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Assessment of Nature-Based Solutions Optimizer (NBS-OPT) for Urban Storm-water Management

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Abstract

Nature-based solutions (NBSs) have proved to be useful in managing stormwater volume and quality. They can control peak flows and treat water while partly restoring the hydrological cycle in urban areas. However, the locations of these NBSs are a crucial factor when determining an optimal cost-efficient design. A NBS simulation-optimization tool, called NBS-OPT, is currently being developed as a screening tool to provide a quick overview of combinations of NBSs and their locations in an urban catchment.

The objective of this study was to assess the performance and functionality of NBS-OPT in suggesting combinations of NBSs for a catchment to manage stormwater volume most cost-efficiently. This was achieved by producing a methodology to calibrate, parameterize, and validate NBS-OPT against Stormwater Management Model (SWMM). The catchment used for this study was a section of Vallikallio, a residential neighborhood in Espoo, Finland. Four cost scenarios were used to test the sensitivity between cost, retention, and detention in NBS-OPT, resulting in four optimal combinations of NBSs. These optimal combinations were then replicated in SWMM to validate the ability of NBS-OPT to produce accurate flows once parameterized.

The four optimal combinations replicated in SWMM were found to reduce the peak flows for a 50-year storm event from 296 l/s (under current conditions) to 180 l/s, 229 l/s, 217 l/s, and 211 l/s, respectively. The results showed that implementing NBSs in 27.0-28.3% of the site area provided a 23-39% reduction in peak flows. Comparing the storm discharge series from NBS-OPT and SWMM resulted in a Nash-Sutcliffe model efficiency coefficient higher than 0.94 and peak flow differences of less than 50.7 l/s for all four optimal combinations. These results demonstrate that NBS-OPT can provide accurate flow calculations. However, NBS-OPT should use more conservative NBS limit areas in order to suggest more realistic optimal combinations. Moreover, separate pervious and impervious measures would enable more accurate parameterization and precise flow results.

Keywords Nature-based solutions, stormwater management, low impact development, sustainable urban planning, Stormwater management model

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Preface

I'd like to first thank SINTEF and Aalto University for giving me the opportunity to contribute to the EviBAN project (Evidence based assessment of NWRM for sustainable water management). The whole EviBAN project is funded under the European Commission (Water JPI 2018) and the specific studies done in Finland are additionally funded by the Academy of Finland (326787). A big thank you to all the stakeholders who made this study possible. I am extremely grateful to have been a part of this project.

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Thank you to the SCICOMP garage group at Aalto University for helping me trouble shoot python code to run NBS-OPT. The help I received from the SCICOMP garage saved me from many headaches.

Lastly, I'd like to thank my family and friends for their love and support.

Jätkäsaari, 11 December 2021
Felipe Da Silva

Abbreviations and symbols

$A_{node,n}$	Nodal area (m^2)
BGI	Blue-green infrastructure
BMP	Best management practice
$C_{Cap,mID}$	Capital cost of a measure (€)
$C_{NBS,mID}$	NBS-OPT cost function (€)
$C_{OM,mID}$	O&M costs of a measure (€)
$D_{peak\ flow}$	Peak flow difference (l/s)
EbA	Ecosystem-based adaptation
Eco-DRR	Ecosystem-based disaster risk reduction
EU	European Union
GI	Green infrastructure
LID	Low impact development
MCA	Multi-criteria analysis
mID	Measure ID
NBS	Nature-based solution
NBS-OPT	Nature-based solution optimization tool (designed by SINTEF)
NSE	Nash-Sutcliffe model efficiency coefficient
NSGA-II	Non-dominated sorting genetic algorithm II
O&M	Operation and maintenance
Q_N	Peak flow of NBS-OPT (l/s)
Q_S	Peak flow of SWMM (l/s)
$Q_{m,t}$	Discharge flow of NBS-OPT at time t (l/s)
$Q_{o,t}$	Discharge flow of SWMM at time t (l/s)
$\bar{Q}_o$	Mean SWMM discharge flow (l/s)
R_{NSE}	Nash-Sutcliffe model efficiency coefficient
$S_{NBS,mID,n}$	Percentage of NBS in a node (%)
SUDs	Sustainable urban drainage systems
SUSTAIN	System for Urban Stormwater Treatment and Analysis Integration
SWMM	Stormwater Management Model
US EPA	United States Environmental Protection Agency
VK	Vallikallio
WJPI	Water Joint Programming Initiative
WSUD	Water-sensitive urban design
$\sum_{t \in \mathcal{T}^E} D_t$	Summation of the discount factor over time

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1 Introduction

In 2018, about 55% of the world's population lived in urban areas, and this number is projected to increase to 60% by 2030 (United Nations, Department of Economic and Social Affairs, 2018). This trend of more dense urban areas increases stress on water resources and climate (Kabisch *et al.*, 2017; Frantzeskaki *et al.*, 2019; Krauze and Wagner, 2019; Ruangpan *et al.*, 2020). Usually, environmental and hydrological systems are vulnerable to modification in urban settings due to large increases in impervious coverage, such as buildings, roads, and any other paved areas. It is well known that large increases in impervious coverage reduce water infiltration, evapotranspiration, and groundwater recharge, causing increases in stormwater surface runoff volume and water pollution (Martin-Mikle *et al.*, 2015; Salvadore, Bronders and Batelaan, 2015; Frantzeskaki, 2019; Khadka *et al.*, 2020).

Tools and strategies for maintaining the local hydrological cycle as close to its natural state are desirable because the trend toward urbanization is difficult to change. In recent years, nature-based solutions (NBSs) have received considerable attention due to their potential for providing climate mitigation solutions and developing climate-resilient cities by reducing surface runoff, treating stormwater, and cooling cities (Martin-Mikle *et al.*, 2015; Kabisch *et al.*, 2017; Wild *et al.,* 2017; Frantzeskaki *et al.*, 2019). According to the European Commission (n.d.), NBSs are typically known as solutions "inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience". Currently, several small-scale NBSs are being used to mitigate stormwater challenges in urban areas. Examples include rain gardens, green roofs, vegetated swales, and permeable pavements (Ruangpan *et al.*, 2020).

Although the impacts on hydrological systems due to urbanization have been studied since 1968 (Leopold, 1968*)*, it can still be difficult to predict and assess the quantifications of this impact (Oudin *et al.*, 2018). Therefore, some cities have been hesitant to use NBSs due to a lack of knowledge concerning issues, such as wide costs and benefits at different scales, the conditions where NBS perform best, and how NBSs can be best combined to provide the most sustainable solution. (WJPI, 2018). Other barriers to the uptake and implementation of NBSs include a silo mentality, lack of design standards and guidance for maintenance and monitoring, and risk aversion and resistance to change (Sarabi *et al.*, 2020).

A new tool kit is currently being developed by SINTEF (EviBAN, 2021) focusing on five different tools shown in Figure 1. To maximize the benefits of NBSs, they are evaluated from a holistic perspective based on knowledge of ecological, economic, and social processes (WJPI, 2018). Thus, the main objective of the WJPI is to "increase the knowledge of how NBSs can be used for management of water resources…and how NBSs should be optimally used under different conditions…" (WJPI, 2018). The project consists of case studies in Finland, France, Norway, and South Africa. However, this work will only focus on the case study in Finland concerning Nature-Based Solution Optimizer (NBS-OPT) boxed in Figure 1. This optimization tool is to serve as a prescreen for optimal combinations of NBSs that can most cost-efficiently meet desired peak flow attenuation. These prescreened solutions set a starting point for a more detailed design and analysis using more advanced tools such as the Stormwater Management Model (SWMM). SWMM is a tool used to model runoff volume and quality for single events or long-term simulations by considering various hydrological processes. It uses spatial variability by dividing a study area into smaller subcatchment areas, each having its own percentages of pervious and impervious sub-areas. SWMM also allows users to assign a set of pre-designed NBS controls to subcatchments (Huber *et al.*, 1975).

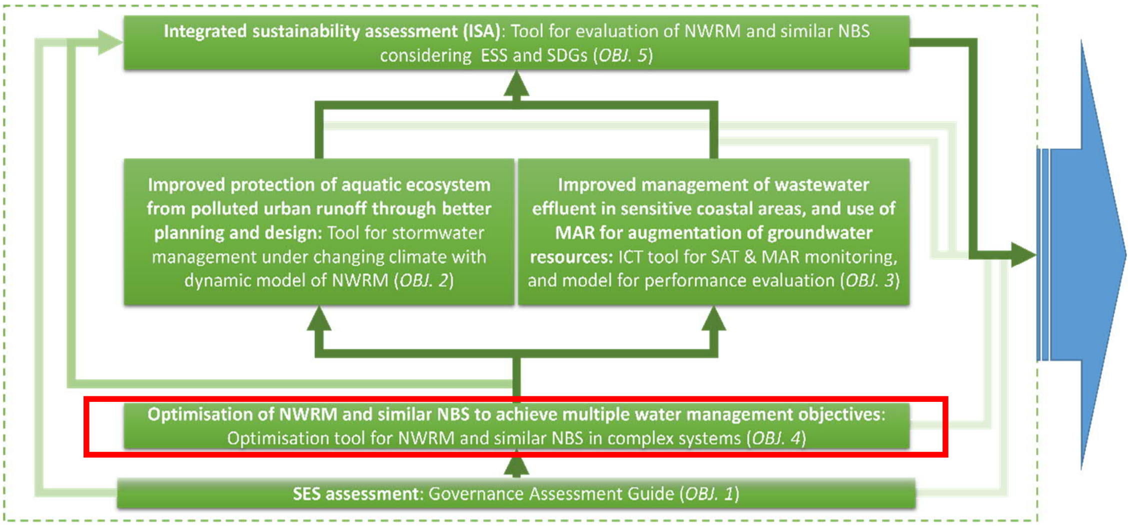

Figure 1: EviBAN toolbox with several paths depending on the level of detail in the assessment (modified from EviBAN Toolbox).

The aim of this study is twofold. The first objective is to assess the performance and functionality of NBS-OPT in suggesting NBS combinations for a catchment to manage stormwater volume most cost-efficiently. This will be achieved by producing a methodology to calibrate, parameterize, and validate NBS-OPT against SWMM. The second objective is to identify areas for improvement and make suggestions to increase the performance and functionality of the optimizer.

This study uses Vallikallio, a residential area in Espoo, Finland as its study catchment to test NBS-OPT. Although the tool kit will eventually provide more variables, such as social and environmental measures, this study is limited to parameterizing and validating NBS-OPT. Water quality is not part of this study, yet it is important to note that NBSs improve water quality, thus improving environmental conditions.

The documentation is divided into the following chapters: Chapter 2 reviews the relevant literature on the effects of urbanization on the hydrological cycle, NBSs and how they are used in urban areas, and current NBS optimization tools. Chapter 3 explains the study area and materials used for this study. Chapter 4 outlines the methodology used in this study. Chapter 5 presents the results of the study. Chapter 6 discusses the results in more detail and makes suggestions for further development of the tool. Chapter 7 concludes the study by summarizing the findings and suggesting directions for future research.

2 Literature review

2.1 Effects of urbanization on the hydrological cycle

Urbanization changes a catchment's hydrological cycle by increasing impervious area (Guan *et al.*, 2015). When the impervious area of a catchment increases, it decreases the total available storage by reducing infiltration and evapotranspiration. This reduction in storage increases runoff volumes, peak flows, and decreases baseflows. These changes increase the risk of urban flooding, pollution of water resources, and depletion of groundwater (Lee *et al.*, 2012; Salvadore *et al.*, 2015; Zhang and Chui, 2018). This leaves urban areas as one of the most vulnerable to the harmful impacts of heavy rainfall (Salvadore *et al.*, 2015). Studies have also warned that the effects of urbanization combined with the potential effects of climate change can intensify these challenges (Zhang and Chui, 2018; Ruangpan *et al.*, 2020).

