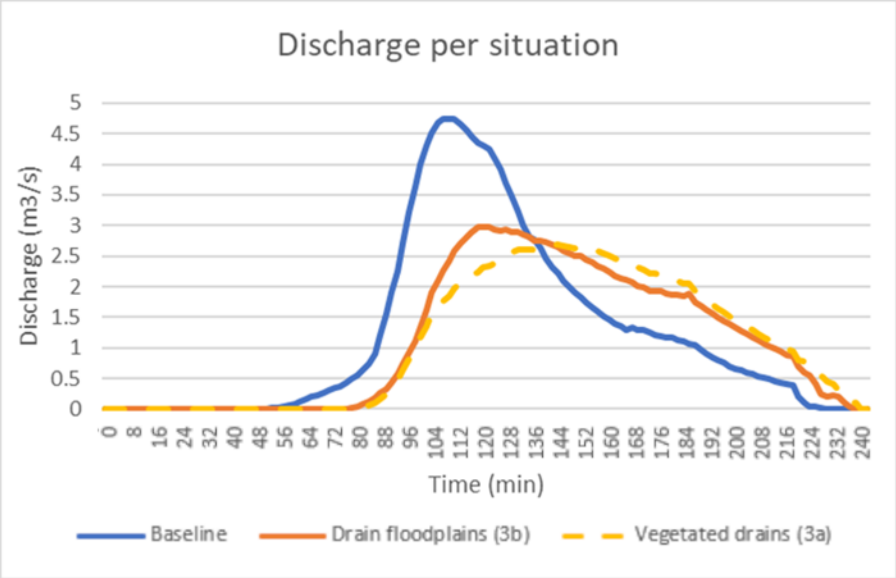


Figure 63 - Different discharge curves for stream renaturation in upstream part of the northern drainage catchment (grey area). In orange the effects of floodplains in the drains, and in yellow the effects of vegetated drains.

To be able to see the effect of drains in terms of the runoff coefficient. The whole top area (sub catchment 1,2,3,4) are selected. Measurement point 3 is used as reference since all the water from the upstream area surpasses this point. This results in the following runoff coefficients:

Table 19 - Runoff coefficients of the northern drainage system and stream renaturation

Situation	Runoff Coefficient
Base	0.51
3a	0.43
3b	0.43

The effect on the water system is also checked in the southern drainage catchment (green area). These results are displayed below. Since the results for scenario a and b are almost identical, only one inundation difference map is shown in appendix 10.3.3. And in the table below the same runoff coefficient is obtained. In addition, an extreme scenario is visualised, where all the drains in southern (green) drainage catchment have increased roughness instead of only the drains upstream in the southern catchment. Increasing the storage volume showed almost the same behaviour, so also here only one plot is generated.

Table 20 - Runoff coefficients for the southern drainage system and stream renaturation

Situation	Runoff Coefficient
Base	0.63
3a/3b	0.62
3a/3b extreme	0.45

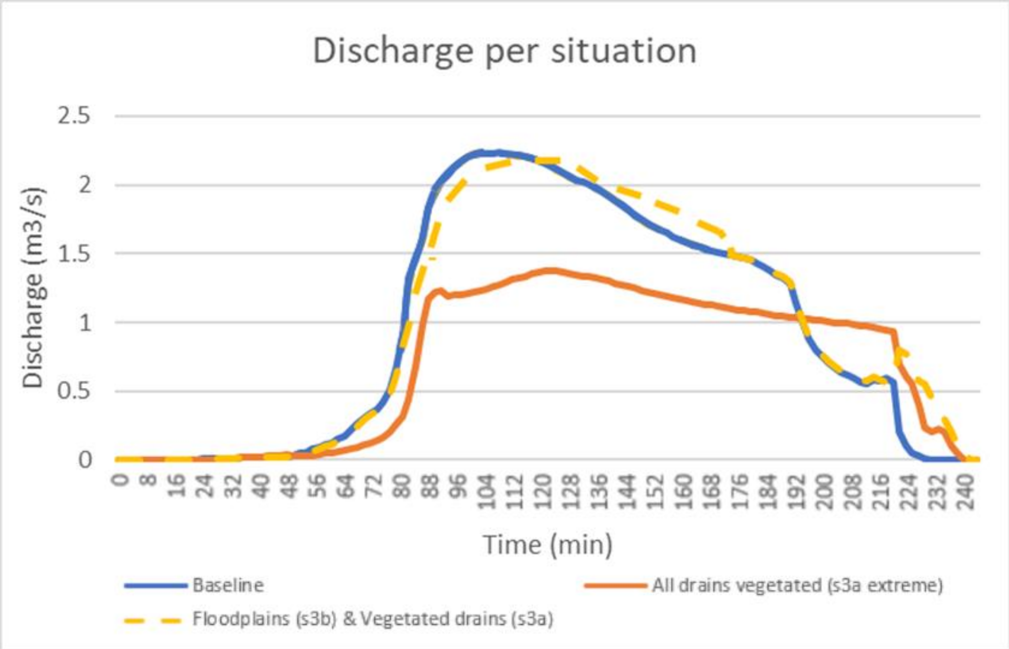


Figure 64 - Discharge curves for the stream renaturation effects in the southern catchment. In orange the effects for the situation where all drains are vegetated (not only upstream). In yellow the effects when the drains are vegetated or/and have a floodplain in the southern catchment.

Increasing the roughness upstream leads to local increase in water depth for both scenarios (3a and 3b) for the northern drainage catchment according to the inundation maps (appendix 10.3.3). The increase in roughness and capacity does not result in increasing water depth more upstream, whereas only increasing the roughness causes increase in water depth even further upstream. Both scenarios 3a and 3b results in decrease in water depth downstream (up to almost 10 cm). The southern drainage system does not experience increase or decrease in water depth for most of the area. Only for the extreme scenario where all the drains have increased roughness and volume.

The peak discharge the area of the northern drainage system reduces significantly from 4.8 m3/s to 2.7 m^3/s when only the roughness is increased (a) and to 3 m^3/s for the scenario where storage and roughness is increased (3b). This difference can be explained by the effect of more volume and a larger wet perimeter with vegetation that obstructs water for the second scenario. The discharge wave is for both scenarios a bit wider and less steep. The southern drainage system experiences no significant change for both scenario 3a and 3b. Only when introducing an extreme scenario, where all drains (not only upstream) have increased roughness, the discharge wave is influenced significantly. The highest peak is lower (from 2.3 m^3/s to 1.4 m^3/s) and the discharge waves gets a more rectangular shape.

The runoff coefficient for the northern drainage part is no different for both scenarios. This is the same for the southern drainage system. The coefficient itself is approximately 16% lower (0.51 to 0.43). Implementing an extreme scenario where all the drains in the southern system have increased roughness and volume leads to a sharp decrease in runoff coefficient (from 0.63 to 0.45). For scenario a and b the runoff coefficient for the southern drainage area

6.6.4 Bioretention areas

The effects of the different bioretention NBS are provided in this section. The hydrographs (discharge curves) and runoff coefficients are given. In appendix 10.3.4 the inundation maps can be found.

Bioswales

The bioswales are implemented according to the procedure and dimensions given in section 6.5.4 An implementation figure of the bioswales can be found in the appendix 10.3.4. The effects on the hydrograph are visualized below as well as the runoff coefficient:

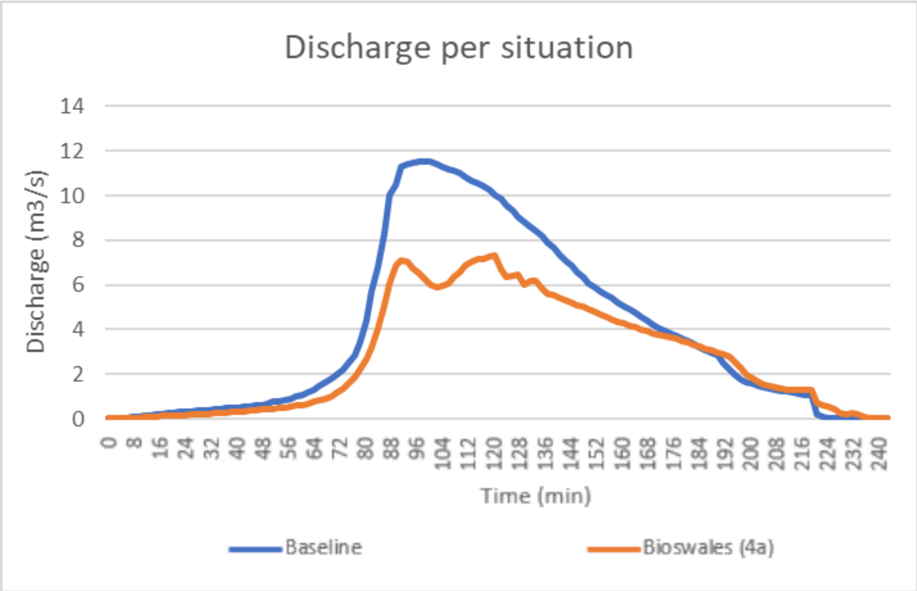


Figure 65 - Discharge curves for the whole catchment

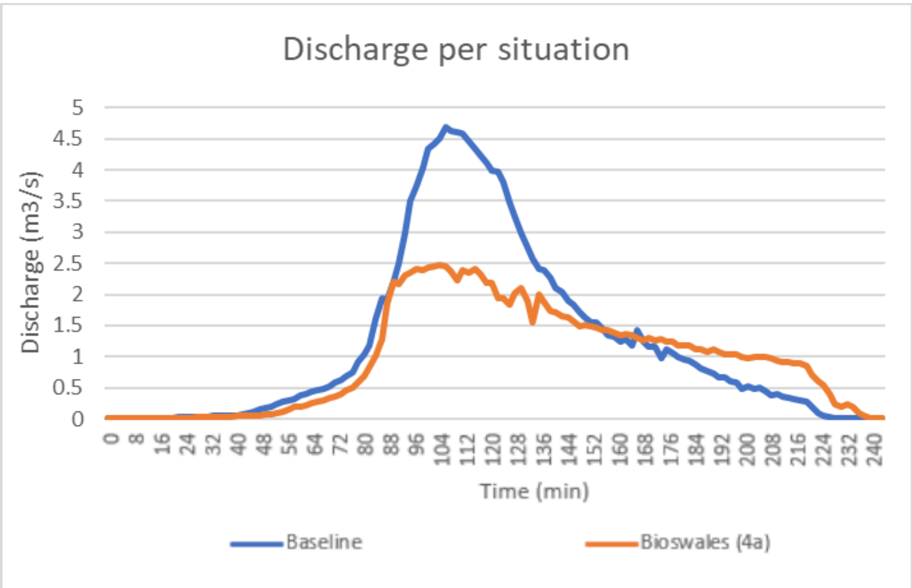


Figure 66 - Discharge curves for sub catchment 1

Table 21 - Runoff coefficients for bioswale implementation

Situation	Runoff Coefficient	Sub catchment 1
Base	0.64	0.78
4a	0.45	0.60

Introduction of bioswales results in local increase of water depth in comparison with the base situation due to the increased retention capacity. At all other places the water depth is reduced significantly (up to 17 cm). The decrease in inundation depth and extend covers the whole catchment.

The maximum discharge peak is significantly lower for the whole catchment, 7.2 m^3/s versus 11.7 m^3/s (38.5%). For sub catchment 1 the percentual change is even more; 45.7% (2.5 m^3/s versus 4.6 m^3/s). The shape of for both situations changes as well. The discharge waves becomes a lot more flat. For sub catchment 1 the discharge stays a bit higher for a longer period of time. Around the maximum peak discharge there are also more fluctuations visible. The decrease, flatter shape, and fluctuations are caused by the characteristics of the (sub) catchment. Sub catchment 1 has steep slopes and a clear lowest point of elevation where the retention area is located and all water surpasses. The size of the bioswale is consequently largely connected to the reduction in maximum discharge.

In with the maximum discharge reduction, the runoff coefficients reduce significantly as well. For the whole catchment a reduction of 29.7% is obtained, and for sub catchment 1 a reduction of 23% is obtained. This is an opposite effect than for the discharge curves. But it could already be seen that the right side of the graph (Figure 66) of sub catchment 1 exceeds the original discharge graph. Whereas for the whole catchment this effect is less present. This indicates that more water stays in the system, resulting in less runoff. Moreover, for the whole catchment, there is more infiltration space.

Green roof results

The building footprints are adjust according to the Table 15 in section 6.5.4. All the footprints in the whole catchments are effected. The inundation map in comparison with the base situation is shown in the appendix 10.3.5. The discharge and runoff coefficients are provided below.

