# A Nonlinear Reservoir Model to Simulate Blue-Green Stormwater Systems

## – An Application to Augustenborg Catchment in Malmö, Sweden

LUND UNIVERSITY

Emmanuel Chijioke Ekwu

Water and Environmental Engineering
Department of Chemical Engineering
Master Thesis 2021

Printed by Media-Tryck, Lund 2021 NORDIC SWAN ECOLABEL 3041 0903

LUND UNIVERSITY
Faculty of Engineering
Department of Chemical Engineering
Water and Environmental Engineering

# A Nonlinear Reservoir Model to Simulate Blue-Green Stormwater Systems

## An Application to Augustenborg Catchment in Malmö, Sweden

by


## Emmanuel Chijioke Ekwu


Master Thesis number: 2021-05


Water and Environmental Engineering
Department of Chemical Engineering
Lund University


June 2021

Supervisor: **Ph.D. Salar Haghigatafshar**
Co-supervisor: **Professor Magnus Larson**
Examiner: **Senior Lecturer Karin Jönsson**

The picture on the front page: A wet pond in Augustenborg. Photo by Emmanuel Chijioke Ekwu


| Postal address | Visiting address | Telephone |
|---|---|---|
| Box 124 | Kemicentrum | +46 46-222 82 85 |
| SE-221 00 Lund, Sweden | Naturvetarvägen 14 | +46 46-222 00 00 |
| **Web address** | 223 62 Lund, Sweden | |
| http://www.lth.se/chemeng/ | | |

# Acknowledgment

Firstly, I want to say a big thank you to Salar Haghighatafshar and Magnus Larson for giving me the opportunity to work on this thesis study and for supervising me during my thesis study. They have been highly supportive and helpful throughout. They assisted me during the site inspection and helped me a lot with the model development. I would also like to thank Karin Jönsson and the Water and Environmental Engineering section, Chemical Engineering Department at LTH, for letting me work on my Master's thesis with them.

Secondly, I would like to thank Assad Mohammad Tahir for his support and encouragement throughout my Master's degree program and the readability check he did on my thesis report. I also want to thank Erik Müller for his contribution during the area schematization in this study. To Mike Jönsson, thank you for your support and kindness from my first day in Sweden till this very moment. To all my friends in Nigeria and Sweden that have supported me one way or another throughout my Master's degree program, I want to say thank you.

I want to show my deepest gratitude and thanks to my wonderful family in Nigeria. I want to thank my dear parents Mr. and Mrs. Ekwu, and my lovely sister Onyinye Precious Ekwu for their tremendous support (financially and spiritually) during my Master's degree program.

Finally, I want to acknowledge and commend myself for a successful Master's degree accomplishment and for being able to adapt quickly to a whole new different environment and culture. I want to say thank you to me for not giving up on the pursuit of my Master's degree and for choosing an interest thesis study.

# Summary

The increasingly rapid urbanization has led to vast impervious surface areas in the urban environment. This situation of impervious surfaces has increased the surface temperature and interrupted the natural water circle, which has negatively impacted the urban environment. Human activities' continuous greenhouse gas emission has contributed to global climate change, which has caused some atmospheric abnormalities like increased precipitation, leading to environmental hazards like pluvial flooding and combined sewer overflow (CSO). Several different stormwater control measures have been practiced and implemented to control the excess rainfall-runoff and help avoid overloading the drainage systems. Research has proven blue-green infrastructures to be efficient for managing stormwater runoff. However, the techniques for modeling blue-green stormwater systems have also been identified to be very complex and complicated due to the large number of parameters involved. This characteristic has made it challenging to develop simple simulation models to relate the area's physical characteristics where the systems are being implemented.

Hence, this study aimed to develop a simple model with few parameters (corresponding to physical characteristics of the systems) for fast and reliable simulation of blue-green systems. The methodology used in this study was to couple "nonlinear reservoir model" to "hydraulic representation". This quantification and calibration were done in a simple nonlinear reservoir simulation model developed in this study using Excel software. Augustenborg is an area located in Malmö, Sweden, consisting of two main sustainable drainage systems (SuDS) implemented in the North and South of the neighborhood. This thesis focused on the blue-green stormwater systems in Northern SuDS in Auguestenborg.

The Northern SuDS consists of seven stormwater control measures (SCMs), including swales, wet ponds, and a rectangular channel connected to a sewer pipe network. Each system has a connecting catchment, and the governing equations used in developing the nonlinear reservoir model are the continuity equation and flow equations. The flow equations used in this study are Manning's equation (for swales and rectangular channel) and a discharge equation through an orifice (for wet ponds).

The nonlinear routing parameters were calibrated for each catchment connecting to a system after relating the physical characteristics of the catchments using Manning's equation. After developing the model and obtaining the calibrated parameter values, the model was tested and validated with measured data. The discharge flows from the model were compared to the measured discharge flows.

The model showed a good response time to the discharge flow when validated with measured data. This study developed an easy-to-use physical-based model and was able to quantify nonlinear reservoir routing parameters based on the physical characteristics of the blue-green stormwater systems implemented in the case study.

**Keywords:** Blue-green stormwater control, Nonlinear reservoir routing model, Stormwater, Modelling, Calibration.

# Popular scientific summary

## Heading

Developing an easy-to-use stormwater simulation model for green structures.

## Introduction

Using green stormwater control structures is an excellent method in controlling accumulated water from rainfall to avoid flooding. However, this method is not easy to monitor because of too many properties involved. This study aims to develop an easier way to monitor this method of stormwater control.

## Main text

The green stormwater control structures consist of several physical properties. These physical properties have made it complicated to develop a straightforward method that can be used to monitor how the stormwater is being transported through the green structures and into the drainage pipe network. This stormwater management method always has different types of interconnected structures, and each system has different physical properties. For example, an area could have a green structural method of stormwater control, consisting of four different types of systems. Each structure might have three properties that make up the structure; in other words, there are many different physical properties to handle when monitoring stormwater discharge from a green structural stormwater control method, excluding the catchment properties where the systems are implemented.

In the case of the study area for this study, Augustenborg, "an area located in the city of Malmö, Sweden," the green structural method focused on in this study area consists of seven systems. Each system has its physical properties and has a catchment area connecting to it. The catchment areas have different parameter values defining them. This study aims to develop a possible way of handling these parameters and develop a simple model to be used in simulating the stormwater discharge through the green systems and into the drainage pipe system in the study area.

The different physical properties of the seven systems in this study were included in developing the model and the physical properties of the catchment areas. This study was able to relate the properties of these catchments using a flow equation in order to determine the storage coefficient value for each catchment. Several modifications (fine-tuning) were carried out on the model to obtain an appropriate value to produce good model results. The results from the model were compared with actual results from the study area to determine the accuracy of the results the model produced.

The simple developed model was able to relate the physical properties of green structural stormwater control systems in the study area using the flow equation and other relevant equations. The model produced similar results to the actual flows recorded in the study area. However, few minor assumptions were made in this study. The model can be applied to other areas with similar green structures by changing the parameter values.

# List of Abbreviations

| | |
|---|---|
| **BGI** | Blue-Green Infrastructure |
| **BMP** | Best Management Practices |
| **CA** | Catchment Area |
| **CSO** | Combined System Overflow |
| **LID** | Low Impact Development |
| **OFAT** | One Factor At a Time |
| **ROC** | Rectangular Open Channel |
| **SCMs** | Stormwater Control Measures |
| **SuDS** | Sustainable Drainage Systems |
| **SW** | Swales |
| **SWMM** | Stormwater Management Models |
| **WP** | Wet ponds |

# Table of Contents

# 1 Introduction

The global urban transformation has created large areas with impervious surfaces that have led to series of environmental hazards and adverse interruptions on the ecosystem's natural life circle. The continuous human industrial activities have led to a change in the climate globally, thereby increasing the intensity, frequency, and type of precipitation (Thakali et al., 2016). According to analysis and research, the probability of increased extreme rainfall events in this present century is above 85% (Thakali et al., 2016) and a probability increase of the average atmospheric temperature by over 1.5 $^{o}$C (Jacometti, 2019). Some urban areas face high water levels of pluvial flooding under extreme rainfall events experienced in those areas when the stormwater runoff is not adequately controlled. The issue of stormwater encroachment into residential buildings and other infrastructures has been a great concern to the municipalities. Therefore, there is a need to implement proper Stormwater Control Measures (SCMs) in the affected areas and improve the drainage system capacity.

Several SCMs have been implemented in most urban areas globally to help control and manage stormwater runoff. Some of these control measures have been referred to by many publications as "sustainable development systems (SuDS), best management practices (BMPs), blue-green infrastructure (BGI), and low impact development (LID)". These measures have proven to efficiently control stormwater and mitigate flooding (Kaykhosravi et al., 2018). This report will be on the BGI method of stormwater management.

## 1.1 Background

The BGI is a type of implementation referred to as a sustainable stormwater management process (Liao et al., 2017). Blue-green stormwater systems are efficient measures to handle stormwater and urban runoff and have proven to be effective in urban flood mitigation (Haghighatafshar et al., 2018). It can employ physical processes like evaporation and sedimentation, also biological processes like BOD-removal and storage to manage stormwater quality and quantity (Liao et al., 2017).

The definition of blue-green systems by Ghofrani et al. (2017) is a connected network of different green components, existing natural landscapes, and open spaces that maintain ecosystem services simultaneously while controlling stormwater runoff. Some listed examples can be a constructed retention or detention ponds, wetlands, green roofs, swales and bioswales, and built vegetative canals of different types (Shukri, 2010).

The blue-green stormwater system has been an efficient application to control stormwater flooding and downstream water pollution in urban areas (Berndtsson et al., 2019). However, the complexity of these structures has made it difficult to evaluate the hydraulic performance of such systems that is essential to consider assessing future proposed projects (Shukri, 2010).