The variables which affect urban hydrology are diverse. While several studies have reported high effects on the hydrological cycle with low levels of imperviousness increase (5%) (Booth and Jackson, 1997; Yang *et al.*, 2010), other studies have reported small effects with high levels of imperviousness increase (up to 20%) (Brun and Band, 2000). This suggests that although the impervious area can be considered the first order of influence, it cannot alone determine the diverse hydrological impacts of urbanization (Oudin *et al.*, 2018). Other factors affecting the hydrological cycle include the spatial distribution of impervious areas (location, interconnectedness, and proximity to drainage network) (Grove *et al.*, 1998; Sheeder *et al.*, 2002; Mejía and Moglen, 2010a, 2010b), the construction of hydraulic structures such as natural pathway modifications and detention basins (Ogden et al 2011), the hydrographic network drainage density, soil types (Guan *et al.* 2015), the size of a catchment area, the presence of aquifers (Konrad 2005), and climate.

SWMM has been used to simulate, evaluate, and better understand the effects of the controlling variables on urban catchment hydrological cycles (Tsihrintzis and Hamid, 1998; Vaze and Chiew, 2003; Jang *et al.*, 2007). The ability of SWMM to simulate surface hydrological processes, drainage network flows, and water quality has allowed for a better understanding of these variables. The ability to model urban catchments has shown that the drainage-efficiency approach is not enough to mitigate the challenges listed above.

The traditional drainage- efficiency approach manages the increase of stormwater flows and volumes by constructing drainage systems that route stormwater to receiving waterways. These systems often convey runoff directly to receiving waters without any treatment. Although this approach deals with the flooding problem, it still changes the volumes of infiltration, evapotranspiration, and subsurface flows, causing changes to the hydrological cycle (Burns *et al.*, 2012). This has led to the development and use of other stormwater management strategies that have objectives to replicate the existing hydrological cycles as much as possible. NBSs have recently received attention for their potential in mitigating many of the above-mentioned negative effects on the hydrologic cycle of high-density urban catchments.

2.2 Overview of NBSs

NBS is considered an umbrella concept for hydro-meteorological risk reduction solutions. It is a term for solutions that solve environmental and societal challenges based on natural processes and ecosystems (Ruangpan *et al.*, 2020). The term NBS was first used in 2008, making it a relatively new term in the scientific literature (Ruangpan *et al.*, 2020). In total there are nine different terms that are commonly used in the scientific literature for hydro-meteorological risk reduction. Information about these terms is presented in Table 1.

Table 1: Glossary of terms for hydro-meteorological risk reduction and their geographical usage. Table modified from Ruangpan *et al.* (2020).

Terminology	Definition, objective, and purpose	Places where commonly used	Reference
Low-impact development (LIDs) 1977	"LID is used as a retro- fit designed to reduce the stress on urban stormwater infrastructure and/or create the resiliency to adapt to climate changes, LID relies heavily on infiltration and evapotranspiration and attempts to incorporate natural features into design."	-US -New Zealand	(Eckart *et al.*, 2017)
Best management practices (BMPs) 1980	"A device, practice or method for removing, reducing, retarding or preventing targeted stormwater run-off constituents, pollutants and contaminants from reaching receiving waters."	-US -Canada	(Strecker *et al.*, 2001)
Water-sensitive urban design (WSUD) 1994	"Manage the water balance, maintain and where possible enhance water quality, encourage water conservation and maintain water-related environmental and recreational opportunities."	– Australia	(Whelans Consultants et al., 1994)
Green infrastructure (GI) 1995	"The network of natural and semi-natural areas, features and green spaces in rural and urban, and terrestrial, freshwater, coastal and marine areas, which together enhance ecosystem health and resilience, contribute to biodiversity conservation and benefit human populations through the maintenance and enhancement of ecosystem services."	-US -UK	(Naumann et al., 2011)
Sustainable urban drainage systems (SuDs) 2001	"Replicate the natural drainage processes of an area – typically through the use of vegetation-based interventions such as swales, water gardens and green roofs, which increase localized infiltration, attenuation and/or detention of stormwater."	-UK	(Ossa-Moreno *et al.*, 2017)
Nature-based solution (NBS) 2008	"NBS aim to help societies address a variety of environmental, social and economic challenges in sustainable ways. They are actions inspired by, supported by or copied from nature, both using and enhancing existing solutions to challenges as well as exploring more novel solutions."	-Europe	(European Commission, 2015)
Ecosystem-based adaptation (EbA) 2009	"The use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change."	-Canada -Europe	(CBD, 2009)
Ecosystem-based adaptation reduction (Eco-DRR) 2010	"The sustainable management, conservation, and restoration of disaster risk reduction ecosystems to reduce disaster risk, with the aim of achieving sustainable and resilient development."	-Europe -US	(Renaud et al., 2013)
Blue-green infrastructure (BGI) 2013	"BGI provides a range of services that include water supply, climate regulation, pollution control and hazard regulation (blue services/goods), crops, food and timber, wild species diversity, detoxification, cultural services (physical health, aesthetics, spiritual), plus abilities to adapt to and mitigate climate change."	-UK	(Lawson *et al.*, 2014)

To simplify the terminology, NBS and its sister concepts (GI, EbA, Eco-DRR, and BGI in Table 1) have a holistic approach using nature to improve the environment, human well-being, and increase resilience to the challenges faced in built environment. The other sister concepts (LIDs, WSUD, and SuDs) refer to NBSs that focus specifically on transforming stormwater management into a more cyclic approach that mimics a more natural water flow (Ruangpan *et al.*, 2020). This current study focuses on the later NBSs – specifically small-scale NBSs such as rain gardens, green roofs, vegetated swales, and permeable pavements.

2.3 Current NBSs for urban stormwater management

Although some cities are still hesitant to adopt NBS strategies, NBSs have been adopted in many urban areas. Increasing the coverage of NBS techniques has been determined to bring positive impacts to the water balance in urban catchments (Khadka *et al.*, 2020). Much of their effectiveness depends on the size and frequency of storm events. This is because each NBS contributes main and co-benefits but not all in the same way (Ruangpan *et al.*, 2020).

Rain gardens are most effective in dealing with small discharges generated by rainfall. When installed, they tend to increase the property value, biodiversity, and can even improve the aesthetic of the site (Ishimatsu *et al.*, 2017; Goncalves *et al.*, 2018). Green roofs perform best during small, frequently occurring storm events and provide co-benefits such as reducing air pollution, reducing nutrient loadings, saving energy, and increasing amenity value (Carpenter and Kaluvakolanu, 2011; Ercolani *et al.*, 2018). Vegetated swales and permeable pavements, on the other hand, perform best in large and short storm events. Vegetated swales help reduce the concentration of pollutants and help increase biodiversity. Permeable pavements help remove diffuse pollution and improve groundwater recharge.

It is important to understand that the performances of all NBSs vary depending on the intensity and duration of a storm event (eg., Joyce *et al.*, 2017; Ruangpan *et al.*, 2020). For this reason, a combination of NBSs has been argued to provide a more effective long-term strategy for mitigating urban stormwater challenges (Ruangpan *et al.*, 2020). This is because each NBS can treat a different portion of run-off in the catchment while working together to achieve the same goal. Permeable pavements seem to be one of the most popular and suitable NBSs to combine with others (Ruangpan *et al.*, 2020).

2.4 Selection of NBS combinations and optimization models

A major challenge storm-water engineers and urban planners face is choosing the best combination of NBSs that will achieve, in a given location, the most practical stormwater management in the most cost-effective way (Lee *et al.*, 2012). This is not an easy task because not all NBSs are appropriate for all situations. Factors such as catchment characteristics, groundwater depth, environmental requirements, land use, political and financial regulations, soil type, and space available can vary significantly depending on the location (Joyce *et al.*, 2017; Eaton, 2018; Ruangpan *et al.*, 2020).

Engineers have been modeling and comparing NBS designs in term of their impact on local hydrology, hydraulics, and water balances for existing and proposed sites to help decision-makers identify effective stormwater management strategies (Jia *et al.*, 2015). This has been the traditional approach. A multi-criteria analysis (MCA) can also be used with more complex assessments to meet multiple objectives that might have conflicting criteria. The MCA approach defines a weight of importance for each criterion to help the decision process (Loos and Rogers, 2016; Majidi *et al.*, 2019). These trial-and-error methods are more appropriate for small-scale applications and are rarely helpful in large catchments (Ruangpan *et al.*, 2020).

In recent years, optimization tools have been developed to help with large-scale catchments that have many scenarios and parameters to evaluate. These optimization tools can be used to maximize the benefits of NBSs while minimizing costs (Ruangpan *et al.*, 2020). These tools usually focus on decreasing surface runoff and improving water quality by determining the optimal type, size, and location of NBS (Behroozi *et al.*, 2018).

A comprehensive modeling system is one type of optimization tool used. These systems are physically based deterministic models and have a user-friendly interface. One example of this kind of model is the System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN). It was developed by the US Environmental Protection Agency (US EPA) and has helped decision-makers select the appropriate NBSs and their placements for optimized hydrological performances (Ruangpan *et al.*, 2020).

Integrated model algorithms are another type of optimization tool. This optimization tool combines hydrological models with optimization algorithms. The non-dominated sorting genetic algorithm II (NSGA-II) was the most used in NBS studies reviewed by Ruangpan et al. (2020).

2.5 Limitation of current optimization tools

Although the optimization models mentioned in Section 2.4 offer effective tools for finding the best combinations of NBS, there are some limitations. For example, comprehensive modeling systems such as SUSTAIN can be difficult to modify with user-specific needs (Ruangpan et al., 2020). In addition, Wang et al. (2015) found that although NSGA-II was the most popular integrated model algorithm, it had limited parameter tuning features. Comprehensive modeling systems can be complex and need diverse input information to give accurate results. Integrated algorithm models usually use nonlinear algorithms, which can become complicated with too many parameters. For this reason, integrated algorithm models tend to be quite simple. It can also be difficult to determine the optimal combination of NBSs when an accurate cost-benefit analysis is difficult to produce (Ruangpan et al., 2020). More specifically, concerning the current study, the optimization tools offer one perspective on what is the best decision. It usually needs to be paired with another tool or analysis to provide the most sustainable solution. NBS-OPT is different in the sense that it is part of a package that tries to offer a holistic perspective with ecological, social, and economic angles. The EviBAN package is trying to give the most sustainable solution (WJPI, 2018).

3 Site description and data

3.1 Study area

Vallikallio (VK) was chosen to be the catchment for this study because data such as rainfall, climate, and storm network layouts were available from previous studies (Sillanpää, 2013; Raudaskoski, 2016). These studies provided a parameterized, calibrated, and validated model compared with measured rainfall-runoff from Vallikallio. The location of the catchment is shown in Figure 2. The catchment is in the city of Espoo, in southern Finland, and is a medium-density residential area consisting of mainly apartment buildings. The total area of the catchment is 11 hectares, of which 53% is impervious. The majority of the pervious area consist of sandy till (Tuomela, 2017). All roads in the catchment have asphalt coating, and most of the rooftops have a direct connection to the storm sewers. The storm sewer network is subsurface and covers the entire catchment area. Elevations range from 29 to 50 meters above the mean sea level. (Sillanpää and Koivusalo, 2015).