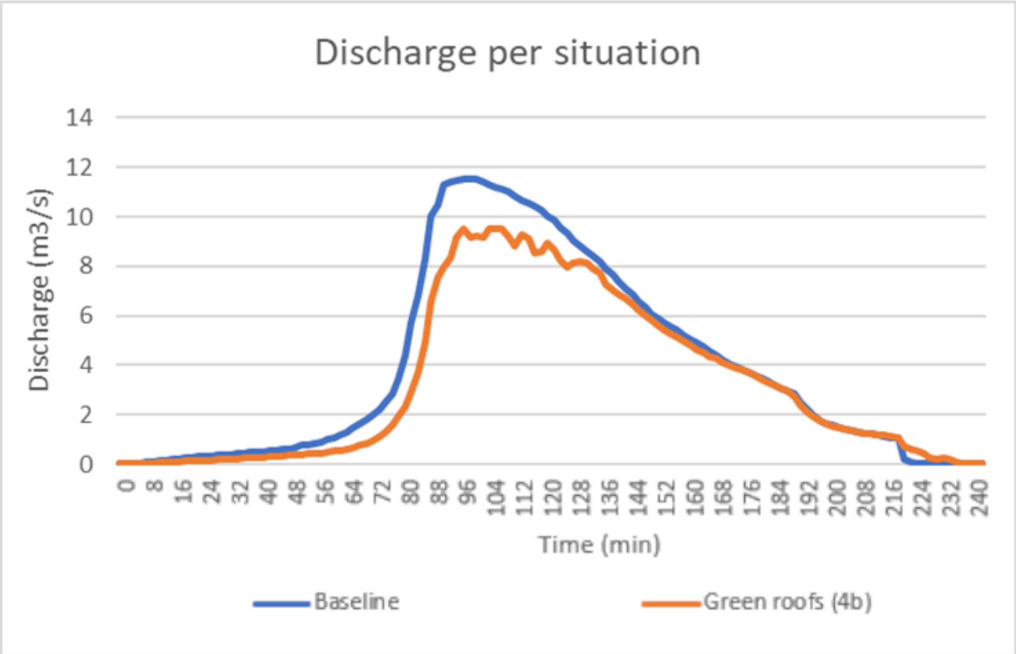


Figure 67 - Discharge curves for the whole catchment for green roof implementation

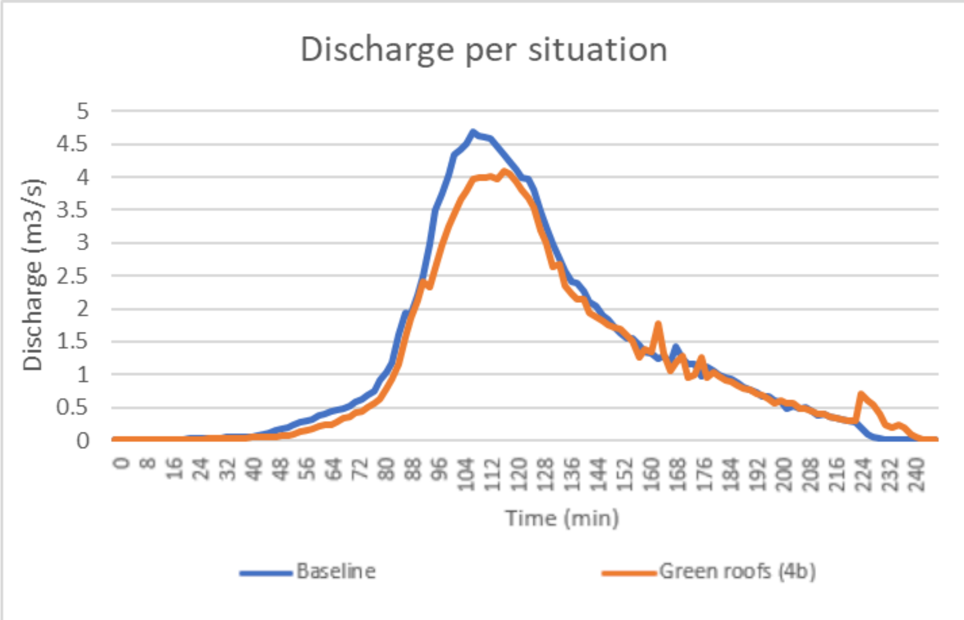


Figure 68 - Discharge curves for sub catchment 1 for green roof implementation

Table 22 - Runoff coefficients for green roof implementation

Situation	Runoff Coefficient	Sub catchment 1
Base	0.64	0.78
4b	0.53	0.70

Water inundation depths decrease everywhere up to a maximum of 9.7 centimetres at extreme location 2 (Figure 96 in appendix 10.3.5). There should not be increase in water depth since water is stored right after it falls (on the green roofs). However, on the right side of the southern drainage system a small increase can be seen. It is unclear how this happens, there might be an error in the model here.

The discharge peak decreases with approximately 2.2 m^3/s for the whole catchment. The shape of the discharge wave maintains the same shape. This is a decrease of 17.1 %. In sub catchment 1, the decrease of the max discharge is 10.9%. This difference is caused by the difference percentual area cover of green roofs.

The runoff coefficient of the whole catchment decreases with 17.1%. The total area of building footprints is 95234 m^2, thus the area of green roofs is 8.2% of the whole catchment area. The runoff coefficient of sub catchment 1 decreases with 10.3%. The total area of green roofs is 4.9% in sub catchment 1, giving a ratio of 0.48 (=4.7%/10.3%). Which is similar to the ratio of the whole catchment 0.45 (=8.2%/17.1%).

Permeable pavements

The effects of permeable pavement are visible in the following figures. Implementation is according to section 6.5.4. In total the permeable pavement area was 11845 m^2 for the whole catchment.

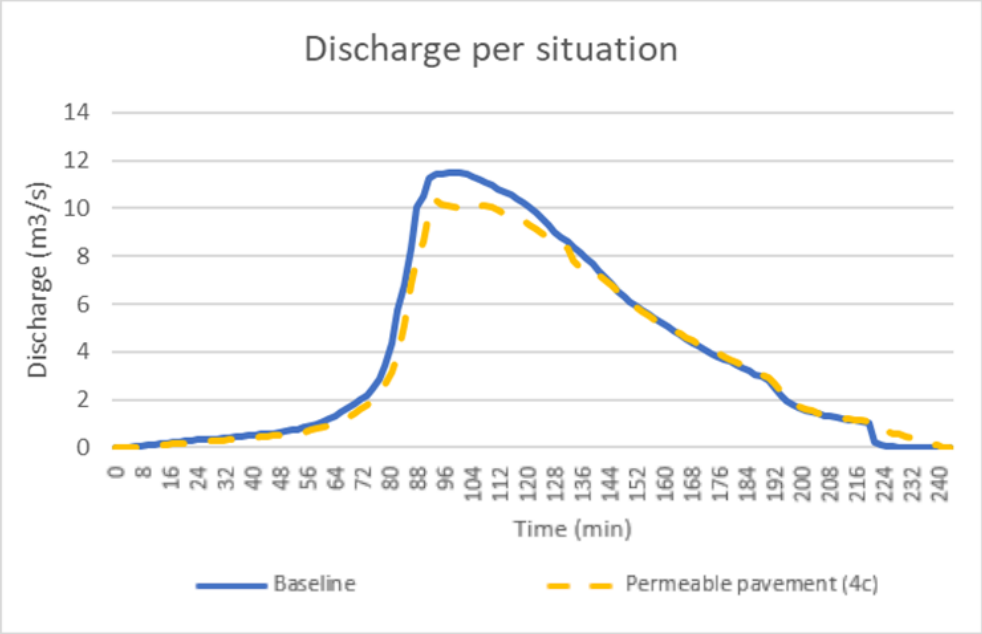


Figure 69 - Discharge curve for the whole catchment for permeable pavement implementation

Table 23 - Runoff coefficient for permeable pavement implementation

Situation	Runoff Coefficient
Base	0.64
4c	0.58

Inundation map shows small increase in water depth in urban areas (appendix 10.3.6). Probably caused by the increased roughness which generally results in local water depth increase in case of the presence of excessive water (P. Li et al., 2015). At other locations small decrease is visible, especially in the northern region (sub catchment 1). Introducing permeable pavement results in a small decrease in the surface runoff discharge. The general flow is a bit lower, but mainly the peak decreases (approximately 1 m^3/s). The total runoff coefficient reduces with 9.4% in due to implementation of permeable pavement. The total catchment area is 1.16 km^2. The permeable pavement area was 1.2% of the area (14325 m^2). If more private residential area could be converted, the runoff reduction would be even more.

6.6.5 General effects and conclusion

To get a comprehensive overview, a summarizing Table 24 is added here. The most prominent effects and conclusion are provided. The inundation map is left out since this would take up to much space. Only presenting the maximum decrease of water that was simulated would not give a good representation of the area, so this is left out as well.

Table 24 - General overview of all NBS implementations and the change in surface runoff coefficient and max discharge peak

Situation/Effect	Catchment	Surface runoff coefficient	Max discharge peak
Forest transition	1	-5.1%	-50.7%
	8	-26.4%	-0.3%
Extreme forest transition	1	-28.2%	-61.7%
	8	-25.3%	-39.5%
Contour planting	1	-3.8%	-50.2%
	8	-26.4%	-0.1%
Check dams (h = 10cm)	All	-7.8%	-12.0%
	1	-7.7%	-8.7%
Check dams (h = 20cm)	All	-9.4%	-11.3%
Upstream stream renaturation	1,2,3,4	-15.7%	-34.8%
	5,6,8,9,10,14	-1.6%	-0.4%
Upstream stream renaturation and expansion	1,2,3,4	-15.7%	-43.5%
	5,6,8,9,10,14	-1.6%	-0.4%
All streams renaturation and expansion	5,6,8,9,10,14	-28.6%	-41.3%
Bioswales	All	-29.7%	-36.8%
	1	-23.1%	-46.7%
Green roof	All	-10.3%	-20.5%
	1	-17.2%	-10.9%
Permeable pavement	All	-9.4%	-13.7%

From table 24 it can directly be noticed that most effects in terms of surface runoff coefficient are there for the forest transition measures, stream renaturation and bioswales. The maximum reduction is occurring for bioswales with -29.7% reduction. There are more measures that have significant influence on the maximum discharge peak. Forest transition, stream renaturation and bioswales cause the biggest changes (above 40%). The biggest influential measure is the extreme forest transition, with a reduction of 61.7% of peak discharge. Peak discharge and runoff coefficient are linked to each other. Runoff coefficient depends on the total area under the discharge curve. Consequently, if the discharge curve maintains the same shape, a reduction in peak discharge is almost directly linked to the surface runoff coefficient. As can be seen, the hydrographs change in terms of their shape due to NBS implementation. Causing it impossible to obtain a direct relationship.

Two different sub catchment areas (and the whole catchment) were selected to see the effects per catchment type. The effects are different in magnitude depending on the spatial characteristics. NBS in steep areas tend to influence the discharge more than the surface runoff coefficient. In general, all NBS have a larger effect on the maximum discharge peak than the surface runoff coefficient. Despite the fact that the discharge peak becomes lower, the total volume of water that leaves the area is not reduced with the same percentage. In areas with steeper slopes the water is also more concentrated and generally has a smaller inundation area but a large inundation depth. and flows through clear routes. Vice versa for flatter areas as can be seen from the inundation maps. It is also interesting to see that the difference in effect on both the runoff coefficient and max discharge curve is almost similar for the whole catchment and sub catchment 1 for check dams. The largest difference is 3.3% for the max discharge and 0.1% for the runoff coefficient. From all other NBS the next closest value is 2.9% and 9.9%, where most difference are much larger. This suggests that check dams are relatively influenced the least by catchment characteristics.

From the inundation maps of individual NBS (appendix 10.3) it could be seen that merely applying a rough type of vegetation in the upstream drains could be more efficient in terms of effect (and also impact to the environment) in comparison to also increasing the drainage capacity. Hence, focus on the drainage system in a catchment is important since its large impact. Almost all measures increase local inundation depth at the extreme locations or in the drainage system, but decrease inundation depth further downstream. Only the three storage type NBS green roofs, permeable pavement and bioswales fall not in this category.

From literature it was concluded that NBS focus on retention and delaying water. However, each NBS has a main focus. The results in this sections underline this main focus: Forest transition, contour planting, check dams, and river and stream renaturation focus on delaying water. Bioswales, green roofs and permeable pavement focus mainly on storing water. This effect is clearly visible when combining the inundation maps, the surface runoff coefficient and the discharge waves.

To get a better understanding of the difference between the individual NBS the unit effects per implemented m^2 of NBS are calculated. The percentual change of both the surface runoff coefficient and the max discharge peak is divided by the total area (in hectares) of the NBS. For this case study, with the described characteristics of each NBS, Table 25 give the unit effects. This helps comparing since the effect of each NBS is directly depending on the scale and spatial implementation of NBS. Now it can be noticed that check dams and stream renaturation have the highest unit effects. Thereafter bioretention measures have the highest unit effect and last but not least the urban forest measures come into play. Accordingly, this sequence indicates which NBS should be placed where, depending on the local space. In practice, more factors will determine which NBS are implemented, for example maintenance and placement costs. Interesting to see, the river and stream renaturation dominates the top of this Table 25 as well as the previous Table 24 with absolute change in effects. Previous research (Van der Zaag, 2022) provides unit effects which are in line with the found data in this study.