Several analytical simulations and optimal models have been developed for reservoir systems analysis in the past decades (Ko et al., 1992; Kim et al., 2018). According to Beven (2012), hydrology models were mainly created due to the impediment to hydrological measurement methodologies. Different developed models can either establish a numerical derivation or provide a futuristic prediction (Beven, 2012). Beven (2012) and Adeloye et al. (2015) explained rainfall-runoff simulation models based on the three different categories of hydrological application, which are the perceptual "black box" application, conceptual application, and physical-based application.

These model development methods have different implementation approaches. The analytical or perceptual application is based on assumptions using the environmental conditions without referring to the physical characteristics controlling the runoff (Adeloye et al., 2015). The conceptual models are dependent on storage elements in the catchment with a straightforward mass balance equation (Beven, 2012). The physical-based model represents the physical characteristics of the hydrological environment using mathematical equations or numerical code (Beven, 2012; Sitterson et al., 2018; Adeloye et al., 2015). Unlike other runoff model categories, the physical-based model is more complex and complicated due to a large number of parameters, variables, and calibration it encompasses (Sitterson et al., 2018; Kolmar et al., 2019).

A nonlinear reservoir is a suitable approach to runoff modeling, where the primary parameters can be related to more realistic characteristics of a blue-green stormwater system in a process-based manner (Larson, n.d). Unlike the linear reservoir model, the systems respond to a straightforward model with one routing parameter (Wittenberg, 1994). The nonlinear reservoir model is not as specific as a linear reservoir as it is primarily based on a realistic hydrological environment with more than one routing parameter (Wittenberg, 1994).

The physical-based application is ideal for developing a nonlinear reservoir routing model to simulate runoff through a blue-green stormwater system, regardless of its complexity and complicated parameter values. They have been few successfully developed physical-based model. However, according to Adeloye et al. (2015), there are very few implementations of the physical-based model in hydrological practices, and they are mostly narrowed down to smaller areas.

The following physical-based model has been implemented in a blue-green stormwater system successfully. The MIKE URBAN applied in the Augustenborg catchment for hydraulic modeling (Shukri, 2010), the US EPA stormwater management model (SWMM) used for flood mitigation modeling of blue-green stormwater system in Augustenborg (Haghighatafshar, 2019), the MOUSE and MIKE SHE model used in hydrological modeling of green urban drainage system (Broekhuizen, 2021). These models can be regarded as advanced physical-based models.

In this study, an easy-to-use stormwater simulation model will be developed for fast and genuine simulation. The calibration of nonlinear reservoir routing parameters will be done in the model. The simulation of stormwater runoff will be performed in SCMs using a catchment in Augustenborg, Malmö, Sweden, as an application study area. The study area consists of two main sustainable drainage systems (SuDS) constructed in the Southern and Northern regions of the neighborhood. A general description of the Southern SuDS was given in this report while the project focused on the Northern SuDS in Augustenborg. Having a clear insight into the case study will establish meaningful background information for the model development and validation.

## 1.2 Objectives

This study primarily aims to evaluate the possibility to quantify and calibrate nonlinear reservoir routing parameters based on the physical characteristics of the blue-green stormwater systems implemented in the chosen study area, "Eco-city Augustenborg," an area suited in the city of Malmö, Sweden. The second aim is to develop an easy-to-use model based on the nonlinear reservoir concept that can simulate the effects of a combination of (SCMs) to reduce and delay stormwater runoff.

## 1.3 Study outline

To successfully achieve the aims of this thesis, the following outlined procedures for this study will be accomplished:

### 1.3.1 Site Study

A comprehensive literature study was undertaken, including a visit to the study area, centering on providing a thorough site description of the area. The blue-green stormwater systems implemented in Augustenborg were also studied to establish the contributing physical characteristics of developing a nonlinear reservoir physical-based model.

### 1.3.2 Data collection

The available data for this study were collected and presented in the report, and data sources were cited. The data used for this study includes six different rainfall events, rainfall duration, measured discharge flow data from the downstream of the SuDS, the catchment areas on the Northern SuDS in Augustenborg, and the physical discharge characteristics of the blue-green stormwater systems implemented in the area with the surface area of the systems. Also, relevant photos and satellite images from the case study are presented in this report.

### 1.3.3 Model development

This section will present the simple nonlinear reservoir routing model equations deployed in developing the simulation model applied in the blue-green stormwater systems in Northern SuDS of Augustenborg using Excel software. The parameter values were determined based on the physical characteristics of the SCMs and the catchment areas.

### 1.3.4 Calibration, validation, and Sensitivity analysis

After developing the model with the given data, the complete model was tested, and the results were validated with data. Also, a sensitivity analysis was performed on the model to evaluate the sensitivity of the model

### 1.3.5 Limitation

Previous research study has been carried out in the study area, primarily focusing on the hydraulic modeling of the blue-green stormwater systems using a more complex physical-based model. In other words, there are limited or no publications/research found having a similar study approach. However, there have been several publications on different stormwater management approaches, hydraulic conductivity, open channel systems, etc. The limited research or publication on this topic has limited the references used in this study.

# 2 Methodology

This section of the report describes the step-by-step method adopted to develop the simulation model for the blue-green stormwater systems in Northern SuDS of the Eco-city Augustenborg. The methodology is based on some hydraulic approximations, which have led to some developed equations using a nonlinear reservoir model and outlet characteristics. A proper description of the Eco-city Augustenborg and schematization of the Northern SuDS was presented.

The model was created to determine the possibility of describing the hydraulic interaction between the SCMs in a relatively simple way. The Northern SuDS in Augustenborg consists of seven blue-green stormwater systems connected systematically to a sewer pipe network. Each SCM has a catchment area connecting directly to it. The blue-green stormwater systems implemented in the Northern SuDS of the Eco-City Augustenborg include two swales, four wet ponds, and one rectangular channel.

The two main governing equations used in calculating and developing the simulation model are the continuity equation and the flow equations. These two equations were used to simulate the runoff from the catchment areas into their connected stormwater control systems and monitor the hydraulic performance in the blue-green stormwater systems.

## 2.1 Catchment areas

Each SCM has a catchment area connecting directly to it (see Table **1** for the different measured catchment areas for each SCM implemented in the study area). The arrangement in Table **1** is placed according to how the SCMs are implemented in the study area.

*Table 1. SCMs in the study area in Augustenborg with the catchment area connected to each SCM (Haghighatafshar et al., 2018).*

| SCMs | Catchment area ($m^2$) |
|---|---|
| **Swale I** | 2780 |
| **Wet pond I** | 3920 |
| **Wet pond II** | 1120 |
| **Wet pond III** | 1620 |
| **Swale II** | 3400 |
| **Rectangular channel** | 2100 |
| **Wet pond IV** | 3500 |

In simulating the runoff from the catchment area to the systems, the continuity equation was used as governing equation which can be expressed as,

$$\frac{dS}{dt} = Q_{in} - Q_r \qquad (Eq\ 1)$$

Where $dS$ is the change in catchment storage over time, $Q_{in}$ is the input flow of rainfall on the catchment area ($m^3/min$), and $Q_r$ is the total runoff flow from the catchment area ($m^3/min$). The input flow of the rainfall into the catchment areas is given as,

$$Q_{in} = I\varphi A \quad (Eq\ 2)$$

Where $I$ is the rainfall intensity $(m/min)$, $\varphi$ is the runoff coefficient of the catchment area which is used as 1 (unitless) (since the catchment area is mostly asphalt surface), and $A$ represents the area of the catchment $(m^2)$. The systems respond to the runoff from the catchment area as a nonlinear reservoir and can be represented as,

$$Q_r = cS^b \quad (Eq\ 3)$$

Where $c$ is the storage coefficient $(min^{-1})$ and $b$ is the nonlinear coefficient (unitless), $S$ is the storage volume $(m^3)$. In a situation where $b = 1$, the systems will respond to the runoff from the catchment as a linear reservoir (Larson, n.d). The continuity equation can further be expressed as,

$$\frac{dS}{dt} = I\varphi A - cS^b \quad (Eq\ 4)$$

The Manning's equation was used as the flow equation to calculate the value of the nonlinear reservior routing parameter, $c$. The Manning's equation was used in relating the physical characteristics of the catchment, and can be expressed as,

$$c = \frac{1}{n}\frac{\sqrt{S_o}}{A_c^{2/3}\,L} \quad , \; b = \frac{5}{3} \quad (Eq\ 5)$$

Where $c\ (min^{-1}), and\ b\ (unitless)$ are the nonlinear routing parameters, $n$ is the Manning's roughness coefficient (unitless) $A_c$ the catchment area $(m^2)$, $L$ the flow length in $(m)$, and $S_o$the slope of the catchment.

## 2.2 Stormwater Control Measures (SCMs)

### 2.2.1 Swales

In recent decades, swales have been increasingly implanted in an urban city to improve water quality (Gavrić et al., 2019). Swales are also implemented in urban areas to detain and delay the stormwater runoff, which at the same time contribute to infiltration and some biological processes. During the model development, the infiltration characteristics of the swale systems in the Northern SuDS of the study area were not considered.

The continuity equation and Manning's equation were used as the governing equation for simulating the hydraulic behavior in the swale. The continuity equation can be expressed as,

$$\frac{dS}{dt} = (Q_r + Q_{o,p}) - Q_{o,s} \quad (Eq\ 6)$$

Where, $Q_{o,p}$ $(m^3/mins)$ is the outflow from the previous SCM connecting directly to the next SCM (if applicable), $Q_{o,s}$ $(m^3/min)$ is the outflow leaving the swales. The swales' discharges were calculated using Manning's equation (Hager, 1983). Manning's equation for simulating the flow discharge is,

$$Q_{o,s} = \frac{1}{n}BhR^{\frac{2}{3}}\sqrt{S_o} \quad (Eq\ 7)$$

Where $Bh$ is the cross-sectional area of the swale $(m^2)$, $R$ is the hydraulic radius $(m)$, $S_o$ is the swale's slope, and $n$ is the Manning's roughness coefficient (unitless). To estimate the change in water level $h$, where the volume of SCM is $(B * L * h)$, Equation **6** will further be developed to

$$\frac{dh}{dt} = \frac{(Q_r + Q_{o,p})}{BL} - \left(\frac{{}^{1}/_{n}\ h^{\frac{5}{3}} \sqrt{S_o}}{L}\right) \qquad (Eq\ 8)$$

Where, $dh$ is the change in water level over time, $B$ and $L$ are the width and length of the SCM $(m)$, respectively. The width, length, and slope of the SCM were estimated using SCALGO live.