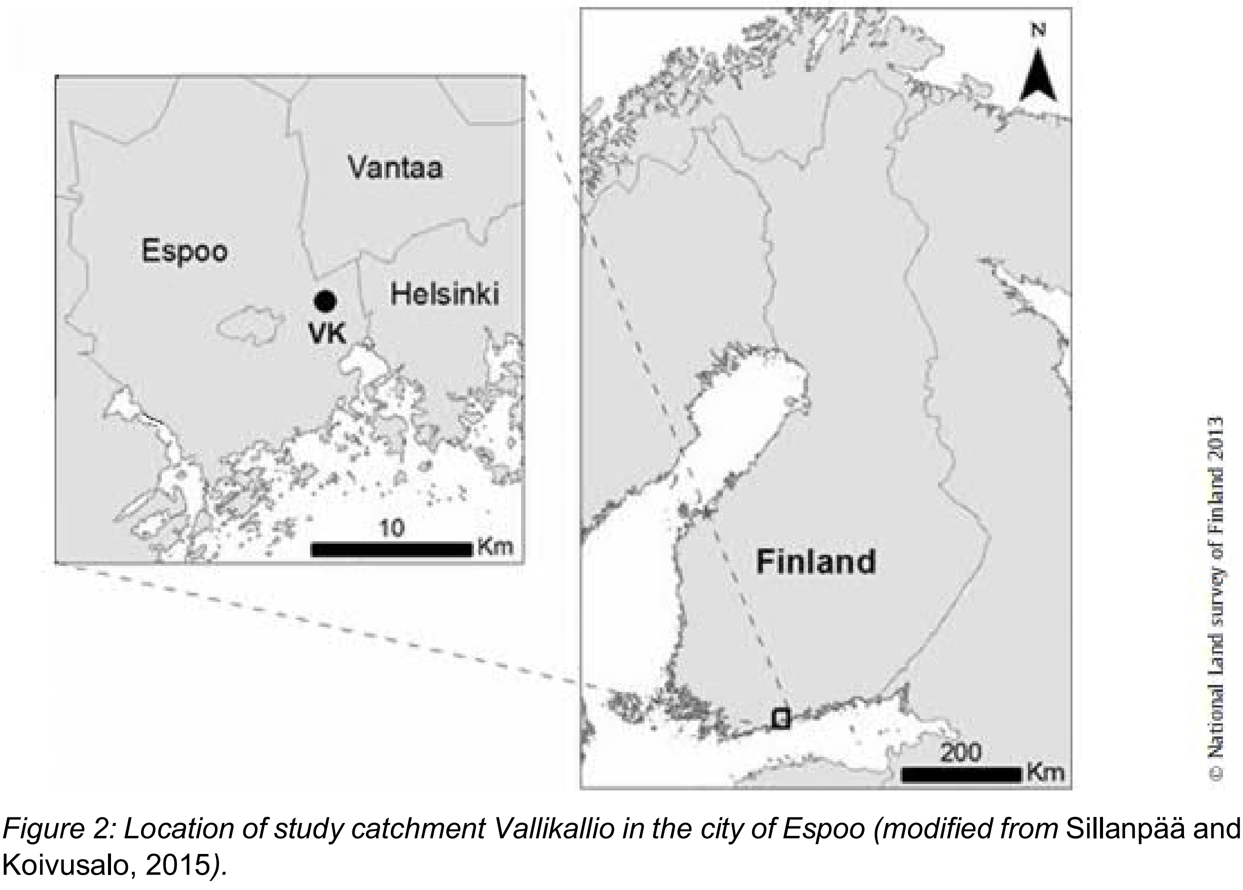

Figure 2: Location of study catchment Vallikallio in the city of Espoo (modified from Sillanpää and Koivusalo, 2015*).*

The catchment was broken down to a smaller subarea of 1.39 hectare in the Northwest, shown in Figure 3, and separated into seven nodes. A node is a catchment area draining to a certain stormwater network junction. The new study catchment consists of seven junctions, and therefore, was split into seven nodes to simplify the parameterization.

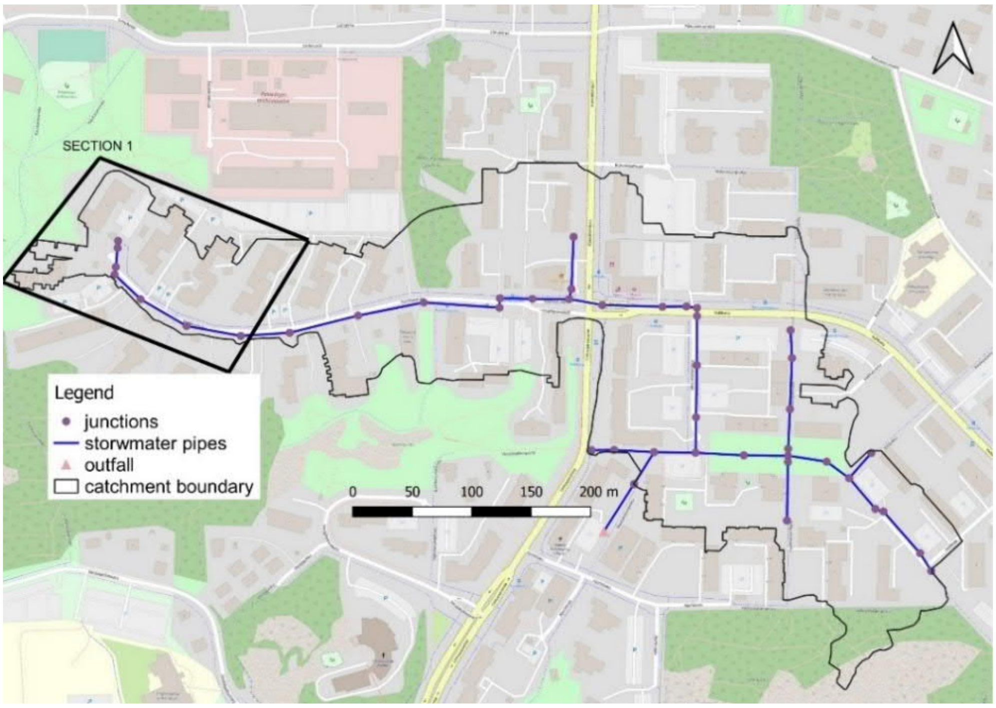

Figure 3: Vallikallio catchment with Northwest study catchment outlined.

The subarea in Figure 3 includes five buildings, two large parking lots, walkways, pavements, sand areas, open rock areas, and roads. The total impervious area in this study area is 73%. Table 2 gives a further breakdown of the surface types and their areas for each node.

Table 2: Break down of nodal area (m^2) by surface in the study catchment.

Node	1	2	3	4	5	6	7	Total
Roof	785	46	17	602	1,038	1,142	1,081	4,710
Walkway	302	274	110	0	485	577	629	2,377
Parking	634	0	962	0	142	145	0	1,882
Road	0	0	233	0	177	264	264	937
Pavements	0	0	0	0	49	95	0	144
Sand	0	0	27	0	74	226	86	413
Rock	0	0	0	0	0	48	49	97
Vegetation	554	527	343	0	645	945	329	3,343
Impervious	76 %	38 %	78 %	100 %	72 %	66 %	83 %	73 %
Pervious	24 %	62 %	22 %	0 %	28 %	34 %	17 %	27 %
Total area	2,275	847	1,692	602	2,610	3,442	2,438	13,903

3.2 Rainfall and climate data

The local climate in Vallikallio is cold and temperate. The average temperature in July is 18.1°C, which is the warmest month. February has an average temperature of -4.8°C, which is the coldest month. Monthly rainfall is fairly evenly distributed, and it is observed even during the driest month of April, with an average of around 35-40 mm of monthly rainfall. The wettest month August has an average monthly rainfall of around 65-75 mm (Climate Espoo (Finland), 2021). The design rainfall data for this study is shown in Table 3 and was taken from Climate Guide (2021).

Table 3: Rainfall data. Ten-minute precipitation sums in two-minute intervals for six storm events (Climate Guide, 2021).

	Precipitation (mm)					
Time	1-year	2-year	5-year	10-year	25-year	50-year
0:02	0.86	1.3	1.9	2.34	2.94	3.38
0:04	0.86	1.3	1.9	2.34	2.94	3.38
0:06	0.86	1.3	1.9	2.34	2.94	3.38
0:08	0.86	1.3	1.9	2.34	2.94	3.38
0:10	0.86	1.3	1.9	2.34	2.94	3.38

Weather data was available from the Finnish Meteorological Institute and is shown in Table 4. The model simulation period covered only a sub-daily period on the 1st of June 2006.

Table 4:Climate data for the day of the simulation on June 1, 2006 (Ilmatieteen laitos, 2021).

Date	Temp high	Temp low
June 1, 2006	19.3	10.2

3.3 Cost data

When determining NBS costs, many factors affect the final cost. Such factors include how established the NBS industry is in a particular country, the quality of material used to install the NBS, the soil type where the NBS is to be installed, and maintenance costs. Although NBS have increased in popularity over the past three decades, there is still minimal documentation regarding costs associated with NBS operation and maintenance (O&M) (Houle *et al.*, 2013). Note that the current study focused on the relative, instead of the absolute performance and functionality of NBS-OPT. The specific costs are not important to the assessment of the performance and functionality of the tool. Costs for this study are shown in Table 5. The first two cost options were taken from literature and provide a fair comparison between the four NBS used in this study (Ruangpan *et al.*, 2020; Khadka *et al.*, 2021). Options three and four were used to test the sensitivity of the model to cost, retention, and detention.

Table 5: Cost data (€). Option 1 (Ruangpan *et al.*, 2020)*, Option 2* (Khadka *et al.*, 2021)*, Option 3 - same costs for all NBSs, Option 4 - similar cost for NBSs, Operation and maintenance (O&M) costs are shown as a percentage of capital costs.*

	Option 1		**Option 2**		**Option 3**		**Option 4**	
Measure	Capital cost per m2	O&M cost per year	Capital cost per m2	O&M cost per year	Capital cost per m2	O&M cost per year	Capital cost per m2	O&M cost per year
Rain garden	501	0.10	20	0.10	10	0.10	21	0.10
Green roof	564	0.07	30	0.07	10	0.10	20	0.07
Vegetated swale	371	0.06	38	0.06	10	0.10	18	0.06
Permeable pavement	252	0.04	45	0.04	10	0.10	22	0.04

4 Methodology

This chapter explains what steps were taken in achieving the objectives of this study. It briefly reviews what models were used, how they were parameterized and calibrated, and how NBS-OPT was validated. Figure 4 illustrates a flow diagram of methods used for this study.

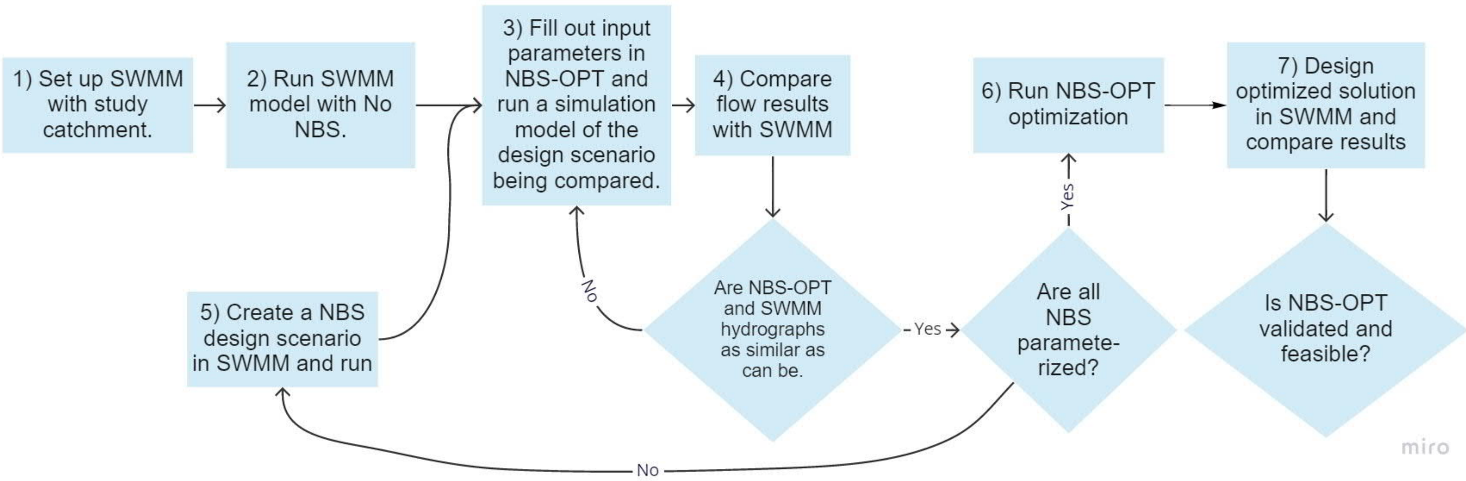

Figure 4: Flow diagram of methods. (Squares represent steps and diamonds represent questions to direct user to appropriate next step.)