Table 25 - Unit effects per NBS implementation

Situation\Effect	Catchment	Length [m]	Area [m²]	Volume [m³]	Unit effect runoff coeff. [%/hectare]	Unit effect discharge [%/hectare]
Forest transition	1	-	92582	-	-0.01	-0.05
	8	-	17238	-	-0.15	0.00
Extreme forest transition	1	-	300479	-	-0.01	-0.02
	8	-	50085	-	-0.05	-0.08
Contour planting	1	-	30280	-	-0.01	-0.17
	8	-	6879	-	-0.38	0.00
Check dams (h = 10cm)	All	11235	1124	112	-0.69	-1.07
	1	3203	320	32	-2.41	-2.72
Check dams (h = 20cm)	All	11235	1124	112	-0.84	-1.01
Upstream stream renaturation	1,2,3,4	1174	1409	1242	-1.11	-2.47
	5,6,8,9,10,14	1323	973	788	-0.16	-0.04
Upstream stream renaturation and expansion	1,2,3,4	1174	1542	1335	-1.02	-2.82
	5,6,8,9,10,14	1323	1793	1302	-0.09	-0.02
All streams renaturation and expansion	5,6,8,9,10,14	1323	2342	1892	-1.22	-1.76
Bioswales	All	-	30139	29849	-0.10	-0.12
	1	-	10294	10245	-0.22	-0.45
Green roof	All	-	95234	-	-0.01	-0.02
	1	-	12336	-	-0.14	-0.09
Permeable pavement	All	-	11845	-	-0.08	-0.12

6.7 VALIDATION

This section answers the following research sub question: *"Are there any observed effects available in literature to validate the results?".* After the simulation of individual NBS effects these effects are validated in this section. This step is necessary to proceed to the next section where NBS are combined in order to substantiate the final outcomes.

There is hardly any data available of the inundation pattern in the original situation as well as possible NBS implementations. The small present data set consisting of flood marks is used by HKV for validation of the original model. Validation of NBS implementations is hard since no real observations of NBS implementations are present. The goal of this study is to provide insight in the effects of NBS implementation on the water system. Not to design exact measures to obtain defined results. Therefore, a more rough validation could suffice. In literature some effects of NBS are investigated. But they are very dependent on the location and Using this information the results of this study can be validated.

Runoff coefficients are the most interesting values that could be compared for validation. These coefficients are closely related to the storage in the area and the discharge curves. The following Table 26 compares literature values for the surface runoff coefficient. The maximum surface runoff coefficient is put in the second column. Only the maximum value is used for validation since this investigated in literature since this is the most interesting value for catchments. It is good to note, that it is very difficult to validate the results without actual data from the study area due to the spatial variability. In addition, in literature most of the percentages are relating to the area of the NBS itself but not the (sub) catchment. The latter is looked at in this research since the surface runoff in the whole area is the essential element which shows the effect of the NBS implementation on the (sub) catchment. Therefore not all values are close as is explained after the table below.

Table 26 - Validation of maximum surface runoff coefficients with literature

Situation/Effect	Max Surface runoff coefficient	Literature
Forest transition	-28.2%	26%-76% (Zheng et al., 2021), 25% (Shrestha et al., 2012), 57% (Waterschap Limburg, personal communication, 2022)
Contour planting	-26.4%	32% (Farahani et al., 2016)
Check dams	-9.4%	10% (Farahani et al., 2016), 12% (Yuan et al., 2022), 10.54% (G. Li et al., 2022)
Upstream stream renaturation	-15.7%	25%-40% (Wenzel et al., 2014)
Bioswales	-29.7%	45% - 59% (Filtrexx, 2021)
Green roof	-17.2%	10%-21% (Liu et al., 2021b)
Permeable pavement	-9.4%	50% (Zhu et al., 2019)

The values found in literature about bioswales are much higher. This is caused by the fact that the value in literature relates to the bioswale itself and the value in this study relates to the whole catchment. The same holds for stream renaturation and permeable pavement. It is hard to say something constructive about these two NBS. Except that in comparison with the other NBS form literature the change in surface runoff coefficient is not exceptionally high. And that it is logical that the literature value is significantly higher than the simulation value due to the spatial dependency and characteristic of a study area. Besides these three values, the other values fall in the same order of magnitude. In conclusion, the reduction in surface runoff coefficient has the same magnitude as values that can be found in literature. The difference is due to the size and characteristics of the catchment (/land-cover) of the simulation or literature reports. The chosen implementation methods suffices and provides realistic outcomes. With this information in mind, the simulated effects of NBS can be used to make NBS design choices in practice

6.8 COMBINED NBS EFFECTS

From section 6.6, it can be noticed that each individual NBS has its own effects in terms of inundation depth, inundation area, peak discharge, and runoff coefficient. These effects depend on the scale of implementation (size) and the spatial distribution. To be able to compare the results for individual and combined NBS, the NBS are implemented together in exactly the same way (in terms of size and location) as described in section 6.5. This has consequences for the possible combinations, there occurs some overlap of NBS. This section answers the second part of the question: *"What are the individual and combined effects of NBS on urban runoff in a hydraulic model?".*

The objective of this section is to see how the effects of combined NBS enhance or decrease individual NBS effects in a structured way, so not only the assumed most effective combinations are researched. If all 8 NBS combinations are investigated independently, this would result in 255 situations. Since a lot of combinations have the same effect, this would give limited additional insight with respect to including NBS families only. Therefore, the NBS are grouped per family since each family has roughly the same effects. This results in 11 combinations:

Table 27 - Combinations of individual NBS

Nr.	Combination name	NBS nr.
1	Forest transition – terraces and slopes	1-2
2	Forest transition – river and stream renaturation	1-3
3	Forest transition – bioretention areas	1-4
4	Forest transition – terraces and slopes – bioretention areas	1-2-4
5	Forest transition – river and stream renaturation - bioretention areas	1-3-4
6	Forest transition – river and stream renaturation – terraces and slopes	1-3-2
7	Forest transition – terraces and slopes - river and stream renaturation – bioretention areas	1-2-3-4
8	Terraces and slopes – river and stream renaturation	2-3
9	Terraces and slopes – bioretention areas	2-4
10	Bioretention areas – river and stream renaturation	3-4
11	Terraces and slopes – river and stream renaturation – bioretention areas	2-3-4

Implementation of the NBS families happens according to the implementation described in section 6.5. It is good to note that only forestation is limited a bit due to overlapping NBS such as contour planting, bio swales, and terraces and slopes. All other NBS are implemented at the same scale as with the individual implementation. From the results it could be noticed that several scenario's resulted in approximately the same results. To visualize some scenarios, a two implementation figures are shown below of scenario 4 and 8. The other scenarios use the same NBS implementations but for different combinations. Details of the exact implementation can be found in the table of the appendix 10.4.1.

Due to similarity in inundation maps it is hard to spot the difference from a rigid 2D map. When exploring the maps, the scenarios could be grouped in 4 generic flood patterns below:

- Scenario 1; shows small reduction (10cm) in flooding only at the location of the three critical points (Figure 34).

- Scenarios 2 – 6 – 8; show large increase in water depth (30cm) at the critical points.
- Scenarios 3 – 4 – 9; show reduction of water depth all over the catchment (up to 30 cm), and increase in water depth (30cm) at the bioswale locations.
- Scenarios 5 – 7 – 10 – 11; show a lot of increase of water depth in the drains (30cm) and at the bioswale locations, and a reduction of water depth all over the catchment (up to 30cm).

When looking at the combination of scenarios, it can be seen that there are two main influential NBS; bioretention areas and stream renaturation. These two NBS mainly determine the inundation map. This corresponds with the sensitivity analysis where these two NBS had a lot of influence on the inundation depth and extent varying over the map. The inundation maps of these variations can be found in appendix 10.4.3. The discharge wave of each scenario are shown in the following graph:

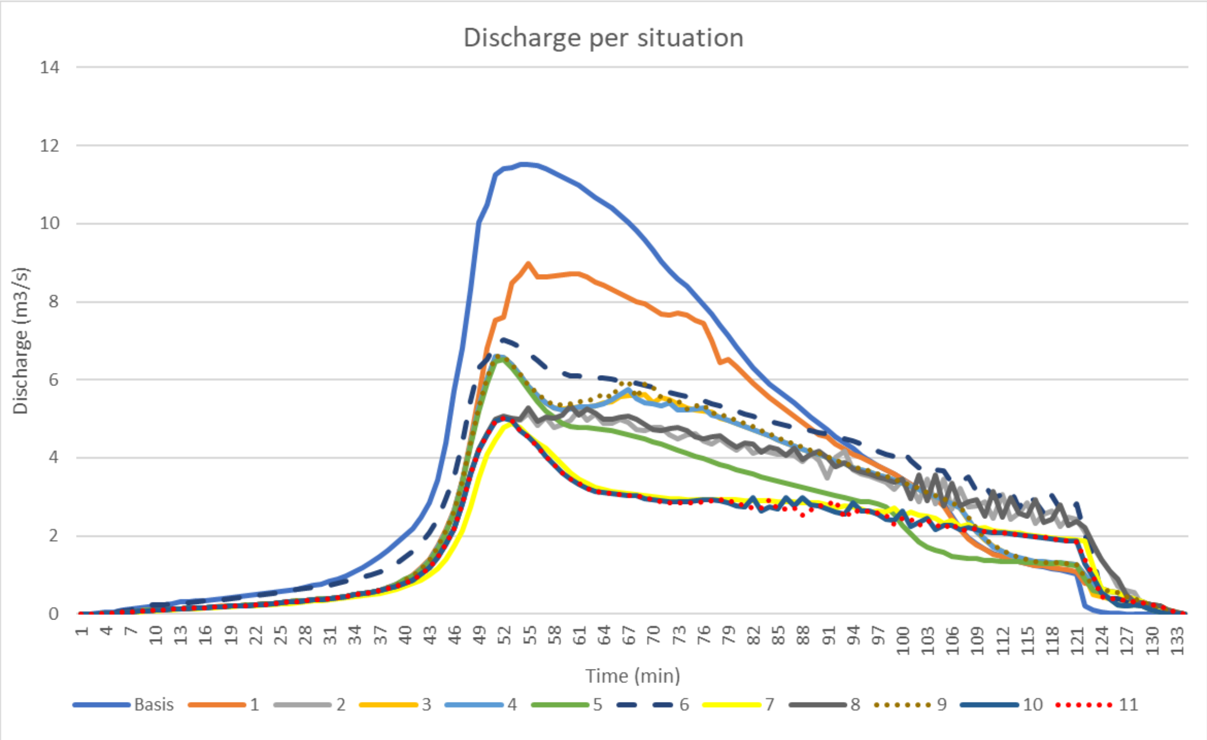


Figure 70 - Discharge curves of all combined NBS scenarios

In addition, the runoff coefficients are calculated per scenario:

Table 28 - Runoff coefficients per scenario of NBS implementations

Scenario	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***
Runoff coefficient	0.52	0.40	0.42	0.42	0.35	0.40	0.30	0.41	0.42	0.31	0.31

When looking at the top two inundation maps in appendix 10.4.3, it can be seen that combining the NBS results in more extreme differences in the catchment. At some places the water depth decreases with more than 30 cm, and at some other locations the water depth increases. A side note here is that at the bioswale locations the water depth increases, but the water level does not increase there. Bioswales and vegetated drains results in even more increase in water depth at the bioswale location.

Each NBS scenario reduces the discharge peak of all the water the flows out of the whole catchment. The combinations change the shape of the discharge wave in comparison with the basis discharge wave. In general, the wave becomes flatter when more NBS are introduced. Especially, when all NBS are applied. In addition, the shape becomes a bit wider than in the basis situation. Terraces and slopes contributes little in comparison with the other NBS. Combining 1-2, 1-3 and 1-4 shows a significant difference between the discharge curves. Moreover, the more NBS are applied, the flatter the discharge peak becomes. Only around 102 minutes the highest peak remains and becomes more visible whereas the discharge curve at later stages becomes flatter. This coincides with the peak of the precipitation event which significantly peaks around 102 minutes. The NBS are apparently not able to cope with this extreme overload of the water system. The discharge a few minutes later, around 118 minutes is reduced more: approximately 68% instead of 57% at 102 minutes. The fast decreasing and increasing discharge curve after 200 minutes e for situation 2, 6 and 8 is also interesting to notice. The common factor is the stream renaturation. The quickly fluctuating discharge around 200 min could be caused by a numerical error in the model.