### 2.2.2 Wet pond

Wet ponds are mainly implemented to provide additional stormwater runoff storage during rainfall events (Stauffer, 2012; Pereira Souza et al., 2019; and Ekwu, n.d.) and discharge the runoff through an outlet (mostly orifice outlet). The discharge outlet is either designed to release the entire detained stormwater within a period or, if implemented few centimeters above the bottom of the pond, discharges a certain amount of water when the stored water reaches the height of the outlet and retaining the rest volume of water in the pond. For the wet pond system in the study area, the orifice outlet has been designed few centimeters above the bottom of the pond.

During simulation of change in hydraulic level for the wet pond, the runoff from the catchment areas connecting directly to the wet ponds was added together with the outflow from the previous SCM connecting to the wet pond. This situation is only applied when a system is connecting directly to another system.

The continuity equation for simulating the change in the hydraulic volume and the discharge from the wet ponds can be expressed as,

$$\frac{dS}{dt} = \left(Q_r + Q_{o,p}\right) - Q_{o,w} \qquad (Eq\ 9)$$

Where $Q_r$ $(m^3/mins)$ is the runoff from the catchment area connected to the system, and $Q_{o,w}$ $(m^3/mins)$ is the outflow from the wet pond through an orifice. The flow equation for the orifice (Wu, Burton and Schoenau, 2002) can be expressed as,

$$Q_{o,w} = C_D A_o \sqrt{2g(h - h_o)} \qquad (Eq\ 10)$$

Where $C_D$ is discharge coefficient of the orifice 0.98 (unitless) (Larson, 2015), $A_o$ is area of the orifice $(m^2)$, $g$ is the acceleration due to gravity 35316 $(m/min^2)$, $h$ is the water level $(m)$, and $h_o$ is the height of orifice from the bottom of the pond $(m)$.

For calculating the hydraulic level in the pond, the continuity equation in Equation **9** can further be developed to,

$$\frac{dh}{dt} = \frac{\left(Q_r + Q_{o,p}\right)}{A_{SCM}} - \frac{C_D A_O \sqrt{2g\ (h - h_o)}}{A_{SCM}} \qquad (Eq\ 11)$$

### 2.2.3 Rectangular channel

An open channel can be an existing natural system or an artificial structure with a freeway surface at atmospheric pressure (Chanson, 2004). In this case of study, the channel to be simulated basing on its physical characteristic is a rectangular channel.

In the rectangular channel, the continuity equation and Manning's equation were used in simulating the hydraulic movement through the channel (just as expressed with the swale). The run-off from the catchment area connecting to the rectangular channel is added to the outflow from the previous SCM connecting directly to the channel. The continuity equation is expressed as,

$$\frac{dS}{dt} = (Q_r + Q_{o,p}) - Q_{o,c} \qquad (Eq\ 12)$$

Where $Q_{o,p}$ $(m^3/mins)$ is the sum of incoming outflows from upstream SCMs directly connected to the rectangular channel and $Q_{o,c}$ $(m^3/mins)$ is the outflow from the rectangular channel. The outflow from the rectangular channel and the change in water level was simulated using the same equations for the swales as seen in Equations **7** and **8**.

## 2.3 Numerical solution to governing equations

The governing equations for simulating the hydraulic runoff from the catchment area and the outflow from SCMs based on its physical characteristics must be solved using an explicit numerical method (Haghighatafshar, 2019) by stepping through time due to the complexity of the input condition in the systems. In solving numerically, the current condition in the storage in a new time step is a total function obtained from the previous time step. To calculate for the storage $(S)$ starting with a condition at $S_o = 0$, when $t = 0$, the numerical method is given as,

$$\frac{dS}{dt} = \frac{S_{i+1} - S_i}{\Delta t} \qquad (Eq\ 13)$$

Putting together Equation **4** in Equation **13** and discretizing the ordinary differential equation in Equation **13**, the numerical solution for the change in storage value at every time step will be,

$$S_{i+1} = S_i + \Delta t\left(Q_{in,i} - cS_i^b\right) \qquad (Eq\ 14)$$

Where $dS$ is change in storage volume over time, $S_i$ is the initial storage condition $(m^3)$, $S_{i+1}$ is the current storage condition at every time step $(m^3)$, and $\Delta t$ is the time step $(1\ min)$

The flow equation controlling the outflow through the SCMs (for a discharge through Manning's equation or orifice equation) and estimating the hydraulic level in the system at every time step with a starting condition of $h = 0$, when $t = 0$, can be shown in as,

For the swale and rectangular channel, discretizing Equation **8**,

$$h_{i+1} = h_i + \Delta t\left(\frac{Q_{tot,i}}{BL} - \left(\frac{1/n\ h^{\frac{5}{3}}\sqrt{S_o}}{L}\right)\right) \qquad (Eq\ 15)$$

For the wet ponds, discretizing Equation **11**,

$$h_{i+1} = h_i + \frac{\Delta t}{A_{SCM}}\left(Q_{tot,i} - C_D A_o \sqrt{2g(h - h_o}\right) \qquad (Eq\ 16)$$

Where, $h_i$ is the initial water level $(m)$, $h_{i+1}$ is the current water level at every time step $(m)$, and $Q_{tot,i}$ is the total runoff into the system $(m^3/mins)$ expressed as $(Q_r + Q_{o,p})$ in the continuity Equation **6**, **9** and **12**.

# 3 Area of study: Eco-City Augustenborg

Urbanization today has created limited available land space, thereby making it challenging to implement blue-green stormwater systems inside the cities. However, blue-green stormwater systems are being practiced outside of the town for new developing cities, where the land is mostly accessible (Haghighatafshar, 2019). Regardless of the population and limited space issue of implementing blue-green stormwater systems inside the city, the Eco-city Augustenborg is a typical example of a successful implementation of a full-scale blue-green stormwater system (Haghighatafshar, 2019).

Augustenborg is an urbanized area located in Malmö, southern Sweden. The neighborhood consists of mostly apartment buildings built in the early '50s having an area coverage of about 32 hectares (Shukri, 2010) (see Figure **1** for the map location of Augustenborg). The Eco-city of Augustenborg comprise of other services like the solar energy industrial area with about $420\ m^2$ solar panel, new school buildings, and new buildings for senior residents (Malmö Stad, 2017). According to (Malmö Stad, 2017), the eco-city Augustenborg has been one of Sweden's most extensive sustainable urban development.


*Figure 1. the outline indicated in orange color, is the map of Augustenborg and where it is situated in the city of Malmö, Sweden.*

Augustenborg experienced a series of basement flood events during the '80s that led to the withdrawal of the inhabitants, thereby causing a decline of the neighborhood's social and economic status (Climate-ADAPT., 2017).

During the '90s, the city municipality developed a sustainable solution to bring Augustenborg to its original state, hence introducing an Eco-city of Augustenborg, funded by the Swedish government, MKB, a housing company in Malmö, and the Malmö municipality (Haghighatafshar, 2019). Most of the combined sewer systems in Augustenborg were replaced with open stormwater control systems during the area's renovation to detain/retain the stormwater runoff from the area before discharging them into the main drainage system (Shukri, 2010).

The SCMs implemented in the Eco-city Augustenborg can be categorized as infiltration systems, storage/detention, and slow stormwater transport systems like the vegetated canals (Shukri, 2010).

## 3.1 Description of blue-green stormwater systems in Augustenborg

The Eco-city Augustenborg consists of two main blue-green stormwater systems, located at the Northern and Southern area of Augustenborg with an additional local separate pipe system, all having a total drainage coverage area of about $19.5\ ha$ (Haghighatafshar, 2019).

### 3.1.1 Southern SuDS in Augustenborg

The southern blue-green stormwater system in Augustenborg is vaster and has a different design structure of SCMs implemented in that part of Augustenborg. The drainage area for the Sothern SuDS is about $9.6\ ha$, and the blue-green systems were designed to suit the physical characteristics of the area (Haghighatafshar, 2019). The pictures in Figure **2** show some of the constructed systems in the Southern SuDS of the Eco-city Augustenborg.

(A)

(B)

(C)

*Figure 2. the types of SCM implemented in the Southern SuDS of Augustenborg.* ***(A)*** *A wet pond downstream of the Southern SuDS.* ***(B)*** *Temporary detention storage.* ***(C)*** *A creek located in a park of the Southern SuDS*

### 3.1.2 Northern SuDS in Augustenborg

A more detailed description study was done on the Northern SuDS in Augustenborg. Unlike the Southern SuDS, the blue-green stormwater systems in the Northern area of the Eco-city have straightforward planning and implementation. The Northern SuDS has an estimated drainage area of 6.3 $ha$ (Haghighatafshar, 2019). The implementation of the blue-green stormwater in the Northern SuDS of Augustenborg comprises swales, wet ponds, and open channels (see Figure **3** for some pictures of the SCMs). All systems are interconnected to a sewer network pipe system from upstream to downstream.

(A) (B)

(C) (D)

*Figure 3. types of SCM implemented in the Northern SuDS of Augustenborg.* ***(A)*** *A building with a green roof,* ***(B)*** *A wet pond located downstream of the Northern SuDS,* ***(C)*** *A rectangular channel,* ***(D)*** *A wet pond situated upstream of the Northern SuDS.*

## 3.2 Rainfall measurement

The rainfall intensity data used in this study were obtained with rainfall measuring equipment, a Casella CEL tipping bucket rain gauge having a resolution of 0.2 mm (Haghighatafshar, 2019). Table **2** shows the rainfall intensity data used in the model simulation.