In Step 1 of Figure 4, the existing SWMM model of Vallikallio was stripped of all sub-catchments, junctions, and pipes that were not part of the new Northwest study catchment (see Figure 3). Steps 2-5 are the parameterization and calibration steps. A total of five measures were parameterized in NBS-OPT: 1) Non-NBS, 2) Rain garden, 3) Green roof, 4) Swale, and 5) Permeable pavement. In Step 2, the SWMM model was run with no NBSs and provided flow results. These results acted as a benchmark for calibrating the Non-NBS measure in NBS-OPT. In Step 3, NBS-OPT was assigned initial retention and detention parameters for the Non-NBS measure and then run as a simulation with no NBSs. In Step 4, hydrographs of the flow results were compared between SWMM and NBS-OPT. Steps 3 and 4 were repeated until the outfall hydrographs showed minimum peak flow differences and the highest Nash-Sutcliffe model efficiency coefficient (NSE). It was only possible to parameterize the NBS measures after parameterizing the Non-NBS measure. In step 5, NBS designs were created in SWMM. The parameterization and calibration Steps 3, 4, and 5 were repeated until all four NBS measures were parameterized. Peak flow, NSE, and hydrograph comparisons focused on the junction closest to where the NBS was designed. In Step 6, the NBS-OPT optimization function was run and produced an optimal design scenario. Step 7 was the validation step, where the optimized design scenario was redesigned in SWMM. The flow results from SWMM were then compared to those of NBS-OPT. Four different cost options were used to test the sensitivity of the tool in terms of retention, detention, and cost. Thus, four optimal combinations of NBSs were compared.

4.1 EPA Storm Water Management Model (SWMM) of Vallikallio

4.1.1 Features of SWMM

SWMM is a tool used to model runoff volume and quality for single events or long-term simulations. A SWMM model consists of a catchment, which is divided into subcatchments, and pipe networks. The model receives two sets of input data, precipitation and climate. The subcatchments receive the precipitation, which then generates runoff and pollutant loads from the remaining water that is not infiltrated or evaporated. This runoff is then transported from the subcatchment area to the pipe network. SWMM considers soil and climate, which affect the losses such as infiltration and evapotranspiration. SWMM tracks values within each catchment such as flow rates, flow depths, infiltration, evapotranspiration, and quality of water in each pipe. (Huber *et al.*, 1975). It is also possible to place different prescribed LID tools that can cover the entire subcatchment or part of the subcatchment. Figure 5 illustrates the modelling process with a flow diagram.

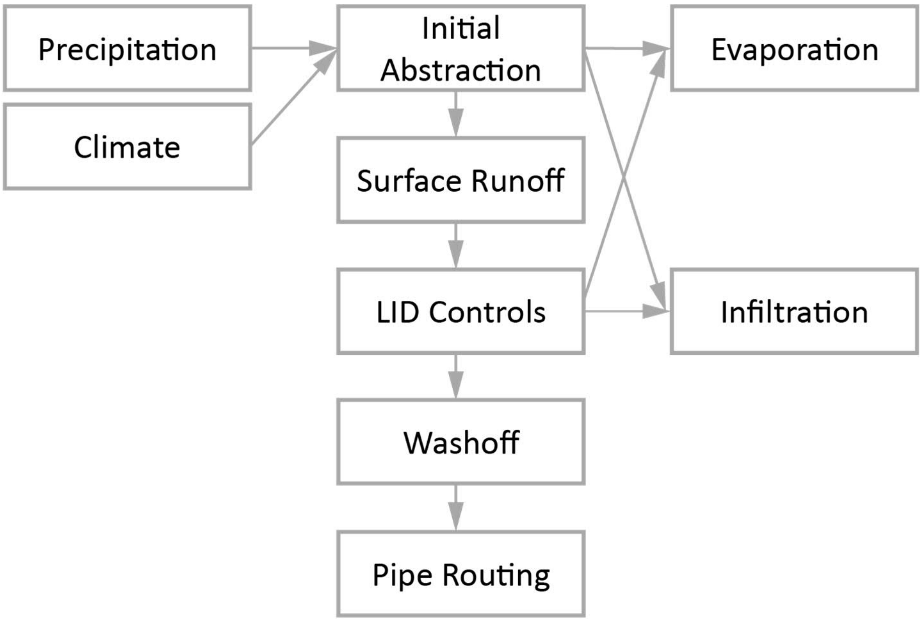

Figure 5: SWMM hydrological modeling process (*modified from* Tuomela, 2017).

4.1.2 Adjustments to existing Vallikallio model

This study used an existing SWMM 5.0 model of the Vallikallio catchment created by Raudaskoski (2016) and then updated by Tuomela (2017). The existing model was simplified and stripped of all subcatchments and pipe networks that were not in the study area outlined in Figure 3. The SWMM model for this study is shown in Figure 6. Note that a section of subcatchments in the last node (Node 7), which is seemingly disconnected from the area, is also connected to the outfall O1. A walkway subcatchment that is between the road and building is routed to another junction downstream. The walkway subcatchment was removed for this model as it does not flow into the outfall.

Figure 6: Detailed surface map of the study catchment and the stormwater network.

4.1.3 Model set up and parameters

SWMM used the Dynamic wave option for the routing of flow in the pipe network. The Green-Ampt option was used to determine water losses in the model, such as infiltration and evaporation. The parameters for each surface type are shown in Table 6.

Table 6: Subcatchment surface area parameters calibrated by Raudaskoski (2016).

Surface area	Imperviousness (%)	Manning's roughness coefficient	Depression storage (mm)
Roof	100.0	0.0084	0.280
Rock	100.0	0.0500	3.160
Walkway	94.1	0.0160	0.826
Road	94.1	0.0160	0.826
Parking	94.1	0.0160	0.826
Stone or tile paving	84.9	0.0190	0.300
Sand	33.0	0.0100	0.400
Vegetation & lawns	0.0	0.5000	2.450

This study used four different small-scale NBSs to assess NBS-OPT. These NBSs have different layers (Figure 7) and specific properties (Table 7). Parameters for the green roof were adopted from Krebs *et al.* (2016) and the rest from Huber *et al.* (2016).

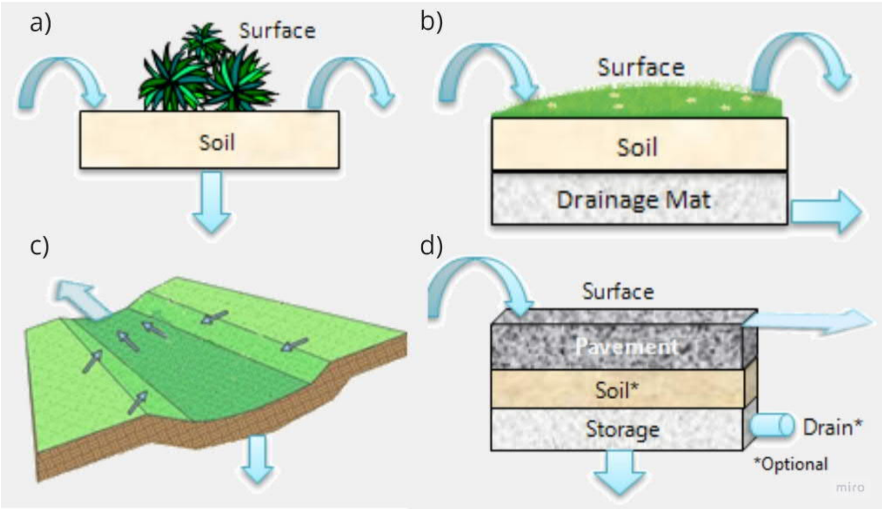

Figure 7: Illustrations of NBSs from SWMM: a) rain garden, b) green roof, c) vegetated swale, and d) permeable pavement (modified from US EPA SWMM 5.1 user interface).

Table 7: NBS SWMM design parameters (Huber *et al.*, 1975; Kling *et al.*, 2015; Krebs *et al.*, 2016).

Layer	Parameter	Rain garden	Green roof	Vegetated swale	Permeable pavement
Surface	Berm height (mm)	200.00	30.000	500.00	0.0
	Vegetation volume fraction	0.15	0.100	0.15	0.0
	Surface roughness (Manning's n)	0.60	0.168	0.60	0.2
	Surface slope (percent)	0.50	8.000	2.00	3.2
	Swale side slope (run/rise)			5.00	
Soil	Thickness (mm)	400.00	100.00		400.000
	Porosity (volume fraction)	0.52	0.41		0.463
	Field capacity (volume fraction)	0.15	0.29		0.094
	Wilting point (volume fraction)	0.08	0.02		0.050
	Conductivity (mm/h)	119.40	37.90		114.000
	Conductivity slope	39.30	40.00		48.000
	Suction head (mm)	48.26	61.30		49.530
Storage	Thickness (mm)				300.00
	Void ratio (voids/solids)				0.43
	Seepage rate (mm/h)	4.21			4.21
	Clogging factor				0.00
Drainage mat	Thickness (mm)		3.80		
	Void fraction		0.41		
	Roughness (Manning’s n)		0.01		
Pavement	Thickness (mm)				75.00
	Void ratio (voids/solids)				0.24
	Impervious surface fraction				0.00
	Permeability (mm/h)				360.00
	Clogging factor				0.00
Underdrain	Flow coefficient				25.0
	Flow exponent				0.5
	Offset height (mm)				150.0

4.2 NBS-OPT

This section briefly describes NBS-OPT. It explains how to set up and parameterize the model and how to interpret the results once ran. A more detailed explanation of how NBS-OPT works can be found in Helness et al. (2021).

NBS-OPT is designed as a simple mathematical model of a real-life situation. The model is held parsimonious as it is intended to be used as a screening tool. It provides a quick overview of suitable solutions to meet objectives with a limited amount of input information. The main objective of the optimizer is to find a combination of NBSs within a catchment that satisfies the target discharge limit at the lowest possible cost, with set boundary conditions. MS Excel spreadsheet program is used as an instrument for organizing the input and output data, and Python is used for setting up and solving the optimization model. The python model uses the “Pyomo (2021)” optimization package and the nonlinear solver “ipopt”.

4.2.1 Technical water management measures

NBS-OPT uses two basic technical measures for modeling stormwater management, which are retention losses (evapotranspiration and infiltration) and detention (delayed release). Both of these measures are expressed as a percentage of water volume entering the measure in a node during a given time period. If a measure occupies 20% of the node, then 20% of the total water entering the node at the time period is assumed to enter the measure. Then the loss of the total volume of water in the measure is determined by the retention percentage. The detention measure now determines how the remaining water in the measure is distributed over the following time periods. An example is shown in Figure 8.