The combination of NBS results in reducing runoff coefficient, varying from 0.30 up and till 0.52 instead of 0.64. The more NBS are added, the more de runoff coefficient value reduces. However, it can be seen that there is almost no difference between scenario 11, 10, and 7. Only implementing river and stream renaturation and bioretention areas accounts for the vast majority of change. It can be noticed that terraces and slopes contribute the least in this situation. Scenario 1, 8, and 9 are not coming close.

7. DISCUSSION & RECOMMENDATIONS

This section addresses the following topics regarding this study: NBS modelling, limitations of the research, and interpretation of results. First the research is discussed, thereafter recommendations for future research are given.

7.1 DISCUSSION

The discussion section is ordered in four sections: modelling, research limitations, results interpretation and generic lessons.

7.1.1 Modelling

A general limitation is the lack of real-life data from the study area. This results in DTM limitations, limited availability of soil characteristics, rainfall distribution estimation, and little land cover information. There are also some limitations due to the use of HEC-RAS. It is a 2D model and does not take into account effects of turbulence that can affect flow patterns in real life. Due to area characteristics such as presence of largely impermeable regions, sub-surface features will have limited impact. Furthermore, the implementation of NBS is limited to the model parameters that are present in HEC-RAS. From these parameters, the manning's n value (roughness) is the most influential parameter in this hydraulic HEC-RAS model, and from literature it was observed that in general the roughness parameter is most important (Kalyanapu et al., 2009). To improve the land cover of models in data scarce regions, satellite images can be used to draw a more detailed land cover which addresses the roughness parameter. Only trees make it hard to create exact polygons due to their larger span width.

Due to the lack of data, the SCS CN method is chosen. This method is accurate with limited amount of data. Especially, for less permeable soils with high curve numbers the SCS CN method is a good choice. This is applicable to the case study area, which is also small (1.16 km^2). The latter justifies the fact that by choosing the SCS CN method, temporal variation in rainfall excess intensity is not considered (Baiamonte, 2019). The SCS CN method is a useful approach for computing direct runoff (Grimaldi et al., 2013).

In order to represent reality, simplifications are made in hydraulic models which could assess the impact of runoff discharge waves due to extreme rainfall. Numerical hydraulic models make use of average properties for a spatial grid. To increase computational speed, the water system's geometry is simplified. As a result, principal flow patterns are relatively uncertain (especially with flat areas), impeding effective implementation of NBS. The inundation pattern displays some so called 'wet islands' (can be seen in Figure 34 in the top right corner). This is not entirely accurate and should be considered. This is the results of HEC-RAS sub grid configuration's struggle to produce a continuous inundation pattern. Before water flows into the second grid, HEC-RAS does not require the first grid to be filled. As a result, water can travel a long distance unless there is a barrier. Introduction of a finer mesh around the critical points (drains for example) mitigates this problem.

7.1.2 Research limitations

Due to a lack of data, validation was difficult. Monitoring data about NBS in the study area is not available for validation. The main validation is based on literature. Little literature is available to validate NBS due to the topic and spatial variability. Only the magnitude of NBS effects on the water system characteristics are compared.

This research considered only a static model, not considering dynamic processes such as erosion and sedimentation. Consequently, analysis of the effects of NBS over a long-time span (multiple years) if their characteristics are changed is impossible. In addition, NBS cannot be incorporated to its full extent since it consists of living systems. For instance, hydraulic conductivity is influenced by seasonal dependency and changing soil or vegetation characteristics. Seasonal variation is not considered in this model because in urbanized catchments since a variation of the ratio over seasons is expected to be small for urban areas. Since this research only focused on the effect of NBS on the water system characteristics, other side benefits of NBS are not considered.

7.1.3 Results interpretation

Interpretation of the results is difficult since not all NBS can be compared directly. In addition, the results are only valid for the input that is given in this study. Results obtained are closely related to the study area characteristics and model characteristics. Validation proved that the results are in the range of realistic values. Despite the dependency of assumptions and local context, this study can give an indication of what would happen to similar urban areas (especially in Africa) when implementing the investigated NBS. In this case, with limited validation, tendencies are worth more than only quantitative numbers.

In general, the combination of inundation depth, inundation area, surface discharge and runoff coefficient should always be investigated together. Investigating individual effects leads to the wrong conclusion due to the complexity of the water system. Moreover, all NBS have a larger effect on the maximum discharge peak than the surface runoff coefficient. Local effects and global effects are often contradictory. In addition, the unit effects scaled from large to small are almost the opposite from the effects visible for individual NBS and combined NBS. The unit effect of each NBS could give an indication how the NBS relate to each other. However, one should be careful when drawing conclusions. In reality one cannot implement only the NBS measures with the smallest surface area and largest change in effect due to local constraints in terms of space and implementation costs or maintenance cost for example. Moreover, NBS variability should be considered. For example, bioswales can vary in depth. Green roofs and permeable pavement have different retention capacities and check dams may vary in height. Thus, the height is important as well to keep in mind. The unit effects are only representative for the characteristics of the NBS implemented in this study. Consequently, one should carefully implement NBS and consider the size and distribution of NBS implementation in future research.

From the sensitivity analysis it could be seen that extreme NBS measures (forestation of the whole upstream part of the catchment) could not achieve the same results as diverting all water from this area with a deep channel (as mentioned in the sensitivity analysis, and visualised in appendix 10.2.1). Even combinations of realistic NBS scenarios, bioretention, vegetated streams and urban forest came nowhere close to the reduction in inundation depth downstream. Consequently, grey infrastructure measures might be necessary to obtain more inundation depth reduction.

7.1.4 Generic lessons

Overall, the application of NBS requires a comprehensive and participatory approach that considers the local context and environmental challenges. Area characteristics are most important for NBS implementation. The first scan of local context is very important since it rules out a lot of NBS possibilities and determines the scale and size of NBS. This study showed with the sensitivity analysis that the roughness parameter is the most influential hydraulic parameter in a hydraulic HEC-RAS model. Since this parameter is directly linked to the land cover, identification of the land cover in a catchment is very important. Data scarcity could partially be assessed by assessing the land cover (and thus the roughness) via satellite imaginary.

All four effect parameters should be examined to have the best insight of the effects of NBS on a water system: inundation depth, inundation extent, discharge, and runoff coefficient. Individual effect parameters could give a wrong image of the situation. The max discharge peak might reduce, but if the surface runoff coefficient does not reduce, most of the water remains in the catchment. Consequently, the inundation maps are important as well. When determining suitable NBS, criteria for NBS implementation should be carefully considered. Local effects near the implementation could have opposite global effects. E.g. the water depth increases upstream, but the water depth and inundation extent decreases downstream. Especially, NBS that influence the vegetation (thus roughness) of an area could cause backwater effects.

A lot of African urban cities are located near the coast, downstream in a catchment. In very dense urban areas implementation of large scale vegetation and natural storage is a challenge. Due to the limited room in urban areas, upstream NBS could be a solution to divert, delay or store water which reduces the pressure on the water system in the (downstream) urban area. In addition, NBS with high unit effect could be used in the dense urban areas to address the necessary water system characteristics. It is advised to mix different NBS in one catchment. Isolated NBS implementation has local effects, primarily relevant for mitigating local flood impact. A whole system of NBS has more effect on the whole catchment and could mitigate flood risk for the whole catchment. From the sensitivity analysis and NBS implementation it became clear that NBS can reduce inundation depths and inundation area. However, the difference between implementation of extreme NBS conditions (e.g. forest transition of a whole upstream catchment area) could not achieve the same results as cutting of the whole upstream area. NBS can mitigate or prevent inundation up to a certain extent. To take care of all excessive water in the area grey infrastructure is necessary.

7.2 RECOMMENDATIONS

The used grid size is 24m x 24m. To obtain better results, a smaller grid size is advisable. For future research a grid of for example 5x5m should be used. Generally, as grid size increases, the magnitude and resolution of flood hazard in flow paths decreases. In addition to creating a correct land cover (and roughness values), buildings and structure could be incorporated in more detail (Schubert & Sanders, 2012). Other methods (BB, BH and BP) could be examined and incorporate of heights would result in more realistic details (Smith et al., n.d.).

Regarding modelling the soil characteristics and infiltration, local measurements are necessary. It is advised to investigate the local soil layers in terms of composition, layer thickness, hydraulic conductivity and water retaining capacity. When more data is available in a study area, the Green Ampt method might be a better infiltration method which takes into account the change of soil moisture in the soil over time (Bouvier et al., 2018). In this way, the seasonal effects can be accounted for. For example the initial abstraction ratio varies over seasons, especially in the case of non-urbanized catchments with a high percentage of area covered with vegetation. A higher value is expected during the vegetation period due to the occurrence of plants' interception. This makes it possible to investigate the effects of NBS over a longer time span. Future research should also consider the evolution of NBS over time because this influences the effects.

It is advisable to monitor implementation of NBS in this study area and use that to improve the model in the future. To do so, maybe small scale implementation in one or more of the sub catchments could speed up the process and make it tangible and manageable. Only then the exact results and implementation strategies can be improved even more. To validate the effects and implementation of NBS in the model, monitoring is crucial. Data about the inundation depth and inundation extent in the catchment should be measured from the start of a storm event up and till all surface water has disappeared again. In the drainage system a few monitoring applications are necessary to measure the discharge for the sub catchments. The degradation or improvement of NBS effects is monitored as well in this way.

NBS are implemented according to data from literature and with input from the sensitivity analysis. However, a lot of assumptions are necessary for this parametrization. It is wise to individually investigate each NBS. Not every NBS might be feasible at each location where it currently is assumed to be feasible. For example, the structure of houses might be worse than expected, resulting in no possibility of green roof implementation. Follow-up research should compare NBS more into detail by varying the size and characteristics of implementation. Compare for example different types of bioswales. In addition, more variation in urban areas (or sub catchments) could improve the results since more situations are examined. To upgrade the NBS comparison, NBS should be applied at the same location in a confined catchment with the same size (in surface area for example) of each NBS.

This research created a basis understanding of the effects of individual and combined urban NBS on the water system. Future research should extend this and look at the impact. By defining clear impact criteria (e.g. damage), the NBS implementation and effects that are observed in this study can be used in practice. Investigating impact of NBS is the next stap that is necessary to determine the best options of NBS that should be implemented in this study area or similar study areas in the world. In addition, other benefits of NBS should be considered as well. This could include upgrading the living environment by improving air quality, reducing urban heat, enhancing biodiversity, improving community cohesion and interaction and improving ecosystem functioning.

8. CONCLUSION

The built environment has strongly modified the urban hydrological cycle resulting in fast runoff and waterlogging risks. The trend of rapid urbanisation and climate change will only lead to more negative impact on the urban hydrological cycle. Nature based solutions are considered to be a sustainable approach that could help tackling these problems. However, quantitative hydro-meteorological studies on urban runoff dynamics are rare. Insights into the effects of NBS on urban runoff are necessary to boost resilient storm water management. Therefore this study poses the following main research question*: "How can the impact of Nature-Based Solutions (NBS) on urban runoff caused by extreme rainfall be modelled for data scarce regions, and what are their effects on the Sekondi-Takoradi area in Ghana?".* With help of a hydraulic HEC-RAS model, literature and expert input, this question is answered by investigation of the following sub questions:

- *"Which NBS are relevant to consider for this study?"*

The World Bank describes 14 urban NBS families. The study area is a dense urban area with narrow streets, lots of impervious area, elevation differences and two existing drainage systems. Taking the area characteristics in consideration, only 4 NBS families are applicable for the study area: urban forests, river and stream renaturation, terraces and slopes, and bioretention areas. For each NBS family the feasible and most occurring NBS are selected: reforestation, contour planting, check dams, vegetated drains, drain floodplains, green roofs, permeable pavement and bioswales.

- *"What is the sensitivity of hydraulic parameters of NBS in a hydraulic model?"*

HEC-RAS consists of 5 input model parameters: manning's n value, minimum infiltration rate, abstraction ratio, curve number, and impervious percentage. These parameters were varied for the most occurring land cover: residential area (49.8% of the catchment). Inundation maps quickly showed that the manning's n value has most influence, followed by the combination of curve number and impervious percentage. The other two parameters yielded no significant differences for parameter changes. Changing the hydraulic parameters to the land cover with the highest water absorption and deceleration effects resulted in large decrease of peak discharges. Steep areas experience a larger drop of peak discharge than flat areas. The steep hydrograph in the hilly areas is converted to more bell-shaped hydrographs with a lower max discharge and a wider curve. Changing the roughness and curve number of only the drains resulted in approximately the same result as changing the land cover of multiple sub catchments. This effect is far more noticeable in the northern (hilly) environment of the catchment than in the southern (flat) environment.

- *"How can the selected NBS be implemented in a hydraulic model?"*

For specific parts where NBS are placed, the model parameters are adjusted using information found in literature and input from the sensitivity analysis. Mainly the manning's n value, curve number and impervious percentage are important for implementing NBS. For reforestation, contour planting, vegetated drains, green roofs and permeable pavements only adjusting the model parameters for polygons of the land cover where NBS are implemented was sufficient. For drainage floodplains, bioswales and check dams in addition to adjusting the model parameters, also the elevation of the grid was adjusted.