*Table 2. Rainfall intensity data used for this study showing the rainfall $ID_D$ as the rainfall ID from the data source, rainfall $ID_S$ as the rainfall ID in this study, the rainfall duration, and the rainfall peak; source of data (Haghighatafshar, Yamanee-Nolin, and Larson, 2019).*

| Rainfall $ID_D$ | Rainfall $ID_S$ | Rainfall duration $(h)$ | Rainfall peak $(h)$ |
|---|---|---|---|
| **E** | **I** | 4.84 | 0.23 |
| **C** | **II** | 2.25 | 0.03 |
| **G** | **III** | 15.58 | 11.77 |
| **I** | **IV** | 4.17 | 1.42 |
| **D** | **V** | 9.34 | 8.75 |
| **J** | **VI** | 9.17 | 6.58 |

## 3.3 Schematization

In schematizing the SCMs, the entire blue-green stormwater systems in the Northern SuDS of Augustenborg were considered. Each SCM is characterized by the catchment area connected to it, the surface area of the system, and the hydraulic depth (Haghighatafshar, Yamanee-Nolin, and Larson, 2019). Table **3** shows the characteristic of the SCMs in the Northern SuDS in Augustenborg used in developing the runoff simulation model. Figure **4** shows the runoff flow direction from the upstream of the Northern SuDS to the downstream of the Northern SuDS in Augustenborg. The schematized components consist of the catchment area, two swales, four wet ponds, and a rectangular channel system. (see Figure **5** for the schematic drawing for the Northern SuDS).


*Figure 4. The location points of the SCM in the Northern SuDS of Auguestentborg. The different types of SCMs are indicated in different shapes and labeled as; (Swale), (Wet pond), and (Rectangular channel) in the legend. Source: Author's creation with data from Lantmäteriet.*

*Tabel 3. According to the flow pattern in Figure 4, the table shows the characteristics of the SCMs in the Northern SuDS of Augustenborg (Values by Haghighatafshar, et al., 2018)*

| **SCMs** | **Storage dept (mm)** | **Surface Area (m2)** | **Catchment area ($m^2$)** |
|---|---|---|---|
| **Swale I** | 5 | 740 | 2780 |
| **Wet pond I** | 250 | 90 | 3920 |
| **Wet pond II** | 250 | 200 | 1120 |
| **Wet pond III** | 250 | 90 | 1620 |
| **Swale II** | 5 | 240 | 3400 |
| **Rectangular channel** | 5 | 80 | 2100 |
| **Wet pond IV** | 350 | 160 | 3500 |

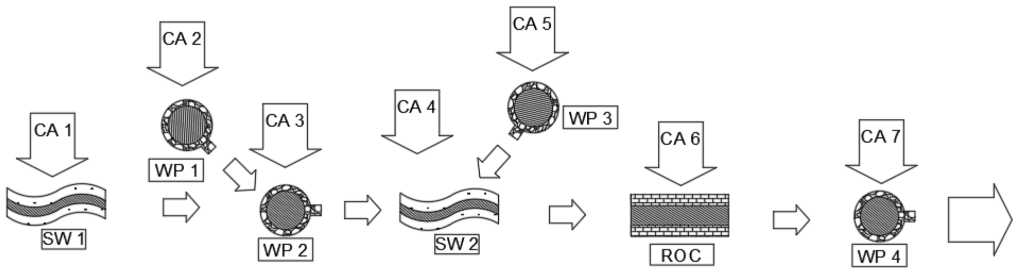


*Figure 5. A view of the modeled SCM in the Northern SuDS and how they are connected serially to each other. CA; the runoff flow direction from the catchment area to the SCM, SW; the swales, WP; the wet ponds and ROC; the rectangular channel. The order of the arrow indicates the flow direction from the upstream to downstream.*

Figure **6** shows a conceptual view of the SCMs and the runoff flow direction from one system to another (Haghighatafshar, Yamanee-Nolin, and Larson, 2019). According to Figure **6**, $q_{r,1}, q_{r,2}, q_{r,3} \cdots q_{r,n}$ are the stormwater runoff from the catchment area into the SCM. The out-flow from the previous SCM is added up with the catchment runoff of the next SCM.

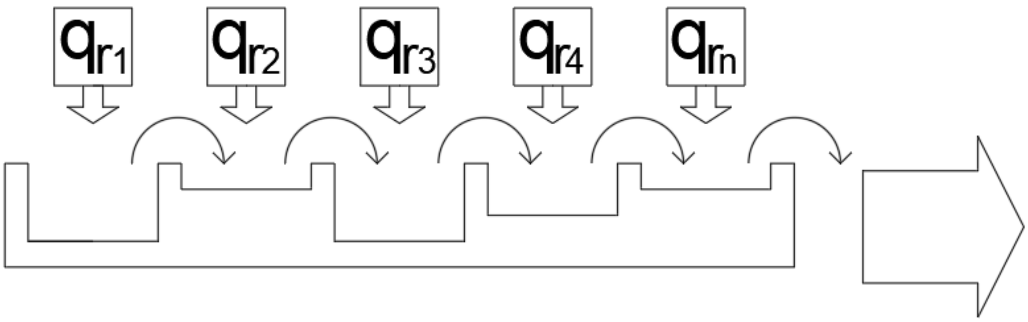


*Figure 6. A conceptual view of the SCM in the study area: inspired by (Haghighatafshar, Yamanee-Nolin, and Larson, 2019).*

# 4 Model calibration

In this section, the calibration for some parameter values of the Northern SuDS was carried out. The available measured data used for the model development were the rainfall intensity data with the rain duration, the catchment areas, and surface areas for the SCMs. The rest of the parameter values used for the simulation were either calibrated or gotten from previous research articles. During the model simulation process, the storage coefficients $(c)$ $(mins^{-1})$ for the catchment areas, the orifice diameter and height of orifice from the bottom of the wet ponds were calibrated to evaluate the hydraulic response on the model using two rainfall events. After the calibration, the final discharged flow from the model was compared with an actual measured/observed flow discharge for accuracy purposes.

## 4.1 Governing Parameters

Before proceeding to the calibration for the parameter values, some assumptions were made due to limitations on available data, inefficient maintenance of the SCMs that hindered taking proper measurements and neglecting some secondary physical characteristics of the SCMs. The following assumptions made in this study are listed below.

### 4.1.1 Catchment storage coefficient

The storage coefficient for the catchment area is an essential parameter for developing the model. There was no set value for the storage coefficient during data collection. The storage coefficient was calculated using Manning's equation (see Equation **5**). However, calibrating for the coefficient turned out to be very complicated because each system has a connecting catchment (making it seven storage coefficients to be calibrated). In order to make the calibration for the storage coefficient less complicated and easy to handle, a constant value was assumed and introduced to the Manning's equation used in calculating the storage coefficient in order to connect the seven different coefficients (see Equation **17**). The calibration for the storage coefficients was based on the constant value.

### 4.1.2 Orifice diameter

A discharge outlet is designed on four wet ponds implemented in the Northern SuDS of Augustenborg. Due to lack of maintenance of the systems (clogging of the orifice hole), an actual measurement for the orifice size was not obtained.

### 4.1.3 Height of orifice

The orifice outlet is designed few centimeters above the bottom of the wet ponds. The exact heights of the orifices in the wet ponds were not obtained due to limited knowledge of the actual geometric shape of the ponds. Therefore, the orifice heights were assumed based on the dept of the pond (Referring to Table **3**). The assumed measurements were included in the calibrated parameters.

### 4.1.4 Infiltration

The infiltration process for the swales in the Northern SuDS was not considered when developing the model for this study. The infiltration was neglected when developing the model due to the trivial effects it might have on the model (Haghighatafshar, Yamanee-Nolin, and Larson, 2019). However, infiltration can be added to the model. The process of including infiltration in the mode will be discussed later in the report.

## 4.2 Initially estimated values

The first approach adopted in finding an initial value for the storage coefficients in the simulation is by using Manning's equation approach to connect the physical properties of the catchment as seen in Equation **5**. An assumed constant value was introduced to the Manning's equation used for calculating the storage coefficient and can be expressed as,

$$c = k_c \left( \frac{1}{n} \frac{\sqrt{S_o}}{A_c^{2/3}\, L} \right) \qquad (Eq\ 17)$$

Where $c$ is the catchment storage coefficient $(min^{-1})$, $k_c$ is the assumed constant value (unitless) with an initial start value of 1, $n$ is the Manning's roughness coefficient taken as an average of 0.015 (unitless) since the catchment area consist of more asphalt material, $A_c$ the catchment area $(m^2)$, $L$ the flow length in $(m)$, the flow length and the slope for the catchment area $S_o$ were estimated using (SCALGO live tool), and Table **4** shows the values applied to Manning's equation for calculating the storage coefficient $c$.

*Table 4. catchment area characteristics values used in calculating the storage coefficients*

| **SCMs** | **Manning's coefficient** | **Catchment area $(m^2)$** | **Flow length $(m)$** | **Slope $(m/m)$** |
|---|---|---|---|---|
| **Swale 1** | 0.015 | 2780 | 45 | 0.0070 |
| **Wet pond 1** | 0.015 | 3920 | 100 | 0.0017 |
| **Wet pond 2** | 0.015 | 1120 | 30 | 0.0017 |
| **Wet pond 3** | 0.015 | 1620 | 45 | 0.0015 |
| **Swale 2** | 0.015 | 3400 | 50 | 0.0123 |
| **Rectangular channel** | 0.015 | 2100 | 45 | 0.0118 |
| **Wet pond 4** | 0.015 | 3500 | 50 | 0.0060 |

The other estimated set values were the diameter of the orifice and the height of the orifice from the bottom of the wet pond. Most SCMs serving as a storage system have an outlet designed to either discharge the stormwater runoff entirely or discharge a certain amount of runoff when it reaches the outlet level. For the wet ponds implemented in the Northern SuDS of Augustenborg, each pond has an orifice outlet. Referring to Equation **10**, the orifice equation is expressed as,

$$Q_{o,w} = C_D A_O \sqrt{2gh} \qquad (Eq\ 18)$$

The wet ponds implemented in the study area have a round-shaped orifice design. The discharge coefficient $(C_D)$ of 0.98 (unitless) was used when calculating the outflow through the orifice (Larson, 2015). The initial diameter of 0.2 m was set to calculate the orifice area, and an estimated height of the orifice from the bottom of the wet pond was set at 0.2 m.