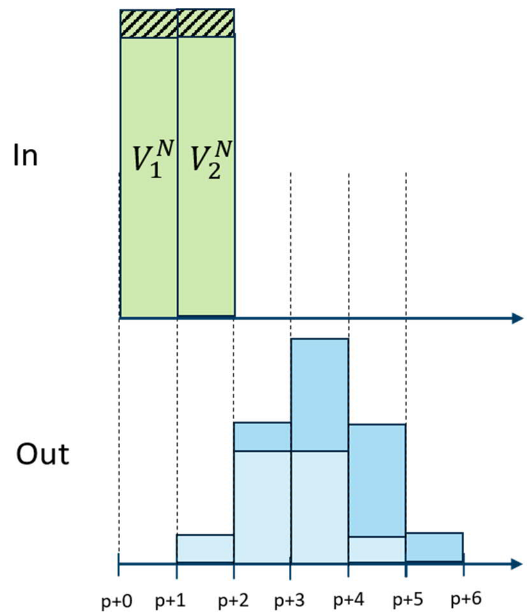

Figure 8: Illustration of water-management properties of a NBS in NBS-OPT. Of the volumes entering the NBS during two consecutive time periods (green boxes), a certain percentage is lost (green/black-hatched boxes) while the remainder is gradually released through the NBS (light and darker blue boxes) (Helness et al., 2021).

4.2.2 Model set up and parameterization in Excel

The NBS-OPT input Excel file has a total of seven sheets. The “Setup” sheet is an explanatory worksheet with some information about the model. No information is read in the Python model from this sheet. The “General Data” sheet contains a list of parameters controlling the setup of the tool. These different parameters are shown in Table 8.

Table 8: “General Data” sheet in the NBS-OPT input Excel file.

Parameter	Explanation	Case study input
Discount rate (%)	A value between 0 and 1 (corresponding to 100 %) – a typical value would be 0.07, corresponding to 7%.	0.07
Time units economic modeling (years)	Optimization horizon for accounting the capital and O&M costs of the water management solutions.	20
Discharge limit in sink node (flow/time interval)	Limit on volume entering the sink node during any given time period.	25000 l/2min for 50-year storm (depends on storm event)
Time units water modeling (#)	Modeling horizon for water management, measured, e.g., as a number of 10-minute intervals. This number should be large enough to allow all rainwater that does not evaporate within the system to reach the sink node	37
Selected rainfall profile (#)	ID number of the hyetograph selected from worksheet “Design Rainfall”.	1-7 (depends what storm event)
Run as simulation (uses fixed NBS shares)	Any non-zero value indicates that the model is run as simulation with given shares for the measures in each node. These shares are read in from the worksheet “Fixed Shares”.	At first 1 to parameterize model by running simulations. Then 0 for optimization.
Limits on installed measure area in nodes	Any non-zero value indicates that there may be individual limits on the area available for each measure in each node. These limits are read in from the worksheet “Nodes”.	1 as there are always limits on nodal areas
Output file name (.xlsx)	Name the output file.	results

The “Measures” sheet (Table 9) describes all NBSs that are considered to be included in the parameterization. Each specific measure is given a name, ID (identifier)number, capital cost, O&M cost, retention rate, and detention ordinates.

Table 9: ”Measures” sheet in the NBS-OPT input Excel file. (1 time step = 12.33 minutes)

		Costs		Retention	Detention (time step) total time = 74 min					
Measure	mID	CAP	O&M	losses	1	2	3	4	5	6
Non-NBS	0	0	0	0.28	0.4	0.3	0.2	0.1	0	0
Rain garden	1	501	0.10	0.92	0.4	0.2	0.2	0.1	0.1	0
Green roof	2	564	0.07	0.83	0.4	0.2	0.2	0.1	0.1	0
Vegetated swales	3	371	0.06	0.46	0.4	0.2	0.2	0.1	0.1	0
Permeable pavements	4	252	0.04	0.92	0.4	0.2	0.2	0.1	0.1	0

Both capital and O&M costs were taken from the literature introduced in Section 3.3. As noted in Section 3.3, costs vary drastically depending on location, quality of materials, contractors, and existing site conditions. This input parameter requires research for a specific location and situation. Retention and detention are explained in Section 4.2.1.

NBS-OPT discretizes the whole catchment into nodes. Each nodal area must be input into the sheet called "Nodes". It was decided to use the area collected by a junction, such as a catchment to one area drain, as one node. For this specific study area, seven nodes were determined as there were seven junctions in the catchment (Figure 6). Next, each node was given a potential NBS area limit as well as a combined NBS area limit. The limit areas of each NBS are defined in Table 10.

Table 10: NBS area limits used in the NBS-OPT input Excel file.

NBS	Limit area formula
Non-NBS	Total node area
Rain garden	Parking + sand + vegetation
Green roof	Roof
Vegetated swale	Parking + sand + vegetation
Permeable pavement	Walkway + parking + pavements
RG & VS	Parking + sand + vegetation
RG & PP	Parking + walkway + pavers + sand + vegetation
VS & PP	Parking + walkway + pavers + sand + vegetation
All NBS	Roof + walkway + parking + pavers + sand + vegetation

The limits described in Table 10 were adopted to ensure that NBS-OPT produced a more realistic solution and only supported NBS locations in areas where they could be designed. For this study, a simplified limit area was used. The potential NBS and combined NBS area limits for each node are shown in Table 11.

Table 11: "Nodes" sheet in the NBS-OPT input Excel file. 0=Non-NBS, 1=rain garden, 2=green roof, 3=vegetated swale, 4=permeable pavement.

Nodes	Nodal	Measures feasible mID (yes>0, no=0) (area in m^2)								
nID	area (m^2)	0	1	2	3	4	1+3	1+4	3+4	All NBS
0	0	0	0	0	0	0	0	0	0	0
1	2275	2275	1188	785	1188	936	1188	1490	1490	2275
2	846	846	527	46	527	274	527	801	801	846
3	1692	1692	1332	17	1332	1072	1332	1443	1443	1459
4	602	602	0	602	0	0	0	0	0	602
5	2608	2608	860	1038	860	675	860	1394	1394	2433
6	3442	3442	1316	1142	1316	817	1316	1989	1989	3130
7	2437	2437	415	1081	415	629	415	1043	1043	2125

In the "Network" sheet shown in Figure 9, the user defines how nodes are routed and at what speed water flows to the outfall. The outfall or sink node is referred to as Node 0. Each of the seven nodes were routed directly to Node 0 with a time of concentration of 1. This was done to simplify the model and ensure that the flow duration time in the stormwater network was small compared to the computation time step of two minutes.

Network from node	To node	Share	Time of concentration (time unit)
1	0	1	1
2	0	1	1
3	0	1	1
4	0	1	1
5	0	1	1
6	0	1	1
7	0	1	1

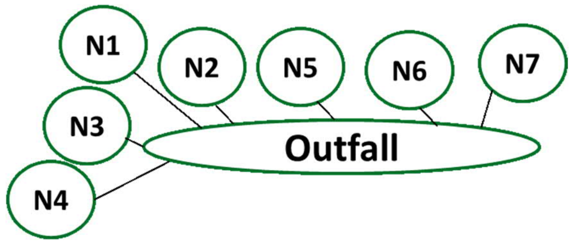

Figure 9: "Network" sheet in the NBS-OPT input Excel file with an illustration of flow routing to the outfall.

Rainfall is input as a volume of rainfall on an area (l/m²) during a given time interval in the sheet called "Design Rainfall" (Table 12). The rainfall profile was input to match the SWMM rainfall profile. The SWMM model was designed in a way that rainfall began ten minutes after the design rainfall started and lasted for a total of ten minutes. Each time step is two minutes. The different rainfall profiles of the NBS-OPT model shown in Table 12 were the same as the rainfall input used in SWMM.

Table 122: "Design Rainfall" sheet in the NBS-OPT input Excel file.

Rainfall event	Rainfall (time step) (liter/m^2 per two minutes)									
	1	2	3	4	5	6	7	8	9	10
1-year	0	0	0	0	0	0.86	0.86	0.86	0.86	0.86
2-year	0	0	0	0	0	1.30	1.30	1.30	1.30	1.30
5-year	0	0	0	0	0	1.90	1.90	1.90	1.90	1.90
10-year	0	0	0	0	0	2.34	2.34	2.34	2.34	2.34
25-year	0	0	0	0	0	2.94	2.94	2.94	2.94	2.94
50-year	0	0	0	0	0	3.38	3.38	3.38	3.38	3.38

NBS design scenarios are input in the sheet called "Fixed Shares" (Table 13). Here, a user can input a NBS area in a node as a percentage of the nodal area. This sheet is only read when a simulation is run. Table 13 shows an example of Design 5 (Table 14), which consists of a rain garden in Node 1. The area of the rain garden is 25% of the area of Node 1.

Table 13: "Fixed Shares" in the NBS-OPT input Excel file.

Nodes	Measures mID (shares <= 1, sum =1)					
nID	0	1	2	3	4	5
0	0	0	0	0	0	0
1	0.75	0.25	0	0	0	0
2	1	0	0	0	0	0
3	1	0	0	0	0	0
4	1	0	0	0	0	0
5	1	0	0	0	0	0
6	1	0	0	0	0	0
7	1	0	0	0	0	0

4.3 Design scenarios

Different design scenarios were modeled both in SWMM and NBS-OPT. To parameterize and calibrate NBS-OPT, this study modeled 32 scenarios, as shown in Table 14.

Table 14: Design scenarios for the parameterization of retention and detention for the "Measures" sheet in the NBS-OPT input Excel file.

Design	Measure	Storm event	NBS area as a percentage of nodal area				
			N1	N2	N3	N5	N7
1	Non-NBS	1					
2	Non-NBS	10					
3	Non-NBS	25					
4	Non-NBS	50					
5	Rain garden	25	25 %				
6	Rain garden	25			25 %		
7	Rain garden	25	10 %	10 %	10 %	10 %	
8	Rain garden	25		10 %			
9	Rain garden	25				10 %	
10	Rain garden	25			10 %		
11	Rain garden	50	25 %				
12	Rain garden	50			25 %		
13	Green roof	10	25 %				
14	Green roof	10				25 %	
15	Green roof	10					25 %
16	Green roof	10	10 %		10 %	10 %	10 %
17	Green roof	25	25 %				
18	Green roof	25				25 %	
19	Green roof	25					25 %
20	Green roof	25	10 %			10 %	10 %
21	Green roof	50	25 %				
22	Green roof	50				25 %	
23	Green roof	50					25 %
24	Green roof	50	10 %			10 %	10 %
25	Permeable pavement	25	25 %				
26	Permeable pavement	25			25 %		
27	Permeable pavement	50	25 %				
28	Permeable pavement	50			25 %		
29	Swale	25	25 %				
30	Swale	25			25 %		
31	Swale	50	25 %				
32	Swale	50			25 %		

The designs in Table 14 are listed in the order they were run. NBSs were designed in a variety of nodes to check for variability in retention and detention rates. For the majority of NBS design scenarios, a NBS area covering 25% of the nodal area was designed. A few design scenarios had one or more NBS with 10% coverage. None of the designs had flow routed to the NBSs because NBS-OPT does not have this option. The only water that enters the NBS is the rainfall which falls directly onto the area of the NBS.

4.4 Determining retention and detention values

Retention and detention values were determined by two factors: 1) peak flow differences and 2) NSEs. Peak flow differences and NSEs were calculated for all seven nodes in all 32 designs. The peak flow difference was calculated using Eq. 1,

$$D_{peak\ flow} = Q_N - Q_S \ , \tag{1}$$

where Q_N is the peak flow of NBS-OPT, and Q_S is the peak flow of SWMM. The NSE was calculated using Eq. 2,

$$R_{NSE} = 1 - \frac{\sum_{t=1}^{T}\left(Q_{o,t} - Q_{m,t}\right)^2}{\sum_{t=1}^{T}\left(Q_{o,t} - \bar{Q}_o\right)^2} \ , \tag{2}$$

where $\bar{Q}_o$ is the mean SWMM discharge flow, $Q_{o,t}$ is the discharge of SWMM at time t, and $Q_{o,t}$ is the discharge of NBS-OPT at time t.