- *"What are the individual and combined effects of NBS on urban runoff in a hydraulic model?"*

The NBS are implemented for a flat sub catchment, a hilly sub catchment and the whole catchment, resulting in 19 individual simulation scenarios. Effects are presented for the inundation area, inundation depth, surface runoff discharge curves and surface runoff coefficients. Results are depending on the characteristics of a (sub) catchment. All measures reduce the surface runoff coefficient and max discharge peak. Largest individual effects in terms of the surface runoff coefficients are caused by stream renaturation, forest transition measures and bioswales. Effects ranging from -15.7% up and till -29.7%. These NBS also have the most significant influence on the maximum discharge peak but now forest transition measures could have more impact, where extreme forest transition results in 61.7% decrease of the max peak discharge. In steep areas reducing the max discharge peak is reduced more than in flat areas. However, the runoff coefficient is not reduce with the same ratio. It is observed that in steep areas the water is decelerated but not retained. In flat areas the opposite effect is more noticeable.

Combination of NBS results in 11 scenarios. Combining NBS results in a flatter and wider discharge curve for the whole catchment, where stream renaturation and bioretention measures have the largest effect. Apparently, NBS are not able to cope with the highest precipitation peak (20 mm for 5 min) as effectively as for other precipitation levels (10mm for 5 min). Combination of all NBS resulted in a reduced runoff coefficient of 0.30 (original is 0.64). Bioretention areas and river and stream renaturation accounts for the majority of change in effects. Bioswales, permeable pavement and green roofs focus on storage, reducing the surface runoff. River and stream renaturation have roughly the same effect as urban forest implementation. Contour planting has approximately the same effect as forest transition. Only extreme (whole catchment) forest transition has larger effects. Check dams almost equally address surface runoff coefficient and the maximum discharge peak. Their effect largely depends on the amount and total length of check dams, the height is not linearly connected to the effects.

- *"Are there any observed effects available in literature to validate the results?"*

In literature almost no information is available about combinations of NBS (2 at maximum). Little information is available about individual NBS. It is limited to some runoff coefficients and sometimes inundation maps are provided as well. No studies look at all four elements of the water system that this study looks at. Most data could be found about surface runoff coefficients. This is used for validation of the individual NBS implementation. Due to spatial variability the results could not be compared directly, only the magnitude of the results is compared. In conclusion, this study shows results in the same order of magnitude and the same tendencies as in available literature.

- *"Which generic lessons on NBS can be drawn from this case study?"*

One of the most useful techniques is the creation of a much more detailed land cover layer with help of satellite images. This helps improving the results significantly since the roughness parameter is the most important and influential model parameter in a hydraulic model. It is very important to analyse the whole water system of a catchment. Always check the following four effects of NBS to get the complete picture: inundation depth, inundation area, discharge in pour points or at border of (sub) catchments, and surface runoff coefficient. Depending on the impact criteria, one can focus on single effects more in depth.

In general all the effects are mainly determined by scale and spatial implementation of NBS. However, the implementation depends on the area characteristics of catchments. Each type of NBS is affected by other area characteristics which determine the possible scale of implementation. Green roofs, permeable pavement and bioswales have significant effect on reducing the runoff discharge curve and coefficient in downstream and upstream areas. Inundation area and depth are reduced for the whole catchment. River and stream renaturation, check dams, forest transition, and contour planting have more effect on reducing the runoff discharge curve and coefficient in upstream areas. Locally, inundation depth and area could increase at the implementation location. But downstream the reduction effect is larger. Focusing on NBS that apply to the drains have more or the same effect as other aerial NBS in this particular study area.

It can be seen that the elevation difference in a catchment are very influential. In steep areas NBS can help reducing the peak discharge, but the surface runoff coefficient does not reduce with the same percentage. In steep areas (slope > 10%), NBS that focus on decelerating or infiltration by increasing roughness or increasing soil permeability do not have as much effect as in less sloped areas. In these areas the focus should be on retention NBS that affect the slopes or are able to store water, e.g. check dams or bioswales. Check dams are influenced the least by catchment characteristics. The unit effects of each NBS show their effects depending on the area of implementation. An opposite trend can be seen in terms of the unit effect versus the absolute effect. In terms of unit effects the check dams and stream renaturation have the highest scores. These types of NBS can be used in dense urban areas. Whereas urban forests and bioretention areas can be used in less dense urban environments.

The results are directly applicable to the Sekondi-Takoradi city in Ghana. The results will also be useful for urban regions experiencing similar circumstances and having similar area characteristics, for example other Sub-Saharan countries. HKV lijn in water can use the implementation of NBS in the HEC-RAS model to simulate waterlogging events, evaluate packages of measures and assess the effectivity of NBS. The method used to incorporate NBS in a hydraulic model for data-scarce regions will help future research to deal with similar situations. Definition of the magnitude and impact of NBS effects on the runoff in urban areas will help policy makers to make well-argued decisions for mitigative solutions. This will boost resilient storm water management, enhance urban resilience and reduce flood hazards. Implications of this research are the improvement of current best practices for implementing NBS in hydraulic models and creating a quick implementation method in HEC-RAS to inform policy makers to base their decisions on. In conclusion, this research creates a new steppingstone for future research regarding the implementation and assessment of NBS effects on runoff in urban areas during extreme rainfall events, consequently, mainstreaming the implementation of NBS as climate-resilient solutions.

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10. APPENDICES

10.1 STUDY AREA

10.1.1 Urban expansion

The rate of urban expansion in the study area was observed to be 4.88% per year. Although, urban growth/expansion was random in all directions, majority of the urban expansion occurred in the south-western part of the metropolis. The study also revealed that about 75% expansion was concentrated within 2.5 km from the main Takoradi-Accra road (Dadzie-Paintsil & Mensah, 2022) Although the accuracy of the simulations was only moderate, the study provides a contextualized scenario of what may occur given the current trends of land use changes, and is also based on biophysical and socioeconomic driving factors.(Aduah & Mantey, 2020)

10.1.2 Elevation

As can be seen there are some hills in the area. Slopes in these hilly regions can reach up to 20%. These hills influence the natural flow of water. The following two figures show the relief of the terrain for two situations: 1) straight form north to south, and 2) following the route with the lowest elevation from north to south.

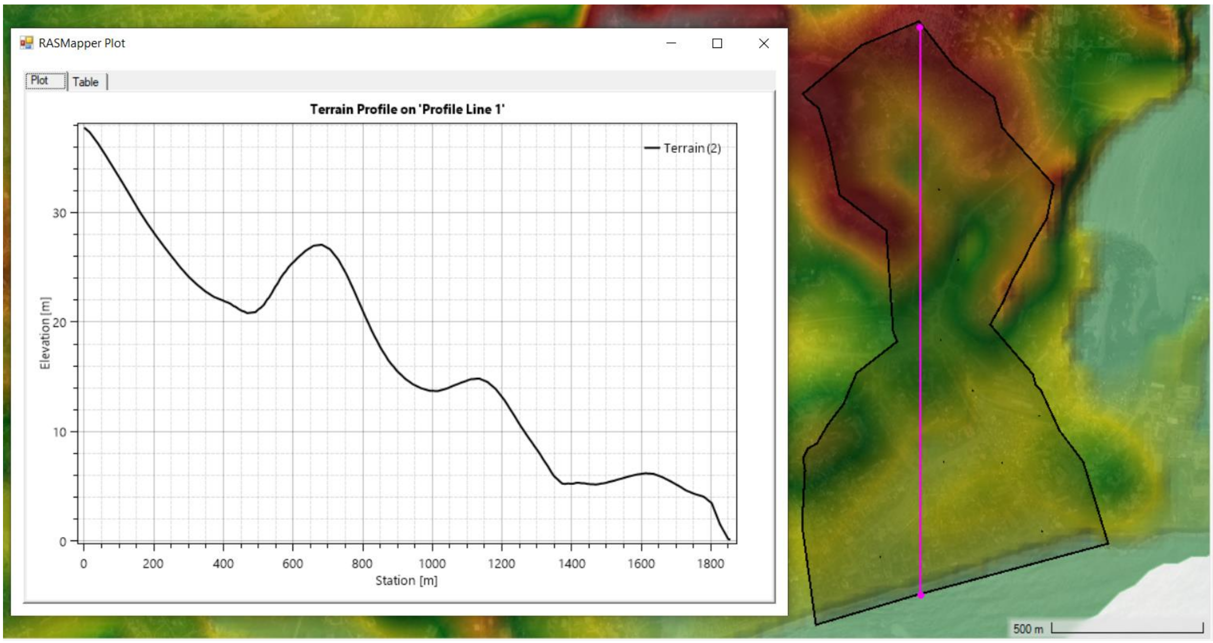


Figure 71 - Relief of the terrain in a straight line from north to south

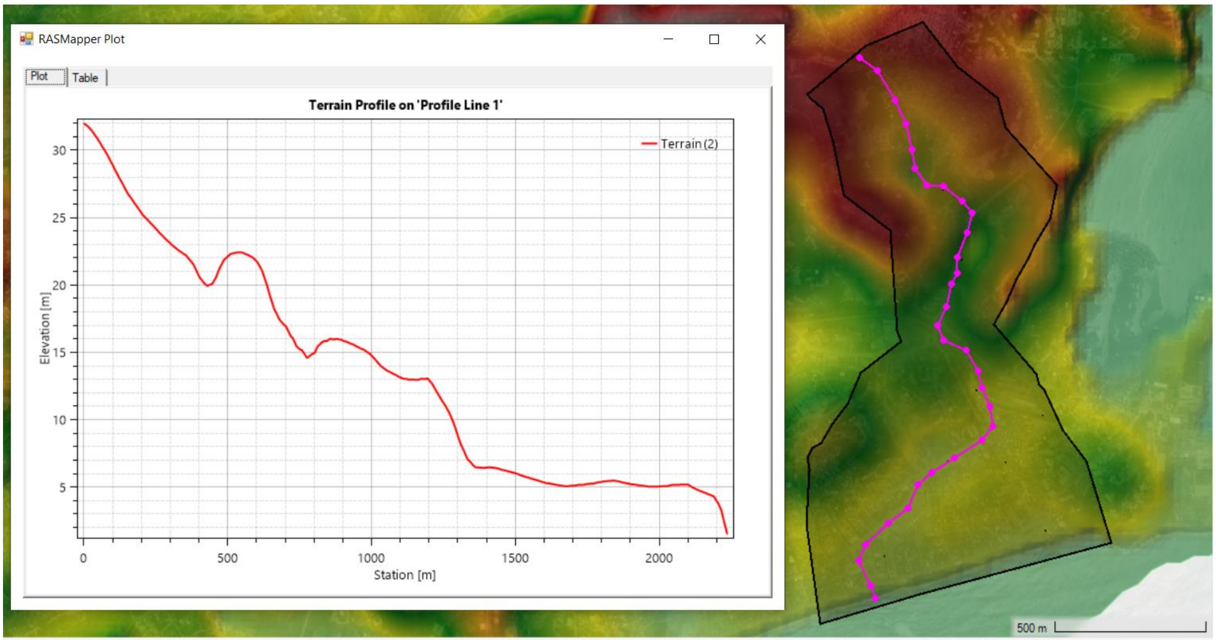


Figure 72 - Relief of the terrain following the lowest elevation area

Water is not able to flow straight from the top of the catchment to the bottom. There are terrain elevations that hinder this and obstruct the water. In practice, there are even more obstructions in the form of houses, infrastructure and vegetation.