## 4.3 Calibration process

The rainfall events used for the calibration are (Rainfall ID **I** and **III**). These rainfall ID were chosen randomly between the short rainfall durations and the long rainfall durations (Referring to Table **2**). The calibration process started after developing the model and simulating the stormwater runoff through the entire connected SCMs in the Northern SuDS of Augustenborg with the initial parameter values. The final discharge flow recorded from the model was used to compare with the actual measured flow to quantify the governing parameters of the developed model. The total sum of squared error method was used as a measurable indicator for the calibration. The aims during the calibration were to minimize the total sum of squared error as low as possible and obtain reasonable governing parameter values.

The total sum of the squared error value is the squared difference between the model discharge flow and the measured discharge. The purpose of this calibration is to obtain appropriate values for the governing parameters, storage coefficient c, orifice diameter, and height of orifice from the bottom of the wet pond. This calibration was done using a particular function in the Excel software known as Solver. The expression for finding the total sum of the squared error value is shown as,

$$Total\ Error = \sum (Q_{T,m} - Q_{T,o})^2 \qquad (Eq\ 19)$$

Where $Q_{T,m}$ and $Q_{T,o}$ is the flow values at time step (t) for each time series from the modeled flow and the measured flow, respectively. After calculating the squared error value between the modeled flow and the measured flow, the calibration for the selected characteristics proceeded to obtain suitable parameter values that will produce a more accurate model result. For the storage coefficient $(c)$ values, the constant $k_c$ set value was calibrated, and different storage coefficients for the catchment areas were obtained based on the physical characteristic of each catchment. Table **5** shows the starting estimated values used for the calibration.

*Table 5. Calibrated parameters and their starting value used in developing the model.*

| **SCM** | **Storage coefficient (c) $(min^{-1})$** | **Orifice diameter $(m)$** | **Height of orifice $(m)$** |
|---|---|---|---|
| **Swale 1** | 0.0110 | - | - |
| **Wet pond 1** | 0.0056 | 0.2 | 0.2 |
| **Wet pond 2** | 0.0167 | 0.2 | 0.2 |
| **Wet pond 3** | 0.0167 | 0.2 | 0.2 |
| **Swale 2** | 0.0056 | - | - |
| **Rectangular channel** | 0.0220 | - | - |
| **Wet pond 4** | 0.0500 | 0.2 | 0.2 |

# 5 Model Validation and Sensitivity analysis

In order to certify the authenticity of the model, the developed model needs to be validated with measured rainfall events from the study area. The model should adequately estimate the discharge flow rate when tested (Haghighatafshar, Yamanee-Nolin, and Larson, 2019). The developed model was validated in this study with four measured data using the same parameter values obtained during the calibration process. The sensitivity of the model was also analyzed by altering some parameter values.

## 5.1 Validation process

The rainfall events **II, IV, V**, and **VI** were used for the model validation to monitor the model's response on the discharge flow and certify the model authenticity if the discharge flow is being compared with the measured flow. The validation was done using the same calibrated parameter values.

## 5.2 Sensitivity analysis

A sensitivity analysis was performed to test how the model responded to the different parameters used in developing the model. An OFAT (one factor at a time) method was used for the sensitivity analysis, which means altering one parameter value to see the effect on the result while keeping other parameter values at their initial state (Nolina et al., 2018). In this study, analyses were primarily performed on few contributing physical characteristics of the SuDS by altering their values by ±25% and ±50% one at a time. During the analysis, the parameters used were the catchment areas, the storage coefficients, and the surface areas of the SCM. The sensitivity was done with the two rainfall intensity data used for the calibration (Rainfall ID **I** and **III**).

# 6 Results

The results outcome from this study is presented in this section. The results presented in this section are obtained from the calibration, validation, and sensitivity analysis.

## 6.1 Calibration results

Table **6** shows the calibrated parameters in the SCMs, and the values obtained from the calibration for the calibration results. Two different rainfall events were used for the calibration when developing the model, aiming to get accurate values for the calibrated parameters to have a minimal sum of squared error between the modeled flow and the measured/observed flow. Figure **7** compares the final modeled discharge flow from the SCMs with the measured flow. The hydrograph data was obtained from the two rainfall events (Rainfall ID **I** and **III**) used for the calibration in this study.

*Table 6. Calibrated parameter values used in simulation the model and obtaining the modeled discharged flow volume.*

| SCM | Storage coefficient (c) $(\boldsymbol{min^{-1}})$ | Orifice diameter $(\boldsymbol{m})$ | Height of orifice $(\boldsymbol{m})$ |
|---|---|---|---|
| **Swale 1** | 0.075 | - | - |
| **Wet pond 1** | 0.013 | 0.12 | 0.16 |
| **Wet pond 2** | 0.102 | 0.12 | 0.20 |
| **Wet pond 3** | 0.158 | 0.12 | 0.16 |
| **Swale 2** | 0.078 | - | - |
| **Rectangular channel** | 0.118 | - | - |
| **Wet pond 4** | 0.051 | 0.15 | 0.35 |

*Table 7. the rainfall events used in this study for calibration and validation, with the volume of measured and modeled discharge flow for each event. Data source (Haghighatafshar, Yamanee-Nolin, and Larson, 2019).*

| Classification | Rainfall ID | Rainfall duration $(\boldsymbol{h})$ | Measured $\boldsymbol{V_{out}(m^3)}$ | Modeled $\boldsymbol{V_{out}(m^3)}$ |
|---|---|---|---|---|
| **Calibration** | I | 4.84 | 96.4 | 124.0 |
| ***Validation*** | II | 2.18 | 107.7 | 106.8 |
| **Calibration** | III | 15.5 | 117.2 | 147.2 |
| ***Validation*** | IV | 4.5 | 258.1 | 282.8 |
| ***Validation*** | V | 9.7 | 86.2 | 122.0 |
| ***Validation*** | VI | 13.04 | 288.50 | 378.9 |

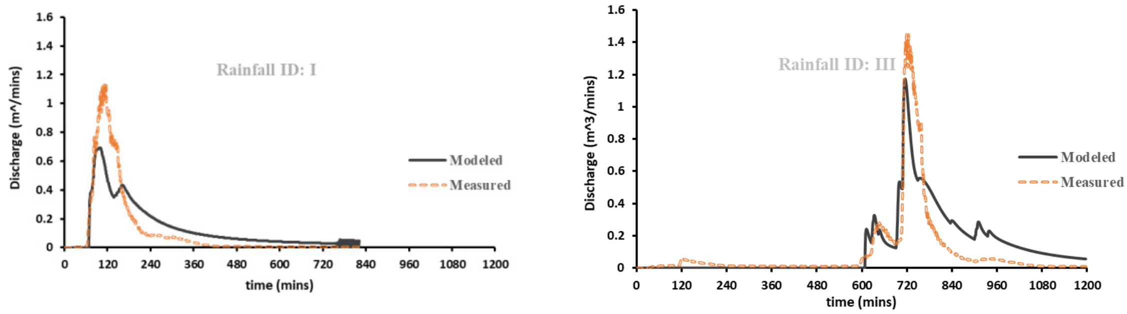


*Figure 7. The hydrographs of the modeled versus the measured flow from the two rainfall ID I and III used for the calibration.*

## 6.2 Validation results

The modeled and measured hydrographs for the validation rainfall events are shown in Figure **8.** During the validation, no parameter value used in the model was changed when simulating the model with rainfall events **II, IV**, **V**, and **VI**.

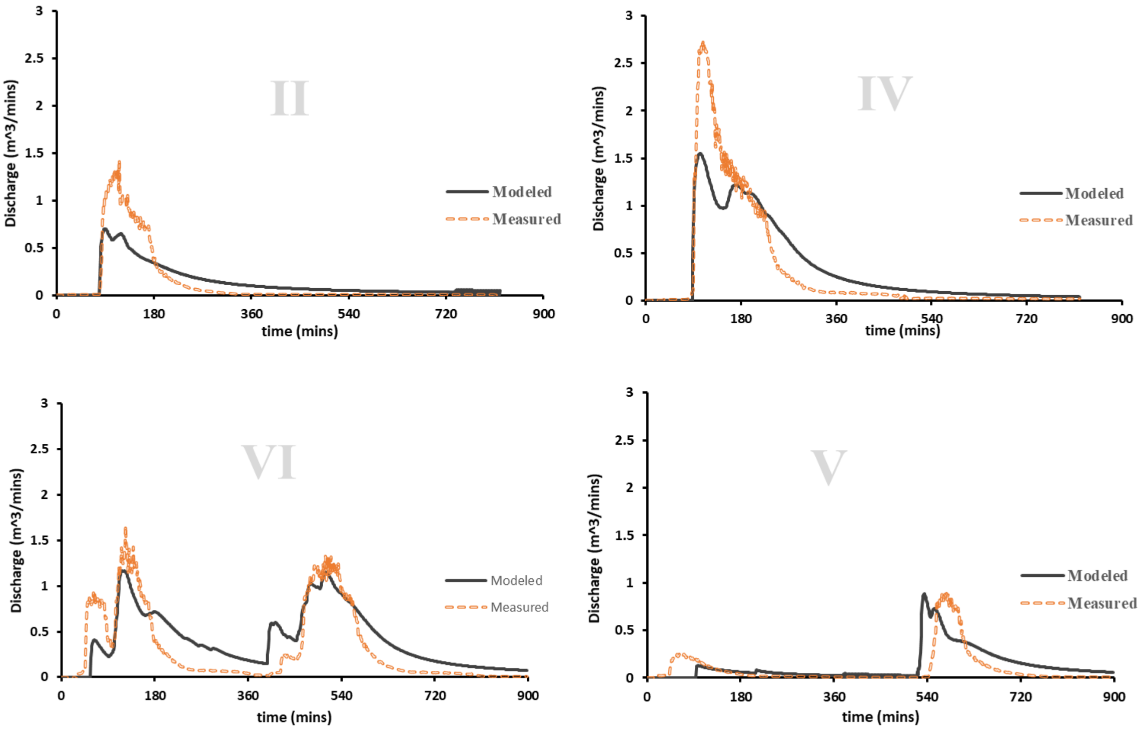


*Figure 8. The hydrographs presentation from the validation with rainfall events II, IV, V, and VI.*

## 6.3 Sensitivity results

The results of the sensitivity analysis show the different effects on the model when altering the parameters. The parameter alterations were carried out using the OFAT method (i.e., altering parameters one at a time). In order to access the effects on the model by each altered parameter, the sum of the squared error method was used to access the sensitivity of the model from both rainfall events **I** and **III**. The vales of the storage coefficient c for the catchments, the catchment areas, and the SCM surface areas were analyzed on two different occasions. However, it is essential to note that, during the sensitivity analysis, there was no further calibration done. The analysis was performed with the values obtained from the calibration. The results from the analysis are presented as bar charts in Figures **9** and **10**, showing the effects on the model. The charts are sum of squared error at ±0% and ±25% in Figure **9**, and sum of squared error at ±0% and ±50% in Figure **10**.