The values for retention and detention that provided the smallest peak flow difference and the highest NSE at each junction were the values chosen to be the parameters for the specific measure being calibrated. The outfall (Node 0 in NBS-OPT) was given the highest priority when calibrating the Non-NBS measure. However, whenever calibrating a NBS measure, the junction collecting runoff where the NBS measure was being designed took priority. This is because the NBS has the highest influence on the flow results of the junction closest to where it is designed, whereas the outfall node would have a less accurate representation of the effect of the retention and detention of the NBS. Other junctions were also considered and influenced the final value of the parameter.

4.5 NBS-OPT optimization model

Once the different parameter values were determined for all measures, the optimization model was run to find the optimal combination of NBSs. The objective function is to minimize total costs, including capital and annual O&M of all installed NBSs, while meeting the given constraints. These constraints include desired peak flow at the outfall (Node 0 in NBS-OPT) and limit areas for each NBS measure per node. This cost function is represented in mathematical terms in Eq. 3,

$$C_{NBS,mID} = \left(C_{Cap,mID} + C_{OM,mID} \sum_{t\in\mathcal{T}^E} D_t\right) \sum_{n\in\mathcal{N}\setminus\{0\}} S_{NBS,mID,n} A_{node,n} \tag{3}$$

Where $C_{Cap,mID}$ is the capital cost of a measure, $C_{OM,mID}$ is the O&M costs of a measure, $\sum_{t\in\mathcal{T}^E} D_t$ is summation of the discount factor over time, $S_{NBS,mID,n}$ is the percentage of NBS in a node, and $A_{node,n}$ is the nodal area.

The results of the optimization run in NBS-OPT include flow results at different locations of the study area per time step, percentages of each NBS measure in each node, graphical results of existing versus optimal discharge, and graphical results of total rain and discharge. Due to the design routing in NBS-OPT, the flow results from the nodes in NBS-OPT were aggregated to correspond to the flow results of SWMM in junctions J1-J6 and outfall o1 in Figure 6. For example, flows from NBS-OPT in junction J6 was the sum of flows in all nodes upstream of J6, i.e., nodes N1-N6.

Table 15 shows an example of a suggested optimal combination of NBSs from the NBS-OPT output Excel file.

Table 15: Example of NBS-OPT optimal NBS combination output – percentage of nodal area for each NBS measure in each node. Here, the optimal combination uses 35 % of Node 1 area to install green roof (measure 2), 5% of Node 2 area to install green roof, etc.

Node	Measure				
	0	1	2	3	4
0	0%	0%	0%	0%	0%
1	65%	0%	35%	0%	0%
2	95%	0%	5%	0%	0%
3	99%	0%	1%	0%	0%
4	100%	0%	0%	0%	0%
5	47%	14%	40%	0%	0%
6	67%	0%	33%	0%	0%
7	78%	0%	5%	17%	0%

Figure 10 shows an example of the graphical output of NBS-OPT from the Excel file. The flow volume results of NBS-OPT are provided in l/2 minutes.

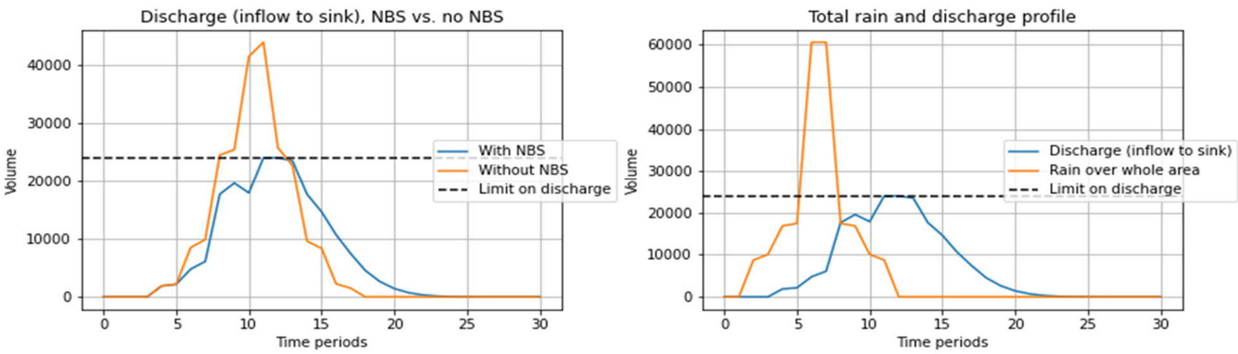

Figure 10: Example of NBS-OPT graphical results. Flow volume units are l/2 minutes.

4.6 Validation of NBS-OPT

Once the optimal percentages of the NBSs were determined for the study site, the model corresponding to the optimization solution was recreated in SWMM. Flow results of SWMM from each junction were then compared with those of NBS-OPT in order to determine validation. Peak flow difference and NSE were used to determine the level of validation of the proposed parameterization method and the ability of NBS-OPT to produce accurate flow results.

5 Results

To assess the functionality and performance of NBS-OPT, this chapter presents the results of the proposed parameterization process and the optimal combinations of NBSs for the 50-year storm using the determined parameters in Section 5.1. The following sections present a comparison of the flows obtained from SWMM and NBS-OPT for each node from Design 4 (Table 14), parameters of all NBS-OPT measures for the 25- and 50-year storm events, optimized NBS designs for the four different cost scenarios, peak flow reductions, and validation of the model. A discussion of each of these results will follow in Chapter 6.

5.1 NBS parameterization for NBS-OPT

In order to make flow comparisons between SWMM and NBS-OPT, the flow results of each junction in SWMM were imported into the MS Excel file of the NBS-OPT results. It was necessary to accumulate flow results from NBS-OPT, since NBS-OPT was set to route flows directly to the outfall. For example, to compare flow results in Junction 2, flows accumulated in Node 1 and Node 2 that were routed to the outfall were summed together. Tables 16 and 17 list the retention rates tested for the Non-NBS measure during the 25- and 50-year storms. These results were determined based on the comparison between the flow results of the NBS-OPT and SWMM outfall (Node 0 in NBS-OPT). Peak flow differences and NSE for the outflow node are also shown in Tables 16 and 17. A retention rate of 0.28 was chosen because it produced the highest NSE and smallest peak flow difference between SWMM and NBS-OPT. This indicates that almost one-third of the design rainfall in the existing catchment is infiltrated or evaporated. This represents the entire site, regardless of the ratio between pervious and impervious coverage in specific nodes.

Table 16: Retention parameterization for Non-NBS measure during the 25-year storm.

Retention rate	Peak flow difference ($\frac{l}{2\,min}$)	NSE
0.28	-396	0.985
0.25	830	0.983
0.30	-1213	0.984

Table 17: Retention parameterization for Non-NBS measure during the 50-year storm.

Retention rate	Peak flow difference ($\frac{l}{2\,min}$)	NSE
0.28	-1715	0.981
0.25	-1769	0.982
0.20	-2044	0.974
0.30	-2655	0.978
0.35	-5004	0.963
0.40	-7354	0.937

In addition to the flow at the outfall, flows from SWMM and NBS-OPT for all junctions were also examined by comparing peak flows and determining their NSE. Figure 11 shows the flow comparison from Design 4 (Table 14) using a retention rate of 0.28 for the Non-NBS measure. For the most part the hydrographs are quite similar. However, it is clear that in Junction 1 SWMM shows a higher peak flow than NBS-OPT, while SWMM shows a lower peak flow than NBS-OPT in Junction 2. A likely explanation for this is that Node 1 has 79% impervious coverage, whereas Node 2 has only 36% impervious coverage. This is a prime example of where the model loses accuracy. Outfall 1 had the highest priority when parameterizing the retention and detention values of the Non-NBS measure. Thus, the outfall would be expected to have the smallest peak flow difference of all the junctions. The retention rate of 0.28 for Non-NBS produced a peak difference of only 14.3 l/s, thus demonstrating the accuracy of this parameter value.

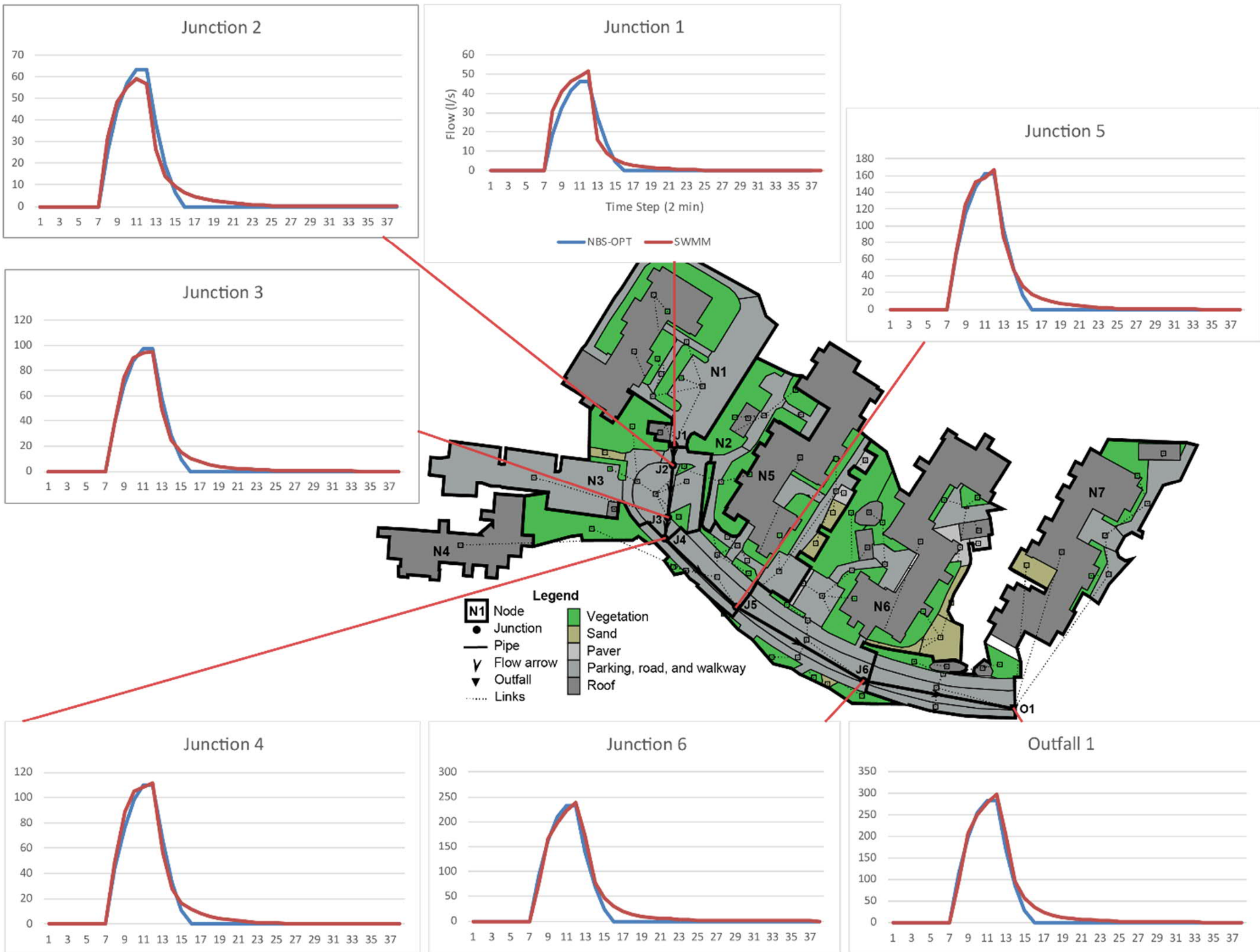

Figure 11: Hydrographs for each junction from Design 4 (50-year storm without any NBSs).