10.1.3 Rainfall

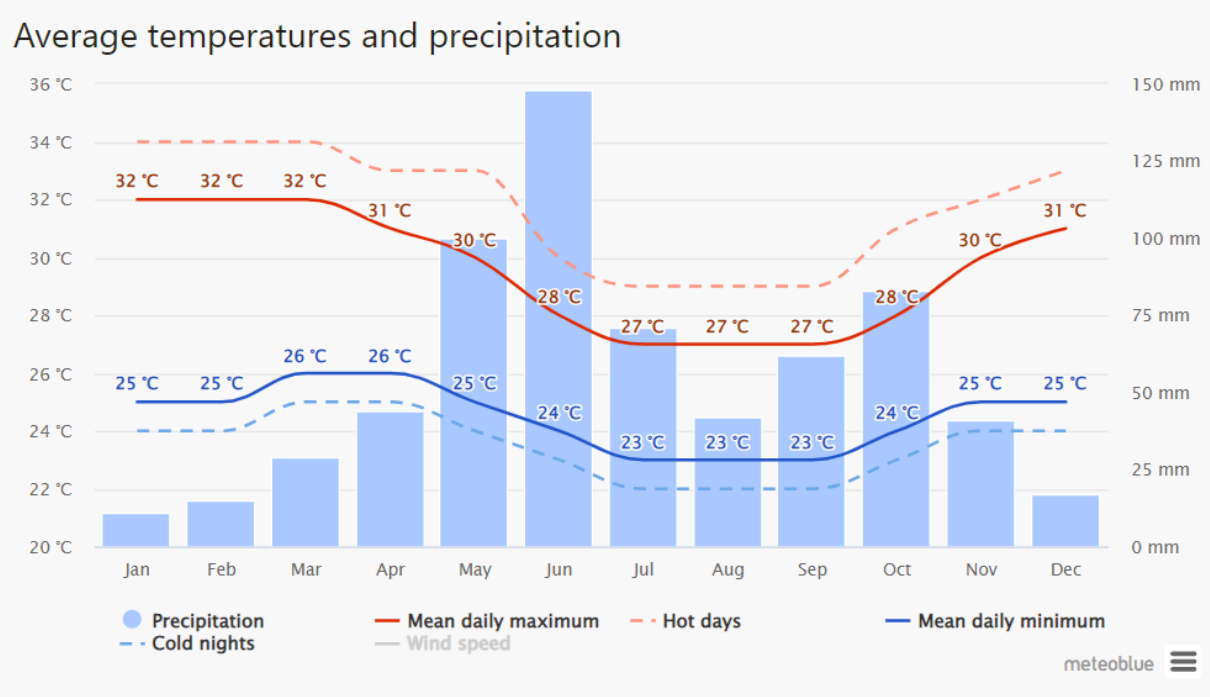


Figure 73 - Average temperatures and precipitation in Sekondi-Takoradi

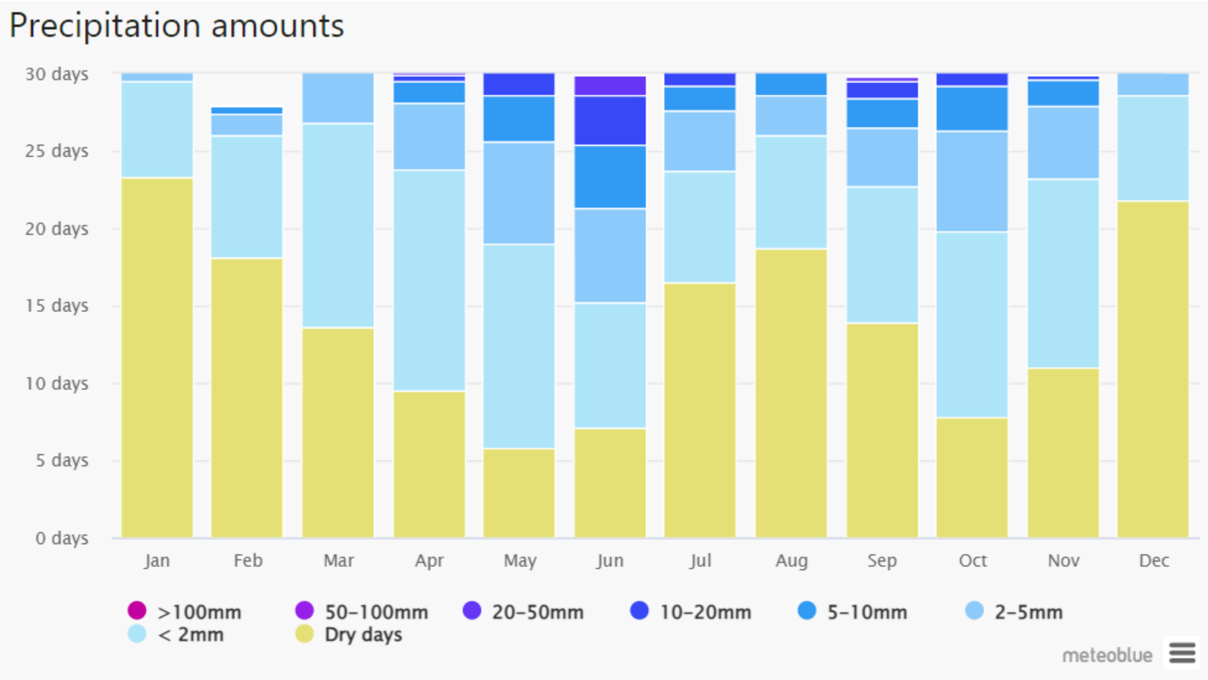


Figure 74 - Annual precipitation amounts in Sekondi-Takoradi

10.2 WATER SYSTEM ANALYSIS

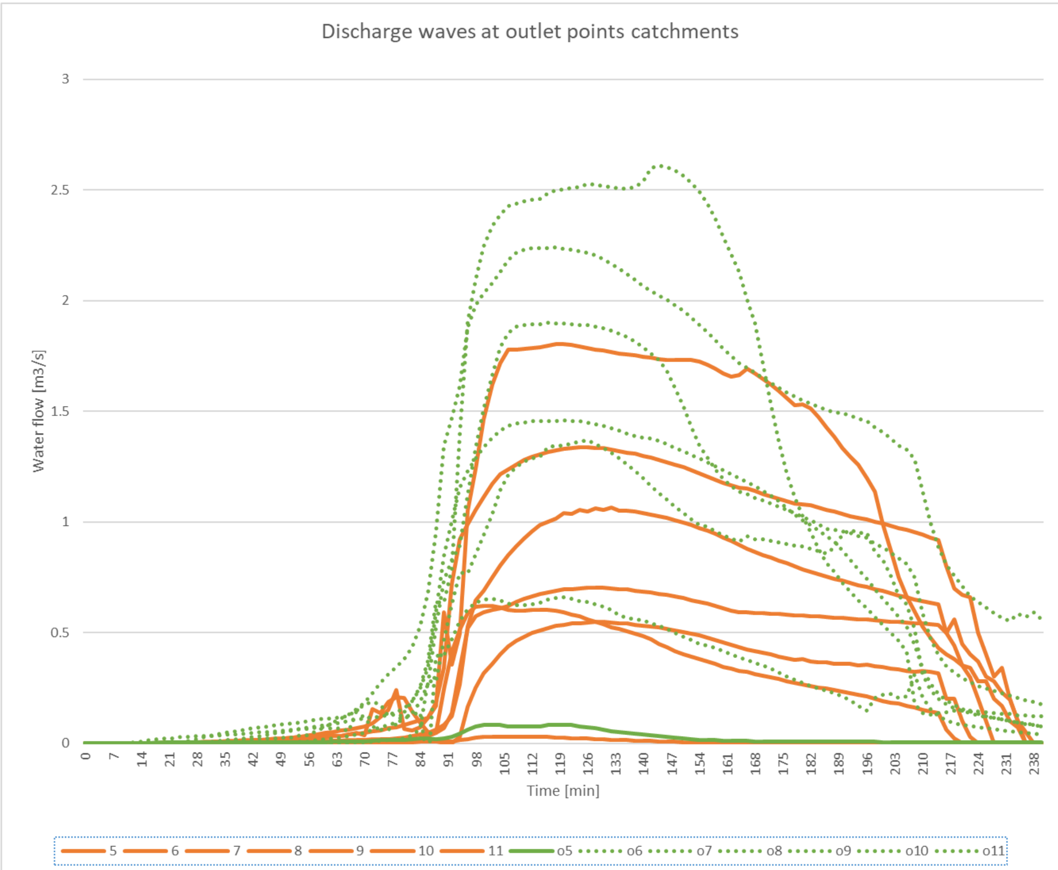


Figure 75 - Difference in old (green) hydrographs and new (orange) hydrographs for the southern sub catchments (scenario 19)

10.2.1 Cut-off area

Figure 76 - Cut-off location of the northern part of the catchment

Figure 77 - Difference inundation map in comparison to the original situation when the northern part is separated

Top part catchment to forest:

Figure 78 - Change land cover of the northern part of the area to forest

Figure 79 - Inundation map in comparison to the original situation, when the northern part consists of forest

10.3 INDIVIDUAL NBS EFFECTS

This appendix contains the inundation maps retrieved after NBS implementation.

10.3.1 Urban forests

(a) (a) extreme (b)

Figure 80 - Implementation of individual urban forest NBS for sub catchment 1

(a) (a) extreme (b)

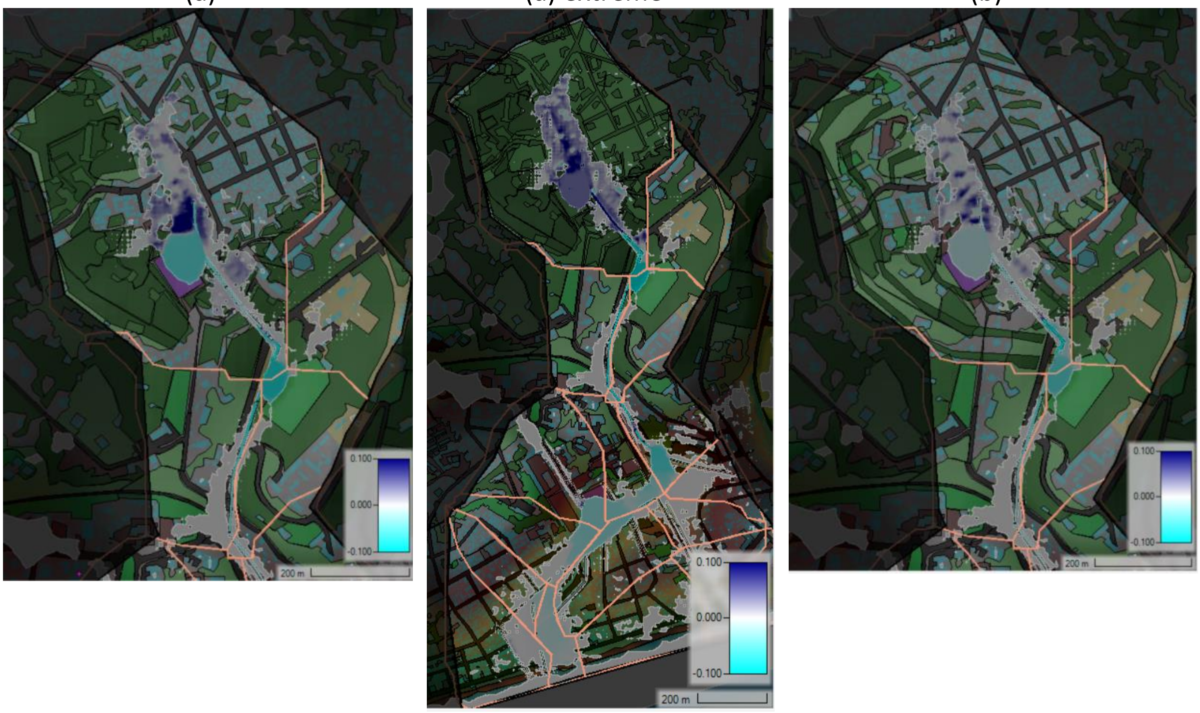


Figure 81 - Inundation maps of individual urban forest NBS

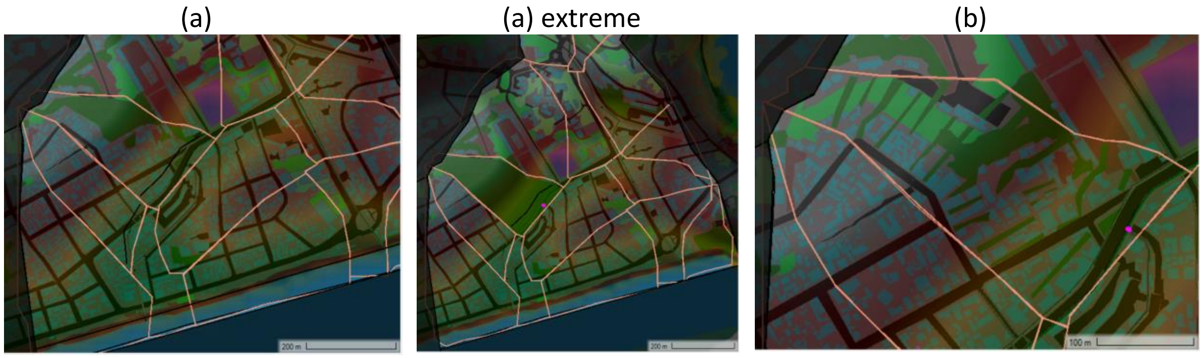


Figure 82 - Implementation of individual urban forest NBS for sub catchment 9

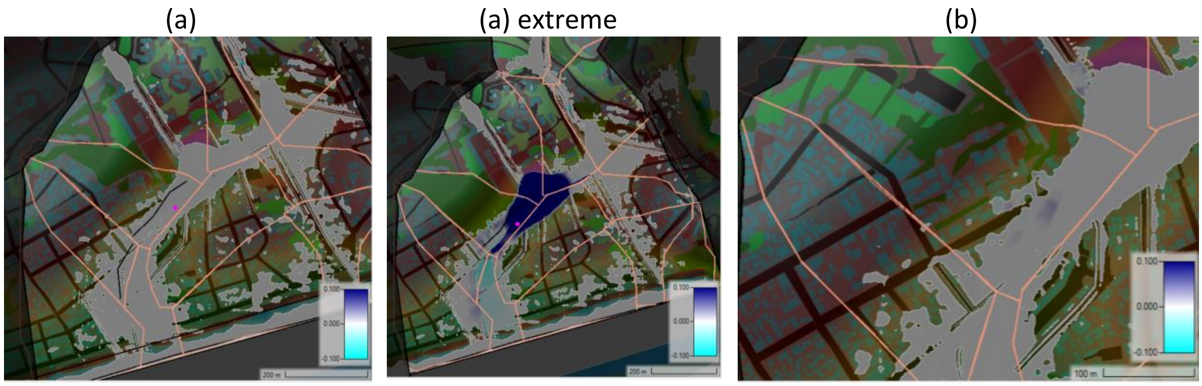


Figure 83 - Implementation of individual urban forest NBS for sub catchment 9

10.3.2 Terraces & slopes

Figure 84 - Implementation of check dams for sub catchment 1 and the whole catchment