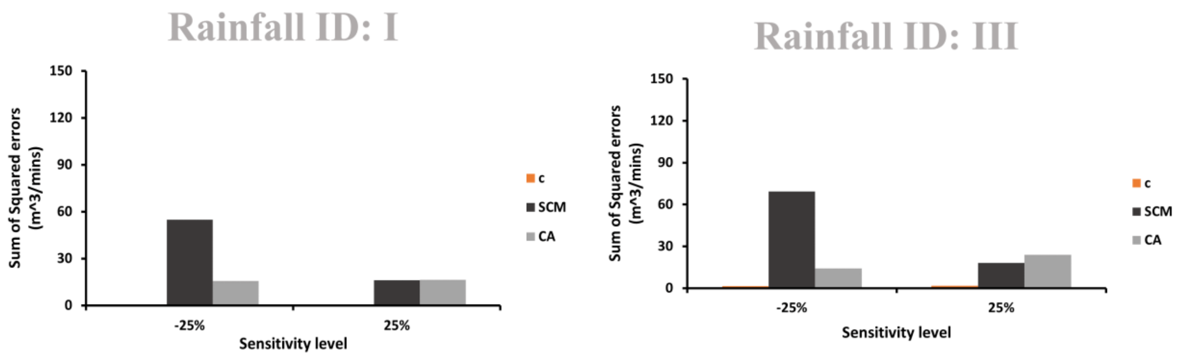


*Figure 9. The sensitivity analysis results, based on the sum of the squared error value at ±0 and ±25. After the OFAT method of altering the storage coefficient c, SCM area, and the catchment area.*

.

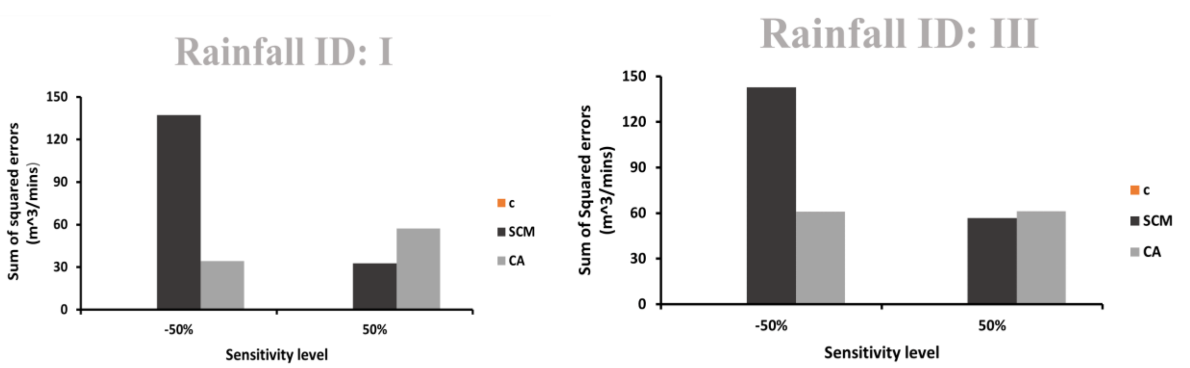


*Figure 10. The sensitivity analysis results, based on the sum of the squared error value at ±0 and ±50. After the OFAT method of altering the storage coefficient c, SCM area, and the catchment area.*

# 7 Discussion

This chapter will outline and discuss the outcome of this study, starting with developing the nonlinear reservoir model to the results obtained from the model.

## 7.1 Data quality evaluation

The data quality is of great importance in this study in order to develop a physically based model on the characteristics of the study area and the blue-green stormwater systems. The rainfall events data used for this study were measured from actual rain events in Augustenborg. They were interpolated to a one-minute duration interval to suit the time step adopted in the numerical solution and for easy simulation in the model.

For the geographical data for the study area, the slope of each catchment area was obtained using SCALGO Live tool and was quantified as part of the physical characteristics of the study area. For the geometric data of the SCMs, the actual geometrical shapes for the wet ponds in the study area were not precisely known. However, their estimated surface area and storage depth data were available and used for the model development.

## 7.2 Catchment area

The runoff material type in the catchment area of Augustenborg consists mainly of asphalt, galvanized roofing sheets in the buildings, and grass. Therefore, an average runoff coefficient of the catchment was estimated based on land cover.

## 7.3 Infiltration

Among the SCMs in the Northern SuDS, two were swales. Based on the physical characteristics of the swales, infiltration can influence the runoff process. The infiltration can be considered as another means of outflow from the swale. However, the infiltration process was neglected when developing the model due to the trivial effect it might have on the model. The infiltration process can be included in the model by introducing it in the continuity equation governing the systems as flow losses. Referring to Equation **6**, the continuity equation with flow losses included can be expressed as,

$$\frac{dS}{dt} = (Q_r + Q_{o,p}) - Q_{o,s} - Q_l \qquad (Eq\ 20)$$

Where $Q_l\ (m^3/min)$ is the flow loss from the SCMs through infiltration. This loss can be interpreted to the physical characteristics of the swale, connecting it to the water dept and introducing a coefficient parameter that can be determined through calibration (Larson, n.d). The flow equations for the loss can be used as,

$$Q_l = kh = k\frac{V}{A_b} \qquad (Eq\ 21)$$

Where $k$ is the infiltration rate coefficient that can be calibrated in the model, $V\ (m^3)$ is the storage volume and $A_b(m^2)$ is the bottom area of the storage.

## 7.4 Calibration

The calibration process was the primary task and focus of this study. The rainfall events data used for the calibration were interpolated to 1 min rainfall intensity interval from its original rainfall intensity obtained from a tipping bucket with 0.2mm resolution. The interpolation was done due to the 1 min time step used in the numerical solution on the model. The purpose of calibrating with two different rain events data is to obtain more suitable values for the calibrated parameters. The calibrated parameter values were different for each rainfall event used during the calibration. An average value of the different obtained calibrated results was taken, and the simulation was done again to get the final modeled discharge result.

The hydrograph for each SCM was plotted, showing the runoff from the catchments into the system and the outflow from each system (see Figure **I-1** and **I-2** in Appendix **I**). According to the hydrographs of the swales and rectangular channel presented in Appendix **I**, the same volume of water that flows into the systems flows out from the system. This discharge is expected considering that Manning's equation was applied as the flow equation in these systems. In order words, no water is retained in the swale and rectangular channel after the discharge period. In the case of wet ponds, the situation is not the same. There were a few minutes of delay for the wet ponds before the outflow. The delay can be related to the level of discharge outlet in the ponds.

According to the hydrographs presented in Figure **7**, the modeled discharge flow volume from both rainfall events **I** and **III** are slightly higher than the measured discharge volume (see Table **7**). This result might be expected, relating it to the exclusion of the infiltration process from the model. Again, the peak of modeled discharge flow is lower than that of the measured discharge. The reason for a low discharge peak from the model can be related to the height of the discharge outlet in wet ponds since the measurements were based on the storage depth of the ponds (see Table **3**).

## 7.5 Validation

For the validation, the model was able to show a good, responsive outcome, as seen in the hydrographs presented in Figure **8**. Although it is not expected to obtain the same discharge volume or discharge peak between the model and measured flow, the model was able to forecast the discharge flow rate for every event used to validate the model (see Figure **8**). According to the hydrograph in Figures **8-II** and **8-IV**, the model forecasted almost the same outflow time as the measured flow, which shows a good response time on the model. Although, for the hydrographs in Figures **8-V** and **8-VI**, the model missed the first peak flow of the measured discharge. This might be that the SCMs had some volume of water retained in them from a previous rainfall event which might have led to a more increased peak flow because the model assumes an empty system (Haghighatafshar, Yamanee-Nolin, and Larson, 2019).

## 7.6 Sensitivity analysis

The sensitivity analysis in this study was performed on the following parameter values: the catchment area, the storage coefficient, and the surface area for the SCMs. The sum of squared error method used in assessing the analysis showed the different effects on the model based on OFAT alteration of the parameter values (see Table **II-1** and **II-2** in Appendix **II**). According to Figures **9** and **10**, effects on the model after altering storage coefficient c for both ±25% and ±50% level was between 0.1 $m^3/min$ and 2 $m^3/min$ (sum of squared error) (see Table **II-1** and **II-2** in Appendix **II**). In order words, the effect from the storage coefficient on the model is trivial and could be neglected. However, altering the catchment areas and SCMs surface areas for both ±25% and ±50% had more significant effect on the model. These effects, as seen in Figures **9** and **10** showed a considerable amount sum of squared error discharge volume, mainly for the -25% and -50% level of the SCM surface areas (see Table **II-1** and **II-2** in Appendix **II**). Although, the effect was expected due to the dependence of the amount of discharge volume on these parameters.

