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Evaluation of different methods for modelling stormwater quality

Master's thesis in Architecture and Civil Engineering

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Evaluating different methods for modelling stormwater quality

Master of Science Thesis in the Master's Program Industrial ecology

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Abstract

Alongside the ever-increasing urban exploitation, the consideration of stormwater quality become more and more important. Since the beginning of the year 2000, water quality in the European Union is regulated by the European Water Framework Directive. This directive includes regulation of reciving water quality. The investigation of, and planning regarding stormwater can be facilitated by the use of models. In this study, different methods for modelling stormwater quality are evaluated. A market survey of available stormwater models in Sweden and internationally are performed. Then, a method description of the models StormTac, MIKE URBAN and SEWSYS are implemented. Each of these three models represents different methods for estimating stormwater quality. StormTac is based on static calculations of the land-use specific method, whereas the other two models are based on dynamic calculations using a pollutant source-based method in SEWSYS and a physical process-based method in MIKE URBAN. A theoretical comparison of the methodology of these three models is provided. A case study with monitoring data is then applied to StormTac and MIKE URBAN, in order to compare the simulated values with monitoring values. The outcomes from these two models turned out to fall into the measured minimum- and maximum-interval. The stormwater quantity, however, was not as well matched with the measured values. The total runoff volume simulated in StormTac was approximately three times higher than the measured volume and around three times lower in MIKE URBAN. Based on this study, StormTac is recommended for simulating long-term event mean concentrations (EMC´s) of pollutants. StormTac is a user-friendly model and it predicts EMC´s close to the measured EMC´s. StormTac can, however, not be used to investigate acute effects due to stormwater quality.

Keywords: Method characterization, MIKE URBAN, StormTac, Stormwater models, Stormwater quality.

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Jorun Lindgren

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List of abbreviations

AADT	Annual Average Daily Traffic
AD	Advection-Dispersion
ADWP	Antecedent Dry Weather Period
BOD	Biological Oxygen Demand
BP	Biological Processes
Cd	Cadmium
COD	Chemical Oxygen Demand
CS	Collection System
Cu	Copper
CV	Coefficient of Variation
EMC	Event Mean Concentration
EPA	Environmental protection authority
GIS	Geographical Information System
KWT	Kinematic Wave Theory
LR	Linear reservoir
MUSIC	Model for Urban Stormwater Improvement Conceptualisation
N	Nitrogen
P	Phosphorous
PAHs	Polycyclic Aromatic Hydrocarbons
Pb	Lead
PPC	Pollutant Partitioning Concept
PSR	Pollutant-Sediment Ratio

RDI	Rainfall Dependent Inflow
RE	Reduction Efficiency
SFA	Substance Flow Analysis
SMHI	Swedish Meteorological and Hydrological Institute
SRQ	Stormwater Runoff Quality
ST	Sediment Transport
STF	Stormwater Treatment Facility
SWMM	Stormwater Management Model
SWQ	Stormwater Quality
T-A	Time-Area method
TOC	Total Organic Carbon
TSS	Total Suspended Solids
UHM	Unit Hydrograph Method
WD	Water Distribution
Zn	Zink

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1. Introduction

1.1. Background

Urban exploitation grows rapidly over the world, which results in a corresponding increase of impervious surfaces. With more impervious surfaces, an increasing amount of runoff water will arise. Stormwater consists of rain and melting water that runs off impervious surfaces (Stockholm Vatten och Avfall, 2014). Pollutants that build up during dry weather periods are transported with the stormwater and end up in receiving waters, e.g. lakes and rivers. When the polluted stormwater enters the receiving water, adverse effects on aquatic life may arise (Hall & Ellis, 1985). To address these problems, stormwater management is important to consider.

Stormwater quality can be expressed as the level of contamination of harmful substances. Examples of such substances are heavy metals, nutrients and organics (Ahlman, 2006). Investigation of stormwater quality has recently been more frequently considered in the planning for urban exploitation (Ramboll, (n.d)). Nevertheless, it is only 8 % of the stormwater generated in urban areas in Sweden that is treated regarding the pollution, according to a compilation performed by the Swedish environmental protection agency (2017). According to their analysis, there is also a lack of knowledge about stormwater quality in respect to sources and the spread of pollutants in stormwater (Naturvårdsverket, 2017).

The investigation of stormwater quality is facilitated by the use of stormwater models. There are, however, several different methods available for simulating stormwater quality (Borris, 2019). Several studies have been performed to evaluate and compare different stormwater models. For instance, a conference paper "Review of urban stormwater models" performed by Rangari, Patel and Umamahesh (2015), a report written by Larsson, Larm, Lindfors & Bodin-Sköld (2014) with the purpose of mapping modelling tools for simulating stormwater treatment solutions and a master thesis performed by Lind (2015) with the purpose to evaluating and comparing different stormwater models have previously been performed. However, none of these studies focus on the performance of stormwater quality methods.