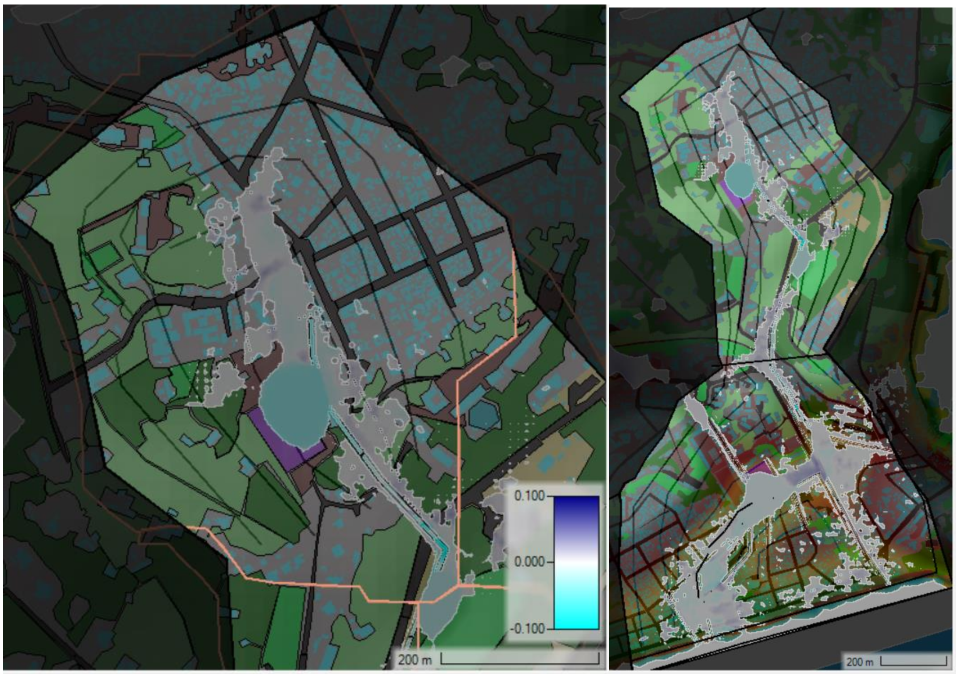


Figure 85 – Inundation maps of sub catchment 1 and the whole catchment for implementation of check dams

10.3.3 River & stream renaturation

Figure 86 - Implementation of stream renaturation at the northern drainage system

a

Figure 87 - Comparison inundation map of stream renaturation

b

Figure 88 - Comparison inundation map of stream renaturation and stream size increase

a & b

a & b - extreme

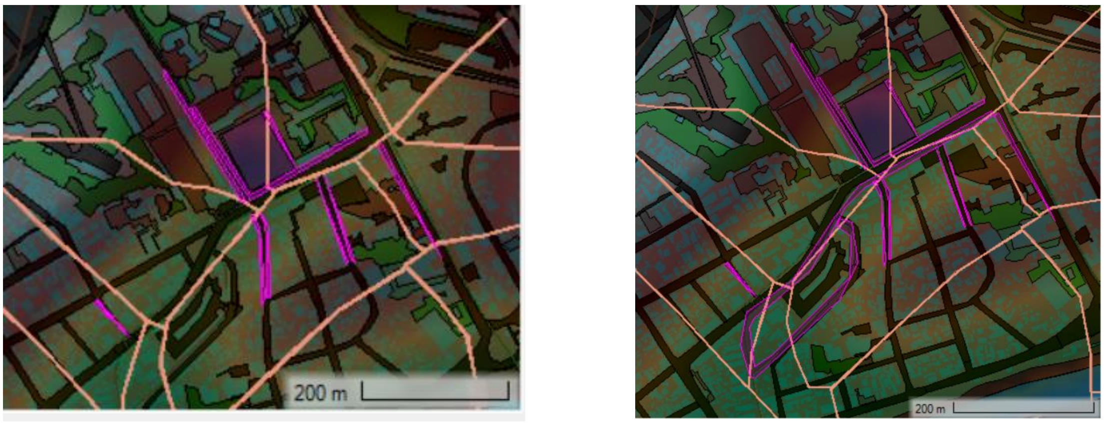


Figure 89 - Implementation of stream renaturation at the southern drainage system

a & b

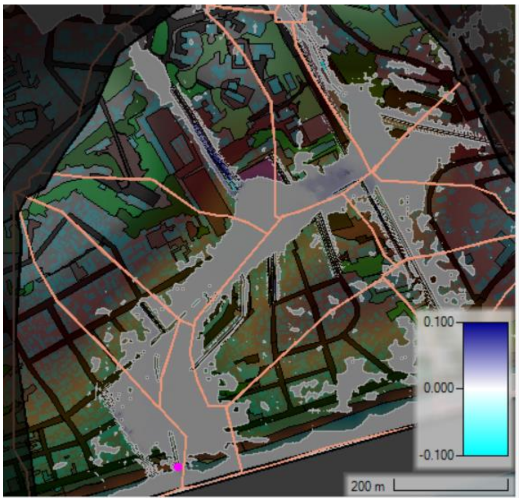


Figure 90 - Comparison inundation map for scenario a & b

a & b - extreme

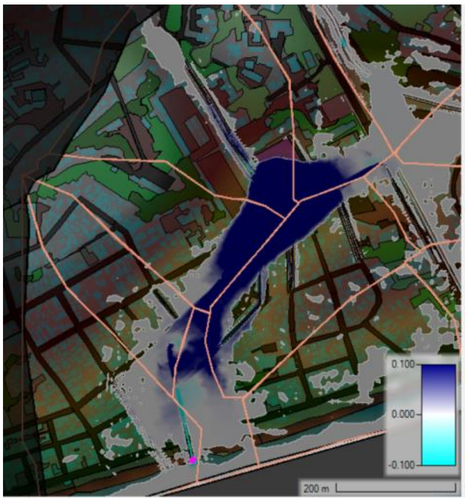


Figure 91 - Comparison inundation map for the extreme scenario for scenario a & b

10.3.4 Bioswales

Figure 92 - Implementation of bioswales (brown polygons) in the whole catchment

Figure 93 - Comparison inundation map with bioswale implementation for the whole catchment

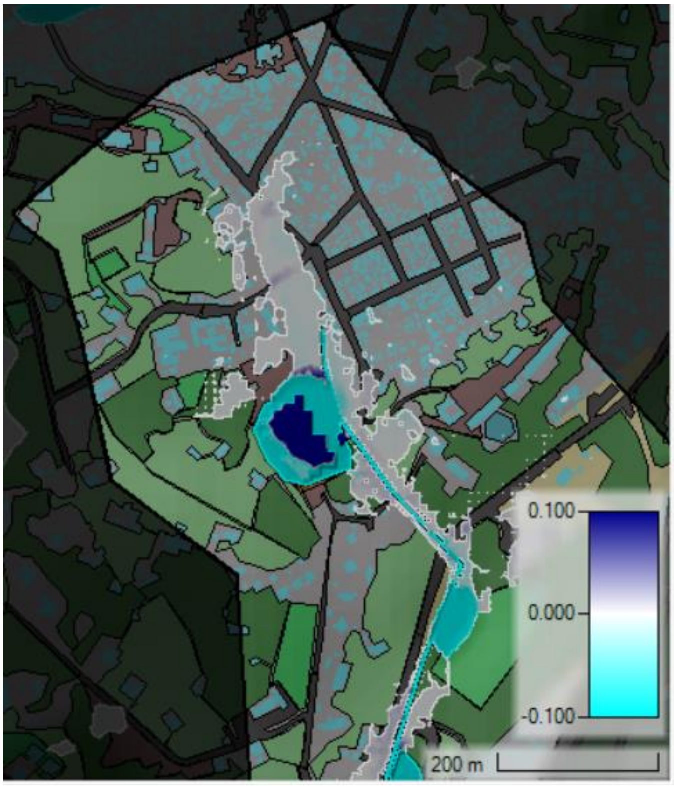


Figure 94 - Comparison inundation map with bioswale implementation for sub catchment 1

10.3.5 Green roofs

Figure 95 - Comparison inundation map of the whole catchment for green roof implementation

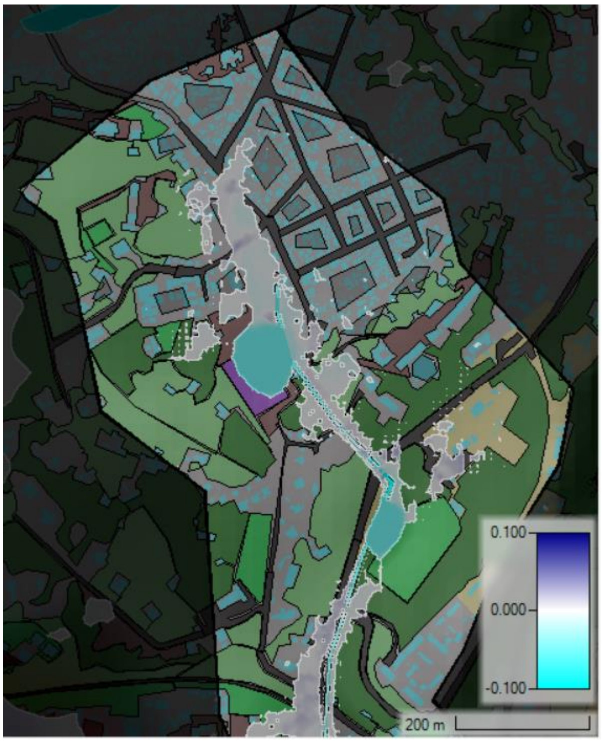


Figure 96 - Comparison inundation map of sub catchment 1 for green roof implementation

10.3.6 Permeable pavement

Figure 97 - Comparison inundation map of the whole catchment for permeable pavement implementation

10.4 COMBINED NBS EFFECTS

10.4.1 Implementation

Table 29 - Implementation of all NBS explained in detail

NBS	Details of implementation
Forest transition	*Implemented throughout whole catchment at land covers: bush, bare, grass. If another NBS (e.g. bioswale) is located at the same place, that NBS has priority because the implementation criteria for the other NBS are much stricter.* Area = 10127 m^2 Manning's n = 0.120 Impervious percentage = 15% Minimum infiltration rate = 3.8 mm/h Curve number = 52 Abstraction ratio = 0.05
Contour planting	*Small strokes of forest implemented throughout whole catchment between building footprints and roads, perpendicular to the water flow.* Area = 1852 m^2 Manning's n = 0.120

	Impervious percentage = 15% Minimum infiltration rate = 3.8 mm/h Curve number = 52 Abstraction ratio = 0.05
Check dams	*Small dams constructed throughout the whole catchment perpendicular to the flow direction of water. Not crossing roads, drains or building footprints.* Area = 1529m^2 Height = 0.1m Width = varying 0.1m
River and stream renaturation	*All drains are only vegetated. Because the sensitivity analysis made it clear that extra storage volume did not have much more effect than just increasing the roughness. To see the effect of implementation on different water characteristics of the whole catchment (this is not done yet), the upstream drainage system has increased roughness.* Area = 23875 m^2 Manning's n = 0.100 Impervious percentage = 30% Minimum infiltration rate = 3.8 mm/h Curve number = 60 Abstraction ratio = 0.05
Bioswales	*5 Bioswales are constructed at low-elevation locations, near the core of the water system (drainage) and at locations where the land cover allows for implementation (e.g. soccer pitch, grass or bare area).* Total volume = 29849 m^3 Total area = 30039 m^2 Manning's n = 0.090 Impervious percentage = 0% Minimum infiltration rate = 3.8 mm/h Curve number = 54 Abstraction ratio = 0.05
Green roofs	*All building footprints are changed to green roofs.* Total area = ? m^2 Manning's n = 0.30 Impervious percentage = 0% Minimum infiltration rate = 3.8 mm/h Curve number = 92 Abstraction ratio = 0.58
Permeable pavement	*All side-walks, public parking and residential parking space for the whole catchment are transformed to permeable pavement.* Total area = 38386 m^2 Manning's n = 0.030 Impervious percentage = 45% Minimum infiltration rate = 3.8 mm/h Curve number = 68 Abstraction ratio = 0.05