# 8 Conclusions

After an in-depth study of the blue-green stormwater system implemented in the Eco-city Augustenborg, this thesis was able to quantify a nonlinear reservoir model based on the physical characteristics of the study area. The nonlinear model developed in this study responded well during the simulation of the stormwater runoff in the SCMs. In relation to the objective of this study, the possibility of simulating several interconnected blue-green stormwater systems using a physical-based nonlinear routing model was demonstrated in this project by developing an easy-to-use model.

This study created an easy-to-use model that evaluated the general hydraulic performance in SCMs implemented in the studied SuDS from the most upstream to the downstream of the interconnected systems (See Appendix **III** on how to use the model). The methodology adopted for this study related the hydraulic characteristics with the hydrologic reservoir model to minimize the calibrated parameters.

The nonlinear reservoir model was developed so that each SCM could be simulated and modified differently if needed. This model proved to be effective and showed a good responsive outcome during the validation. In other words, the model can be used to test other blue-green stormwater systems in a different case study by changing the parameter values.

The Excel software used in developing the nonlinear reservoir model showed its suitability in modeling stormwater runoff in blue-green stormwater systems, as seen in this study and the resulting outcome. The SCMs implemented in the study area were connected serially in the Excel software. The software could simulate the rainfall-runoff from the catchment into the connecting systems from upstream to the discharge point downstream. The model achieved a reasonable discharge volume compared with the measured discharge volume despite the complexity of relating the physical characteristic of the system in the model. The issue experienced with the software was the enormous amount of data sets it produced during the model's development, making data handling challenging. However, the SCM components were modeled on different Excel worksheets to elevate the user-friendliness of the model structure.

# 9 Recommendation

For future research purposes and approaches to evaluating the hydraulic behavior of the blue-green stormwater system using a nonlinear reservoir routing model, more adequate measurements of the systems should be provided, mainly on the wet ponds implemented in the Northern SuDS of Augustenborg. To optimize the model's performance, the discharge loss from the swale through infiltration should be included, and the actual measurements for the diameter and height of the orifice should be taken.

Since the case study consists of two SuDS (the Northern and Southern SuDS), and this study focused on the Northern SuDS, it will be recommended to study the Southern SuDS of Augustenborg using a similar approach.

More sensitivity analysis is recommended to be carried out on the model since the only sensitivity analysis done on the model is a case for ±25% and ±50%. Also, since this study used a sum of squared error method for the sensitivity analysis, it is recommended to use a different method to test the sensitivity of the model.

Lastly, the rainfall events used for the study are not extreme. In other words, it will be interesting to test the model with an extreme rainfall event (High intensity rainfall) to evaluate the model performance.

# 10 References


Adeloye, A., Bhuyan, M., Jena, J. and Bhunya, P., 2015. A Simple Nonlinear Rainfall Runoff Model for Small Catchments. *AGU International Journal of Science & Technology*, [online] 1. Available at: <http://www.aguijst.com> [Accessed 28 April 2021].

Berndtsson, R., Becker, P., Persson, A., Aspegren, H., Haghighatafshar, S., Jönsson, K., Larsson, R., Mobini, S., Mottaghi, M., Nilsson, J., Nordström, J., Pilesjö, P., Scholz, M., Sternudd, C., Sörensen, J. and Tussupova, K., 2019. Drivers of changing urban flood risk: A framework for action. *Journal of Environmental Management*, *240*, pp.47-56.

Beven, K., 2012. Rainfall-Runoff modelling: the primer. 2nd ed. Chichester, West Sussex: *John Wiley & Sons LT*D, pp.1-22.

Broekhuizen, I., 2021. Hydrological modelling of green urban drainage systems. *Urban Water Engineering,* [online] (1402-1544). Available at: <http://www.ltu.se> [Accessed 29 April 2021].

Chanson, H., 2004. Environmental Hydraulics for Open Channel Flows. Burlington: Elsevier, pp. 3-10

Climate-ADAPT ., 2017. Urban stormwater management in Augustenborg, Malmö. Green and Blue Space Adaptation for Urban Areas and Eco Towns (GRaBS), Malmö city and Scandinavian Green Roof Institute.

Ekwu, E., n.d. Stormwater control measures and their modeling with emphasis on Stormwater ponds. pp.2-6. (unpublished).

Gavrić, S., Leonhardt, G., Marsalek, J. and Viklander, M., 2019. Processes improving urban stormwater quality in grass swales and filter strips: A review of research findings. *Science of The Total Environment*, *669*, pp.431-447.

Ghofrani, Z., Sposito, V. and Faggian, R., 2017. A Comprehensive Review of Blue-Green Infrastructure Concepts. *International Journal of Environment and Sustainability*, *6*(1).

Hager, W., 1983. Open channel hydraulics of flows with increasing discharge. *Journal of Hydraulic Research, 21*(3), pp.177-193.

Haghighatafshar, S., Nordlöf, B., Roldin, M., Gustafsson, L., la Cour Jansen, J. and Jönsson, K., 2018. Efficiency of blue-green stormwater retrofits for flood mitigation – Conclusions drawn from a case study in Malmö, Sweden. *Journal of Environmental Management*, *207*, pp.60-69.

Haghighatafshar, S., la Cour Jansen, J., Aspegren, H. and Jönsson, K., 2018. Conceptualization and Schematization of Mesoscale Sustainable Drainage Systems: A Full-Scale Study. *Water, 10*(8), p.1041.

Haghighatafshar, S., Yamanee-Nolin, M. and Larson, M., 2019. A physically based model for mesoscale SuDS – an alternative to large-scale urban drainage simulations. *Journal of Environmental Management, 240*, pp.527-536.

Haghighatafshar, S., 2019. Blue-green stormwater systems for citywide flood mitigation. *Water and Environmental Engineering*, pp.1-18.

Jacometti, V., 2019. Climate Change Litigation: Global Trends and Critical Issues in the Light of the Urgenda 2018 Decision and the IPCC Special Report "global Warming of 1.5 °C". *Global Jurist*, *20*(1).

Kaykhosravi, S., Khan, U. and Jadidi, A., 2018. A Comprehensive Review of Low Impact Development Models for Research, Conceptual, Preliminary, and Detailed Design Applications. *Water, 10*(11), p.1541.

Kim, H., Fontane, D., Julien, P. and Lee, J., 2018. Multiobjective Analysis of the Sedimentation behind Sangju Weir, South Korea. *Journal of Water Resources Planning and Management*, *144*(2), p.05017019.

Kolmar, J., Thum, O. and Baganz, F., 2019. Improving Product Specificity of Whole-Cell Alkane Oxidation in Nonconventional Media: A Multivariate Analysis Approach. *Biotechnology Journal*, *14*(10), p.1800581.

Ko, S., Fontane, D. and Labadie, J., 1992. Multiobjective Optimization of Reservoir Systems Operation. *Water resources bulletin, 28*(1), pp.111-112.

Larson, M., 2015. Hydromechanics: Summary of Definitions, Equations, Tables, and Graphs. *Water resources engineering faculty of engineering, Lund University*, p.28.

Larson, M., 2020. Nonlinear reservoir model for SCMs in SuDs. *Water Resources Engineering. LTH, Lund University, Lund, Sweden* (unpublished paper).

Malmö stad, 2017. Ekostaden Augustenborg. [online] Available at: <https://malmo.se/Nice-to-know-about-Malmo/Sustainable-Malmo-/Sustainable-Urban-Development/Augustenborg-Eco-City.html> [Accessed 9 March 2021].

Nolina, M., Anderssona, N., Nilssona, B., Hansenb, M. and Pajalicb, O., 2018. Analysis of an Oscillating Two-Stage Evaporator System through Modelling and Simulation: An Industrial Case Study. Chemical Engineering Transactions, [online] *69*(2283-9216), pp.481-486. Available at: <http://www.aidic.it/cet> [Accessed 24 April 2021].

Pereira Souza, F., Leite Costa, M. and Koide, S., 2019. Hydrological Modelling and Evaluation of Detention Ponds to Improve Urban Drainage System and Water Quality. *Water, 11*(8)

Sitterson, J., Knightes, C., Parmar, R., Wolfe, K., Avant, B. and Muche, M., 2018. An Overview of Rainfall-Runoff Model Types. *International Congress on Environmental Modelling and Software.*

Shukri, A., 2010. Hydraulic Modeling of Open Stormwater System in Augustenborg, Sweden. *Master thesis at Water and Environmental Engineering, Department of Chemical Engineering, Lund University, Sweden*.

Stahre, P. (2008) Blue-Green Fingerprints in the City of Malmö, Sweden. Malmö, VA-SYD.

Stauffer, B., 2012. Stormwater management. Sustainable Sanitation and Water Management, [online] p.14. Available at: <http://creativecommons.org/licenses/by/3.0> [Accessed 9 November 2020].

Thakali, R., Kalra, A. and Ahmad, S., 2016. Understanding the Effects of Climate Change on Urban Stormwater Infrastructures in the Las Vegas Valley. Hydrology, *3*(4), p.34.

Wittenberg, H., 1994. Nonlinear analysis of flow recession curves H. *Water Resources Arid Environmental Management.*

Wu, D., Burton, R. and Schoenau, G., 2002. An Empirical Discharge Coefficient Model for Orifice Flow. *International Journal of Fluid Power, 3*(3), pp.13-19.

# Appendix I

## I.1 SCMs

Appendix **I** presented the hydrographs of the different SCMs that were implemented in the Northern SuDS of Augustenborg. Figures **I-1** and **I-2** show the hydrographs from rainfall event **I** and rainfall event **III**, respectively. These rain events were used for the calibration in this study. The hydrographs are presented as implemented in the study area.