This study focused only on the 25 and 50-year storm events because the retention rates for NBS measures for smaller events were all 1. This indicates that SWMM calculated that all the NBS options retained 100% of the rainfall that entered the NBS in all storm events smaller than the 25-year storm. The 25- and 50-year storm NBS parameters are shown in Tables 18 and 19. Three out of four NBS measures for the 25-year storm retained 100% of rainfall. A higher intensity rainfall was necessary to allow NBS-OPT to optimize NBSs with different retention rates.

Table 18: 25-year storm parameters for NBS-OPT measures.

	Retention losses	Detention (time step) total time = 74 min					
Measure		1	2	3	4	5	6
Non-NBS	0.28	0.4	0.3	0.2	0.1	0	0
Rain garden	1.00	0.4	0.2	0.2	0.1	0.1	0
Green roof	1.00	0.4	0.2	0.2	0.1	0.1	0
Vegetated swales	0.56	0.4	0.2	0.2	0.1	0.1	0
Permeable pavements	1.00	0.4	0.2	0.2	0.1	0.1	0

Table 19: 50-year storm parameters for NBS-OPT measures.

	Retention losses	Detention (time step) total time = 74 min					
Measure		1	2	3	4	5	6
Non-NBS	0.28	0.4	0.3	0.2	0.1	0	0
Rain garden	0.92	0.4	0.2	0.2	0.1	0.1	0
Green roof	0.83	0.4	0.2	0.2	0.1	0.1	0
Vegetated swales	0.46	0.4	0.2	0.2	0.1	0.1	0
Permeable pavements	0.92	0.4	0.2	0.2	0.1	0.1	0

In the 50-year storm, none of the NBS solutions retained 100% of the precipitation, and only the rain garden and permeable pavements had the same retention rates. Therefore, these parameters were selected to analyze the performance of NBS-OPT. Different detention values for the NBS measures were tested and showed surprisingly little to no effect on the flow results. Therefore, all NBSs were prescribed with the same detention values. The values shown in Tables 18 and 19 were able to produce flow results that were similar to those of SWMM for both the 25- and 50-year storm events.

Retention rates varied for the NBSs depending on what node they were designed in. For example, green roofs installed in Node 7, downstream of the catchment, had much lower retention rates than if they were designed in Node 1, upstream of the catchment, for the 10-, 25-, and 50-year storm events. Vegetated swales also showed a large variability in retention rates during a 50-year storm. A swale designed in Node 1 retained only 46%, whereas a swale designed in Node 3 retained 100%. Rain gardens and permeable pavements showed little variability. The retention rate variability is shown in Table 20.

Table 20: Retention variability for NBS measures when 25% of the node area in nodes N1, N3, N5, and N7, were designed to have one NBS at a time.

NBS measure	Storm event	N1	N3	N5	N7
Rain garden	25	1.00	1.00		
Rain garden	50	0.93	0.91		
Green roof	10	1.00		0.89	0.44
Green roof	25	1.00		0.85	1.00
Green roof	50	0.85		0.83	0.42
Permeable pavement	25	0.99	1.00		
Permeable pavement	50	0.93	0.92		
Swale	25	0.54	0.58		
Swale	50	0.46	1.00		

Node 4 was not considered a good node for comparisons (Table 20) because it only consisted of roof area. There was no specific reason to exclude or include Nodes 2 and 6, which were left out of the simulations in Table 20.

5.2 Optimized solutions

After determining the parameters shown in Table 19, NBS-OPT was prepared to run its optimization function. NBS-OPT was parameterized to reduce the site's existing peak flow of 282 l/s, corresponding to 100% of the site area represented by Non-NBS measure, by 26% to 208 l/s during the 50-year storm event.

The optimal combination of NBSs suggested by NBS-OPT for the four cost scenarios are shown in Tables 21-24. As shown in Tables 21 and 22, Options 1 and 2 represent the two optimal combinations of NBSs using costs from the literature mentioned in Section 3.3. In Option 1, NBS-OPT suggested to only use the permeable pavement. This result was expected because the permeable pavement had the least expensive capital and O&M costs as well as the highest retention rate. In Option 2, NBS-OPT suggested to use only the rain garden. This was for the same reasons as those for Option 1, except that rain gardens had the highest O&M costs. The more intricate part of the results for Option 1 and 2 was that NBS-OPT determined what specific NBS area for each node would meet the desire peak flow with the minimum costs.

Table 21: Optimal combination of NBSs, in terms of nodal areas (%) covered with NBSs, for Option 1 during the 50-year storm event, using costs from Ruangpan et al. (2020).

Node	Non-NBS	Rain garden (€501)	Green roof (€564)	Vegetated swale ($371)	Permeable pavement (€252)
1	59 %	0 %	0 %	0 %	41 %
2	68 %	0 %	0 %	0 %	32 %
3	75 %	0 %	0 %	0 %	25 %
4	100 %	0 %	0 %	0 %	0 %
5	74 %	0 %	0 %	0 %	26 %
6	76 %	0 %	0 %	0 %	24 %
7	74 %	0 %	0 %	0 %	26 %

Table 22: Optimal combination of NBSs, in terms of nodal areas (%) covered with NBSs, for Option 2 during the 50-year storm event, using cost from Khadka et al. (2021).

Node	Non-NBS	Rain garden (€20)	Green roof (€30)	Vegetated swale (€38)	Permeable pavement (€45)
1	48 %	52 %	0 %	0 %	0 %
2	100 %	0 %	0 %	0 %	0 %
3	100 %	0 %	0 %	0 %	0 %
4	100 %	0 %	0 %	0 %	0 %
5	67 %	33 %	0 %	0 %	0 %
6	62 %	38 %	0 %	0 %	0 %
7	83 %	17 %	0 %	0 %	0 %

Option 3 was used to examine what the optimal combination of NBSs would be without cost differences being a determining factor. The optimal combination of NBSs for Option 3 shows that the majority of NBSs are designed downstream in Nodes 5-7 (Table 23). For this option NBS-OPT suggested to include green roofs on the small 46 m² structure in Node 2 and the 17 m² structure in Node 3. Lastly, NBS-OPT did not design any NBSs in Node 1, which has a possibility to install all four NBSs in its area.

Table 23: Optimal combination of NBSs, in terms of nodal areas (%) covered with NBSs, for Option 3 during the 50-year storm event, using the same unit costs for all NBSs.

Node	Non-NBS	Rain garden (€10)	Green roof (€10)	Vegetated swale (€10)	Permeable pavement (€10)
1	100 %	0 %	0 %	0 %	0 %
2	62 %	0 %	5 %	0 %	32 %
3	99 %	0 %	1 %	0 %	0 %
4	100 %	0 %	0 %	0 %	0 %
5	47 %	28 %	0 %	0 %	26 %
6	72 %	4 %	0 %	0 %	24 %
7	57 %	17 %	0 %	0 %	26 %

In Option 4, all four NBSs were assigned similar costs. As shown in Table 24, NBS-OPT suggests a larger area of green roof than that suggested for the rain garden area, even though the rain garden had a higher retention rate at 92% compared to the rain garden's 83%. It is likely that the green roof was preferred over the rain garden since the green roof was 1€ less in capital costs and 3% cheaper than the rain garden in O&M costs. The permeable pavement was not suggested at all, and for the first time, the swale was suggested.

Table 24: Optimal combination of NBSs, in terms of nodal areas (%) covered with NBSs, for Option 4 during the 50-year storm event, using similar unit costs for all NBSs.

Node	Non-NBS	Rain garden (€21)	Green roof (€20)	Vegetated swale (€18)	Permeable pavement (€22)
1	65 %	0 %	35 %	0 %	0 %
2	95 %	0 %	5 %	0 %	0 %
3	99 %	0 %	1 %	0 %	0 %
4	100 %	0 %	0 %	0 %	0 %
5	47 %	14 %	40 %	0 %	0 %
6	67 %	0 %	33 %	0 %	0 %
7	78 %	0 %	5 %	17 %	0 %

The four optimal combinations of NBSs showed that the desired peak flow of 208 l/s was achievable using a variation of NBSs costs and NBS designs. Option 4 illustrated that even if there is only a €1 or €2 difference, NBS-OPT will find a way to meet the desired peak flow using the least expensive NBS. Throughout all four cost options, none of the

NBS measures were designed in Node 4. The only possible NBS that could be designed in Node 4 was a green roof because the node only consisted of a 602 m^2 building. Node 4 has the smallest area of all the nodes and the largest impervious area at 100%. For each optimal combination of NBSs, NBS-OPT determined a NBS area ranging from 26.8-28.3% of the total site area. In NBS-OPT, this range of NBS area showed a peak flow reduction of 26%. When the four optimal combinations of NBSs were replicated in SWMM, the flow results provided a range of 23-39% in peak flow reduction (Table 25).

Table 25: Percentage of NBS area in each optimal design and their reduction of peak flow.

Option	Area of total site (%) Non-NBS	Rain garden	Green roof	Vegetated swale	Permeable pavement	Total NBS area	NBS-OPT Reduction of peak flow (l/s)		SWMM Reduction of peak flow (l/s)	
1	73.0 %	0.0 %	0.0 %	0.0 %	27.0 %	27.0 %	74	26 %	116	39 %
2	72.8 %	27.2 %	0.0 %	0.0 %	0.0 %	27.2 %	74	26 %	67	23 %
3	73.2 %	9.1 %	0.5 %	0.0 %	17.2 %	26.8 %	74	26 %	79	27 %
4	71.7 %	2.6 %	22.7 %	3.0 %	0.0 %	28.3 %	74	26 %	85	29 %

Results from Options 1 and 2 in Table 25, suggest that the permeable pavement measure is more effective at reducing peak flow. Although they had the same retention rates in NBS-OPT, SWMM shows that permeable pavement actually has a higher retention rate than that defined in NBS-OPT. Results from Option 4 indicate that the green roof measure could also have a higher retention rate than the rain garden measure. The average peak flow reduction in SWMM for the four combinations of NBSs is 29%, using an average NBS area of 27% of the total site. The hydrographs of all four optimal combinations of NBSs are shown in Figure 12.

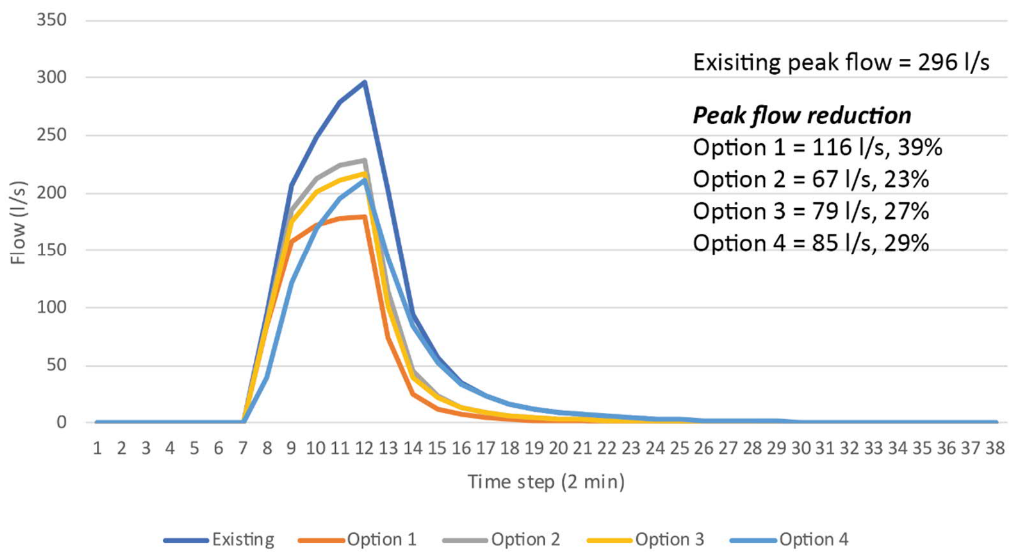

Figure 12: Performance of the four optimal combinations of NBSs from four cost options in SWMM (Outfall discharge).