10.4.2 Implementation visualisation:

Figure 98 - Implementation of scenario 4

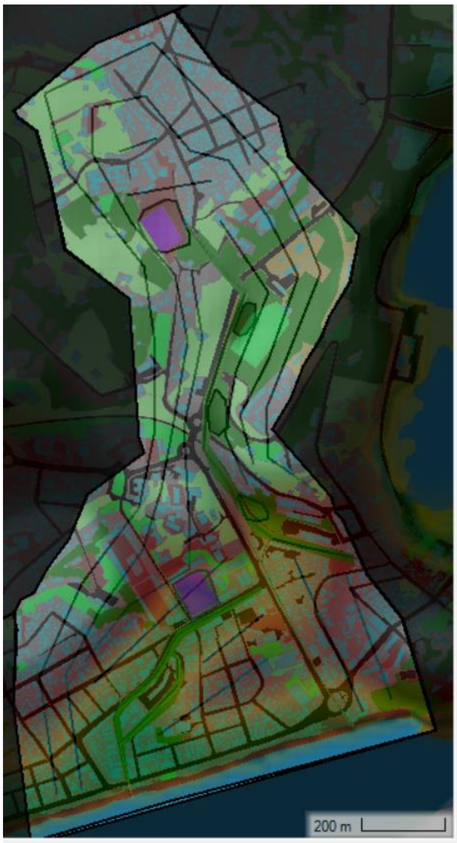
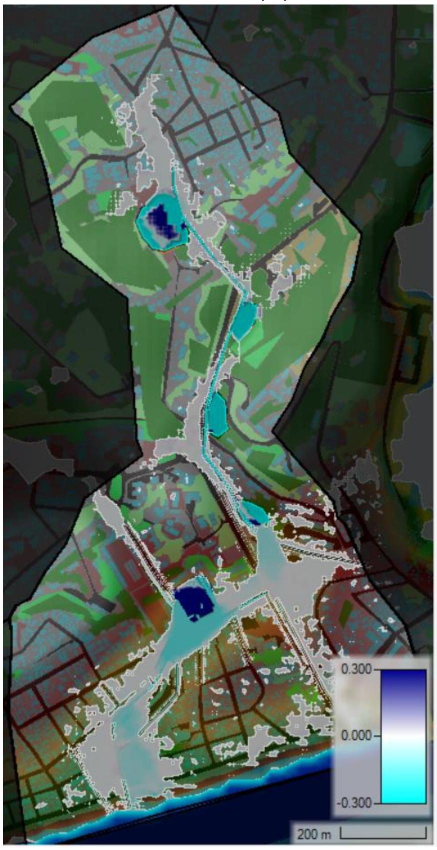


Figure 99 - Implementation of scenario 8

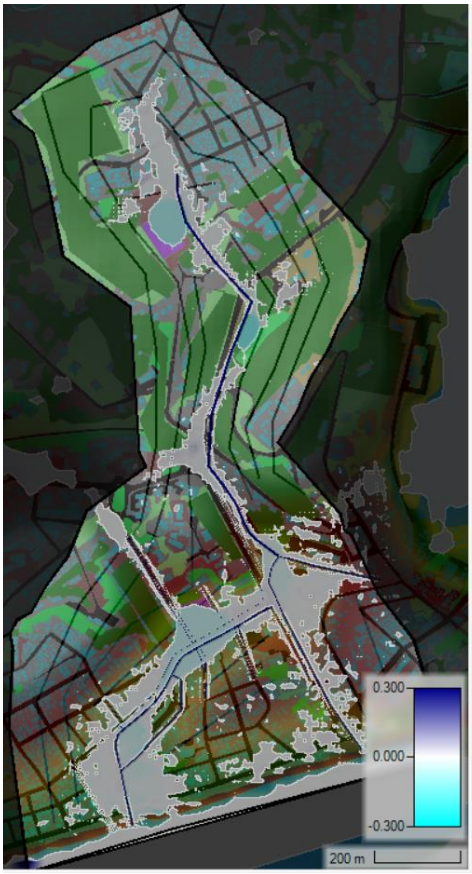
10.4.3 Inundation maps main scenarios

Scenario 3,4,9



Scenario 5,7,10,11

Scenario 1

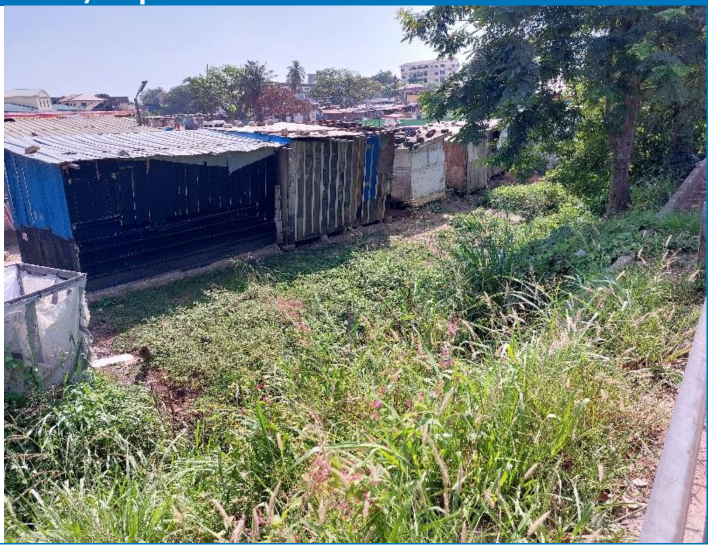


Scenario 2,6,8

Figure 100 -Comparison implementation map of the four approximately the same scenarios

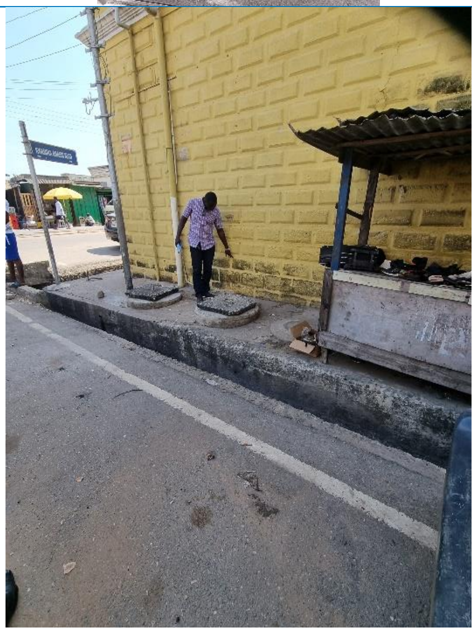
10.5 STUDY AREA CHARACTERISTICS

Characteristics specific study area (from photo's/maps above):

What	Photo/Map
Drains overgrown	

Drains partially covered	
Drains clogged	
Drains collapsed	

Height differences +2m NAP vs +25m NAP	
Area next to drains: concrete/stones	
Waste laying around	

Self-made solutions; sill	
Water level indication due to waterlogging	

10.6 SOIL CLASSIFICATION

Information about soil groups and soil classifications (USACE Hydrologic Engineering Center, 2023b):

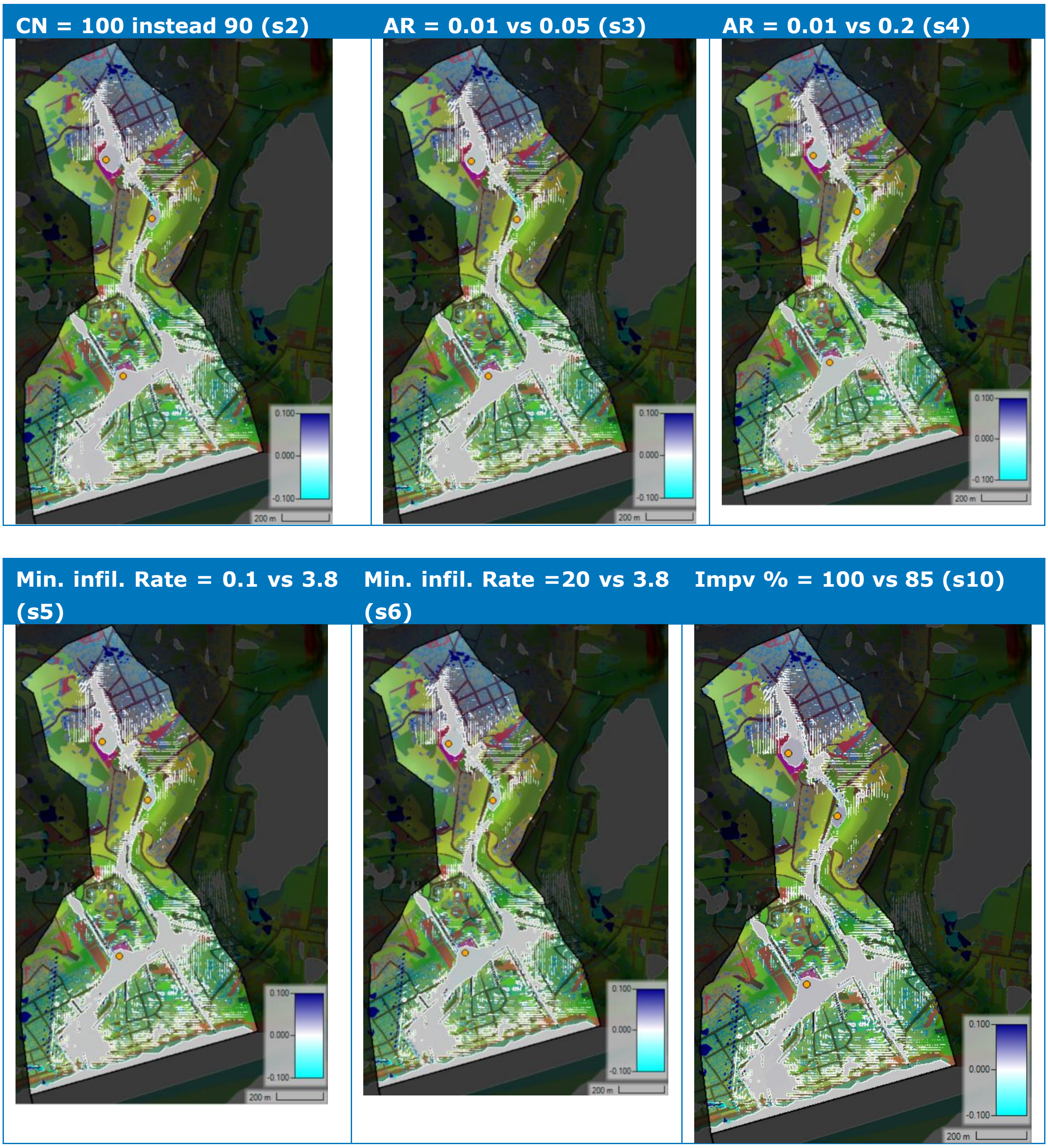
SCS Soil Group	Description	Range of Loss Rates (in/hr)
A	Deep sand, deep loess, aggregated silts	0.3 - 0.45
B	Shallow loess, sandy lam	0.15 - 0.30
C	Clay loams, shallow sandy loam, soils low in organic content, and soils usually high in clay	0.05 - 0.15
D	Soils that swell significantly when wet, heavy plastic clays, and certain saline soils	0.00 – 0.05

Figure 101 - Soil classification of SCS soil groups

Texture Class	Effective Water Capacity (C_w) (inch per inch)	Minimum Infiltration Rate (*f*) (inches per hour)	Hydrologic Soil Grouping
Sand	**0.35**	**8.27**	**A**
Loamy Sand	**0.31**	**2.41**	**A**
Sandy Loam	**0.25**	**1.02**	**A**
Loam	**0.19**	**0.52**	**B**
Silt Loam	**0.17**	**0.27**	**B**
Sandy Clay Loam	**0.14**	**0.17**	**C**
Clay Loam	**0.14**	**0.09**	**D**
Silty Clay Loam	**0.11**	**0.06**	**D**
Sandy Clay	**0.09**	**0.05**	**D**
Silty Clay	**0.09**	**0.04**	**D**
Clay	**0.08**	**0.02**	**D**

Figure 102 - Hydrologic soil properties

10.7 GLOBAL SENSITIVITY



10.8 GENERAL INFORMATION

This appendix chapter serves as a general information page regarding the master's thesis. The contact information of the involved parties is listed. Furthermore, personal learning goals of the student are described. Last but not least, agreements made regarding execution of the master's thesis are stated.

10.8.1 Contact information

In brief, the most important details about the Master student, the internal supervisors and the external supervisors are listed below.

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