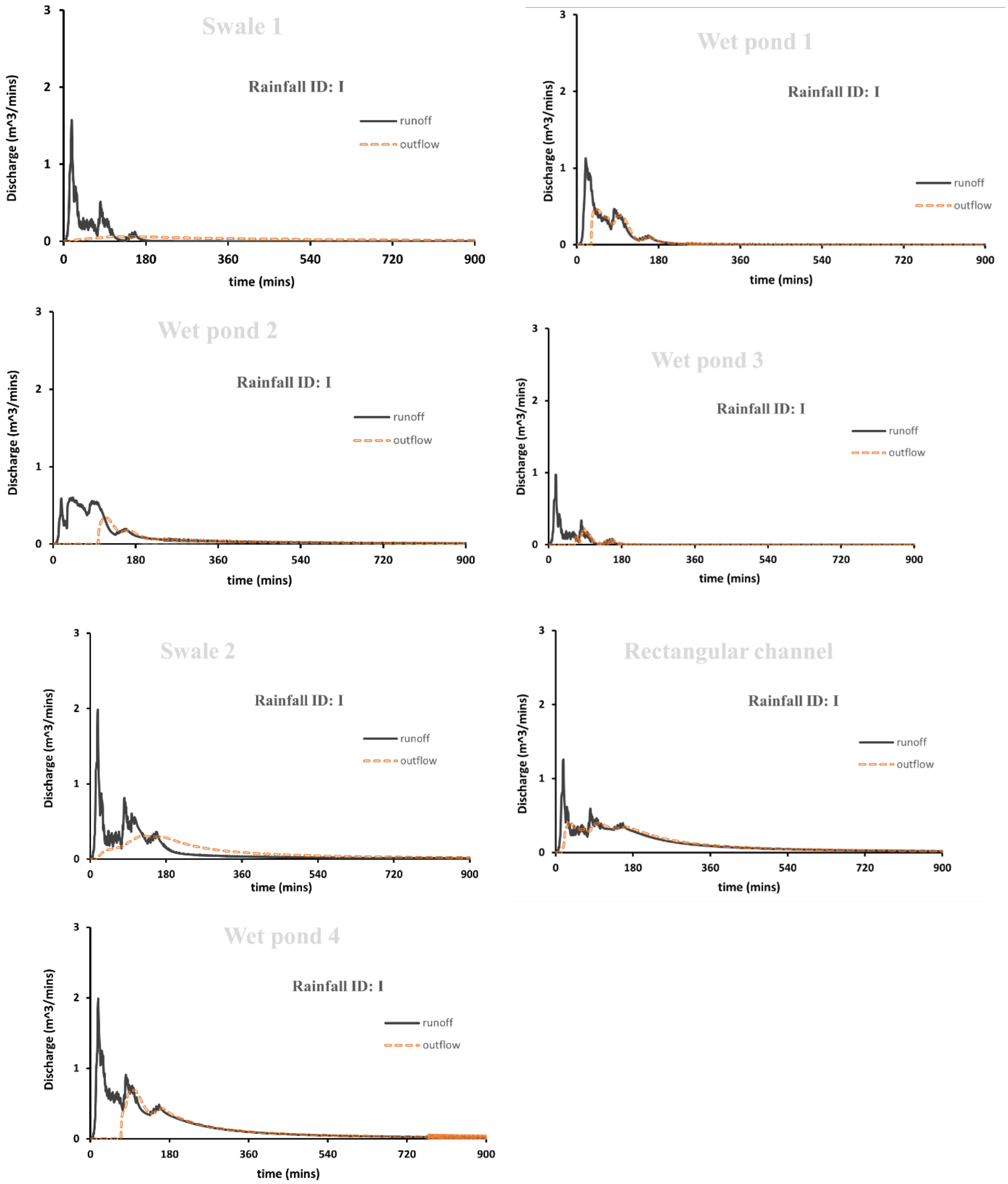


*Figure I-1; The hydrograph for each SCM with rainfall event ID I.*

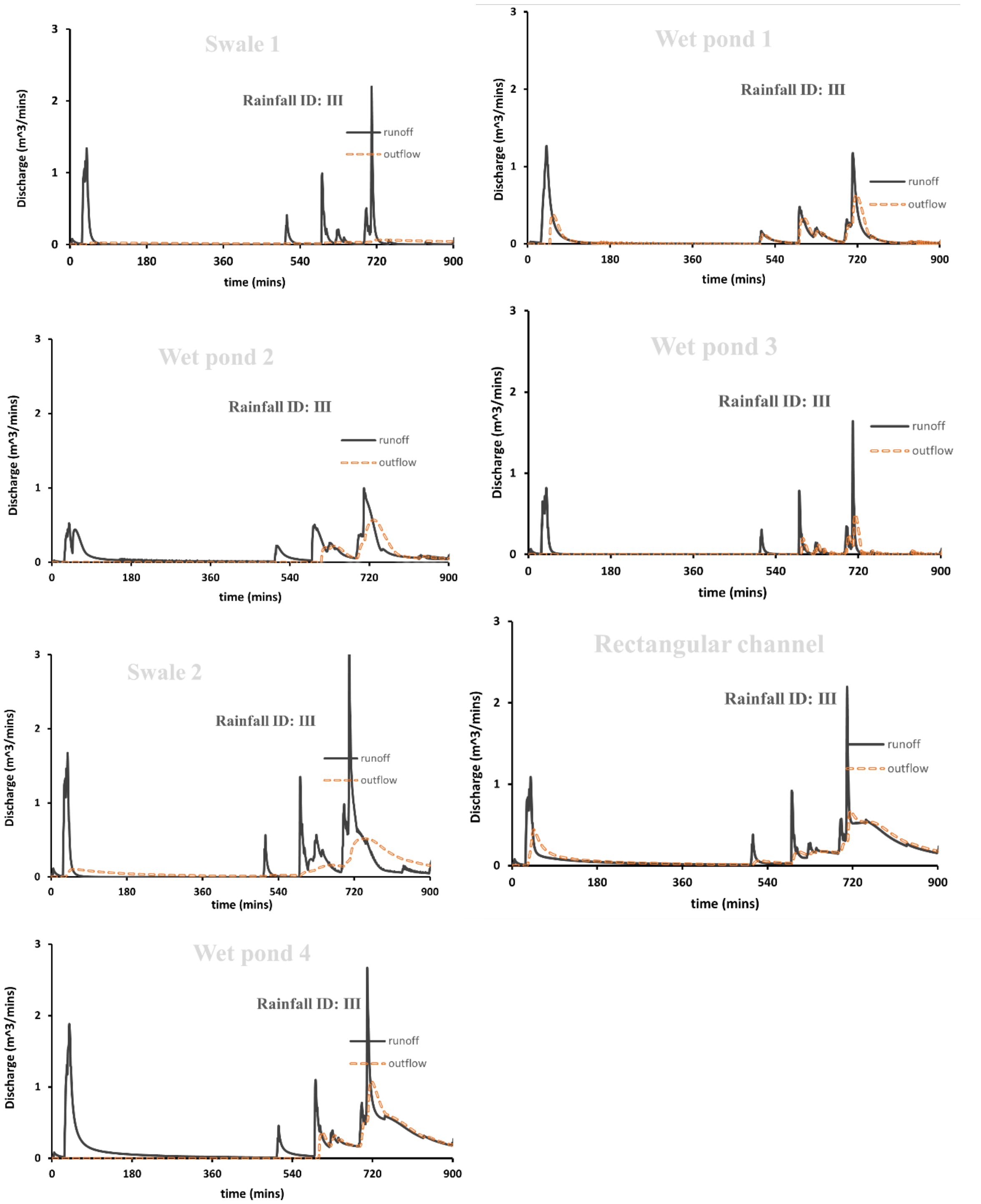


*Figure I-2; The hydrograph for each SCM with rainfall event ID III.*

# Appendix II

## II.1 Sensitivity analysis

The results from the sensitivity analysis were assessed quantitatively using the sum of squared error equation to get the squared error value at ±0% and ±25%, and at ±0% and ±50%. Table **II-1** and **II-2** listed the squared error value from each parameter value that were altered based on OFAT method with rainfall event **I** and **III** respectively**.**

*Table II-1. Parameters altered for the sensitivity analysis and the Sum of Squared error discharge volume at ±25% and ±50% from rainfall event I*

| **Parameters** | **Levels (%)** | **Sum of squared error for Discharge ($m^3$/min )** |
|---|---|---|
| **Storage coefficient c** | **-25** | 0.205 |
| | **+25** | 0.303 |
| | **-50** | 0.729 |
| | **+50** | 0.402 |
| **SCM surface area** | **-25** | 54.756 |
| | **+25** | 16.205 |
| | **-50** | 137.190 |
| | **+50** | 32.560 |
| **Catchment area** | **-25** | 15.714 |
| | **+25** | 16.361 |
| | **-50** | 34.357 |
| | **+50** | 57.366 |

*Table II-2. Parameters altered for the sensitivity analysis and the Sum of Squared error discharge volume at ±25% and ±50% from rainfall event III*

| **Parameters** | **Levels (%)** | **Sum of squared error for Discharge ($m^3$/min )** |
|---|---|---|
| **Storage coefficient c** | **-25** | 1.485 |
| | **+25** | 1.707 |
| | **-50** | 0.226 |
| | **+50** | 0.820 |
| **SCM surface area** | **-25** | 69.248 |
| | **+25** | 17.985 |
| | **-50** | 142.877 |
| | **+50** | 56.779 |
| **Catchment area** | **-25** | 14.216 |
| | **+25** | 23.975 |
| | **-50** | 61.058 |
| | **+50** | 61.176 |

# Appendix III

## III.1 How to Use the Model

This section explains how the model developed in this study can be used and applied in any study area with blue-green stormwater control systems.

The calculation equations used in developing the model are continuity equations and flow equations. All calculations and equations have been imputed into the model. In other words, no further calculations are required. The two flow equations used in the model are Manning's equation and orifice discharge equations (a reference to chapter 2 of this study). If the model wants to be used for study purposes, what is needed is changing the parameter values in the model to new data set values to be applied to the model. However, further calibration is required to be carried out on the storage coefficient value for the nonlinear reservoir routing. (See section 4.3 in chapter 4 of this study) on how the calibration process could be done using the sum of squared error method as a measurable indicator.

Finally, this model has been validated with data. However, if the user needs further validation of the model, no further calibration is needed during the validation process. In other words, all parameter values in the model are to remain in their initial calibrated values during the validation.