NBS-OPT produced the exact same hydrograph for all four cost options. Although the maximum peak flow was expected to be the same, the flow values in other time steps were not expected to be the same. In a real situation it is nearly impossible to have the same hydrograph for different design scenarios. Similar hydrograph shapes could be attributed to the fact that NBS-OPT is a simple model and had no differences in the detention ordinates of different NBS measures (Tables 18-19).

5.3 Validating the accuracy of NBS-OPT with SWMM

NBS-OPT was validated after obtaining the optimized solutions for all four cost options. Validation was performed by redesigning the optimal design scenarios in SWMM and comparing outfall flow results with those from NBS-OPT. For example, the optimal combination of NBSs in Option 1 asks for 41% of Node 1 to be permeable pavement. Therefore, in SWMM, walkways, parking, or pavers needed to be changed to permeable pavement until reaching an area of 933 m² (41% × total area of Node 1) of permeable pavement in Node 1. The flow results from NBS-OPT and SWMM for all four optimal combinations of NBSs are shown in Figure 13.

The peak difference between outfall flow values in SWMM and NBS-OPT for Option 1 is 30.9 l/s and the NSE between the two discharge series is 0.943. These results are accurate enough to validate the ability of NBS-OPT to produce flow results for the given 50-year design storm. However, the four hydrographs in Figure 13 show that there is still room for improvement. Option 1 had the largest peak flow difference of the four options. The rest of the optimized solutions had more accurate peak flows and higher NSEs.

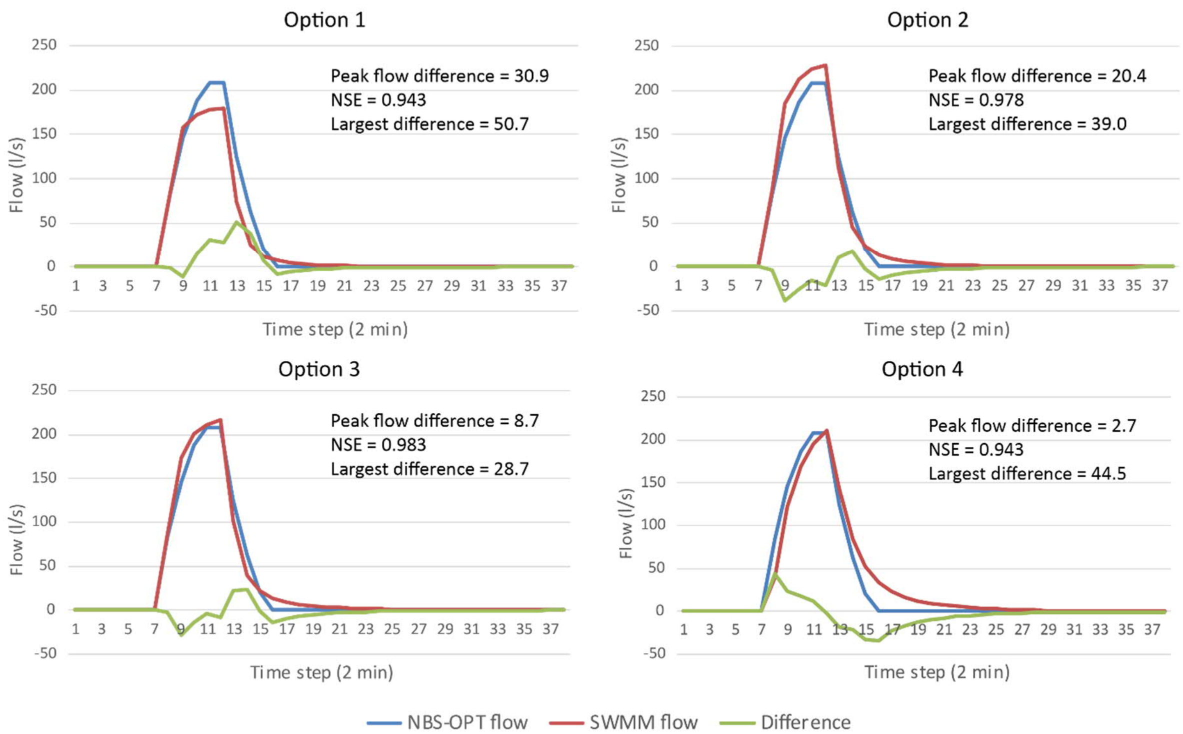

Figure 13: NBS-OPT and SWMM comparison of flow results in outflow node from optimal combinations of NBSs for cost options 1-4.

6 Discussion

Currently, NBS-OPT uses one measure to represent the entire existing site without considering the imperviousness differences between each node. The absence of separate measures for impervious and pervious surfaces resulted in NBS-OPT yielding higher peak flows in nodes with smaller imperviousness areas and lower peak flows in nodes with larger imperviousness areas compared with SWMM. An example of this is shown in Figure 11, demonstrated by the peak flow differences between NBS-OPT and SWMM in Junctions 1 and 2 from Design Scenario 4. This result is not surprising based on the work of Jato-Espino et al. (2019), who found that the percentage of imperviousness for calibration had a major impact on the simulations of the studied optimizer. In fact, the most influential predicators determining NSE, R-squared coefficient, and the Root-Sum Squared Error in their study were those related to imperviousness of the catchment area. NBS-OPT should allow for the user to parameterize a pervious and impervious measure and then define the imperviousness percentage for each node. Such an addition to NBS-OPT would enable the user to set up the site in more detail, resulting in more accurate flow results in every node. More accurate flow results in every node could decrease the NBS retention variability experienced when designed in different nodes and the number of needed simulations to parameterize a NBS measure, thus enabling a more accurate parameterization of NBS measures.

The input of different detention time steps had very little effect on the flow results of NBS-OPT. This is most likely attributed to the two-minute time step interval used for the design rainfall in this study. Smaller catchments require smaller time scales than larger catchments (Booij, 2003), thus, using a smaller time step interval might have been more appropriate in this study since the study catchment has an area of only 1.39 hectare. Doing so, might have increased the effects of detention on the flow results from NBS-OPT. Further testing of the detention variable is recommended.

The current NBS-OPT model uses only one node (Node 0) to represent a junction or outfall. Thus, the flow collected from each node was routed directly to the outfall node neglecting separate description of delays in the pipe network, which are accounted for in SWMM (Huber *et al.*, 1975). A simple scheme was used to compare flow results from NBS-OPT with flows in the pipe network junctions from SWMM. Runoff flow from each node was added cumulatively to runoff flow in the subsequent node. Thus, for example, runoff flows from Node 1 and Node 2 were summed when compared with the flow from Junction 2 in SWMM. Runoff flows from Nodes 1-3 were then summed when compared with the flow from Junctions 3 and so on. Including more junction inputs could help NBS-OPT eliminate this flow adjustment step taken in this study to compare flows with SWMM.

NBS-OPT provides an optimal combination of NBSs for only one storm event at a time. However, the performance of NBSs vary depending on the intensity and duration of a storm event (Joyce *et al.*, 2017; Ruangpan *et al.*, 2020). This variation in performance highlights the importance of assessing multiple storm events when selecting water management interventions, especially in order to mitigate high probability storm events while also proving resilience for low-probability storm events (Webber et al., 2018). NBS-OPT would be even more useful for engineers and urban planners if it were able to optimize NBS combinations for multiple storm events at once. Therefore, it is recommended to further research the possibility of NBS-OPT to suggest one optimal NBS combination that can meet peak flow limits for multiple storm events.

The limit area restricting the maximum spatial extent of NBS is an important parameter that must be included to avoid unrealistic NBS areas in the optimal combination of NBSs. Although NBS-OPT yielded accurate flow results using the defined limit areas, not all suggested areas for NBS made practical sense. For example, all lawn areas were included as limit areas for swales and rain gardens. This limit area resulted in NBS-OPT suggesting that in Options 2 and 3, the lawn area in Node 5 be maximized as a rain garden. However, in practical design terms, an entire lawn area would rarely be transformed into a rain garden. Instead, only a fraction of it would be. Thus, a methodology or guidelines should be developed for determining the limit areas for each measure in each node.

Currently, NBS-OPT lacks the ability to route flow to NBSs. Therefore, NBSs designed in NBS-OPT can only collect rainfall that falls directly on the NBS. Although this accurately represents green roofs, it is not common practice for the other NBSs. Typically, water from other areas of the catchment is routed to rain gardens, swales and permeable pavements. For NBS-OPT to meet its objective of acting as a prescreen, this feature is not necessary. However, it would add another feature to increase its ability to model more realistic NBS designs.

As shown in Tables 21-24, the majority of NBSs are designed downstream in Nodes 5-7. This could mean that in terms of mitigating peak flows, downstream locations of a catchment could be the preferred location. However, because NBSs provide water quality benefits as well, water quality should also be an influential factor when determining the location of an NBS (Brasil *et al.*, 2021). If a certain part of a catchment is prone to poor water quality, that could be a great place to install an NBS to avoid the spread of the pollutants to other subcatchments. A better analysis of optimal locations for NBSs can be made when considering the up- and downstream characteristics (EU Commission 2020). A more holistic estimate of how NBSs preform in mitigating urban stormwater challenges could be determined by adding pollutant-load-reduction parameters to NBS-OPT. The parametrization methodology developed in this study can also be used to test the accuracy of pollutant load reduction in NBS-OPT, since SWMM can model pollutant loads and can therefore be used as a benchmark.

7 Conclusion

This study assessed the performance and functionality of NBS-OPT in suggesting combinations of NBSs for a catchment to manage stormwater volume most cost-efficiently. In order to assess NBS-OPT, a methodology was developed to calibrate, parameterize, and validate the tool against SWMM. The proposed methodology to parameterize NBS-OPT proved to be effective in determining parameter values for the four NBSs used in this study. Its effectiveness was demonstrated by NBS-OPT suggesting four different combinations of NBSs that yielded NSEs higher than 0.94 and peak flow differences less than 50.7 l/s when comparing discharge flows against SWMM.

The proposed methodology included the following steps: NBS parameters were determined using a trial-and-error approach that consisted of assigning retention and detention parameter values in NBS-OPT, comparing the flow results between NBS-OPT and SWMM of the same design scenarios, and lastly, adjusting the parameters in NBS-OPT accordingly to match the flow results of SWMM. The retention and detention values that produced the smallest peak flow differences and highest NSEs were selected as the final parameters. Limit areas were then assigned for each NBS in all nodes. Once NBS-OPT provided the optimal combination of NBSs, the optimal combination was replicated in SWMM in order to validate the ability of NBS-OPT to model water flows. Flow results from both models were compared using peak flow differences and NSEs.

Although NBS-OPT is in its preliminary stages, it shows potential in being used as a prescreen for determining optimal combinations of NBSs when paired with SWMM. Once NBS-OPT is parameterized, it is easy to use and quick to run. However, if the use of the tool is to act as a quick prescreen for optimal combinations of NBSs, the proposed parameterization method can be considered laborious. It requires setting up a SWMM model of the study area and running many simulations both in SWMM and NBS-OPT. If enough research is conducted, perhaps standardized retention and detention values can be determined for standardized NBSs depending on the location of the catchment. This would eliminate the parameterization step for the user and allow them to use NBS-OPT immediately for its intended purpose, which is to prescreen potential optimal combinations of NBSs.

Specific suggestions for improving NBS-OPT have been identified and are presented in Chapter 6. If the proposed suggestions are implemented, they would improve the performance of NBS-OPT as a prescreening tool for identifying NBS combinations to cost-efficiently manage stormwater volume and quality.

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