1.2. Aim

The aim of this study is to find out what different methods the stormwater models are based on. A market survey of existing stormwater models used in Sweden and internationally is carried out. The investigated models are compared based on the outcomes from each model, and model outcomes are then compared to monitoring data. The focus is on stormwater quality and for this purpose, stormwater quantity is also studied since it affects how much pollution that is washed off from the land surface and also how concentrated the solution is. To fulfil this purpose, the following research questions are investigated:

- Which methods for stormwater quality modelling are used in Sweden and internationally?

- What distinguish the models from each other considering important modelling aspects and characteristics?

- Do the model outcomes, i.e. stormwater quality and quantity, differ compared to measured values and between the various models?

1.3. Delimitations

This study focus on the modelling of stormwater quality and therefore not all functions within the models are evaluated. The comparison of the models is thus based on existing opportunities of simulating stormwater quality and the performance of the quality methods. In Sweden, there are two frequently used models for the investigation of stormwater quality: StormTac, developed during a PhD study in Sweden and MIKE URBAN, powered by the Danish Hydraulic Institute (DHI). Those two models are applied to a case study, using monitoring data collected in 1997-1998.

2. Stormwater quality

2.1. Pollution of stormwater

Pollutants on earth´s surface originate from both natural and anthropogenic sources. Anthropogenic pollution frequently increases due to population growth. Industrial, agricultural and transport activities are common anthropogenic sources to land surface pollution. Common transport paths of pollutants are through air and by direct emission on the land surface (Ahlman, 2006). Transportation by air enables substances to travel longer distances and can, therefore, give rise to regional or even global transportation of pollutants.

Common stormwater pollutants are, for instance: heavy metals, organics, nutrients and solid particles. Metals such as Cu, Zn, Pb and Cd can be highly toxic to aquatic ecosystems. Cu and Zn as well as Pb are frequently occurring around traffic areas. Pb was, however, much more common before it was prohibited in gasoline in the year of 1995 in Sweden (SPBI, 2014). Cd occurs naturally in all soils and is therefore relevant to investigate for all exploited land areas. In addition, Cd is often used in industrial processes and emitted when burning fossil fuels (Livsmedelsverket, 2019). The nutrients P and N can give rise to eutrophication and therefore those substances are important to analyse. In southern Sweden, the major source of P and N in the ocean are arable land and from forest (SLU, 2010). Solid particles can act as an adsorbent for other contaminants and is therefore an important parameter when estimating the transportation of pollutants. This concept is called pollutant partitioning (DHI, 2017). Sediment is often used as an umbrella term for the total content of fine and coarse particles. The build-up of sediment on the land surface is due to natural processes, such as erosion of pervious surfaces and dust by wind, and to anthropogenic activities, e.g. road wear and construction activities (Minnesota stormwater manual, n.d.). The degree to which the different pollutants bind to particles depends on various chemical and physical parameters. The attraction to solid particles can be explained by e.g. distribution coefficients, pH and temperature (Westrich & Förstner, 2007).

The build-up and wash-off of pollutants are vital for the understanding of stormwater quality and many of the models are also based on those concepts (Ahlman, 2006). Build-up of land surface pollutants differs significantly on land-use. For instance, urban land-use is generally more polluted than rural ones. Several different pollutant sources such as road traffic, metal roofs and industries are more prevalent in urban areas. Road traffic is a large source of both metals and organic pollutants. For instance, corrosion of vehicles and tire breaks generate emissions of e.g. Cu and Zn, whereas use of fossil fuels in vehicles may cause emissions of e.g. polycyclic aromatic hydrocarbons (PAHs) and oil spill (Ahlman, 2006). Other parameters affecting the build-up of pollutants is e.g. the removal of pollutants by wind as well as biological and chemical degradation of pollutants (Chen & Adams, 2006).

During rainfall, accumulated pollutants are washed off from the land surface. The physical process of pollutant wash-off is commonly explained in stormwater models as sediment wash-off (DHI, 2017). Erosion of sediment particles is caused by detachment by raindrops and overland flow (Ali, Bonhomme & Chebbo, 2016). According to a study by Hong, Bonhomme, Le and Chebbo (2016), raindrops are the main reason for the erosion of sediment on land surface.

The amount of washed off pollutants from the land surface depends e.g. on the antecedent dry weather period (ADWP). The longer the ADWP, the longer the time for the pollution to build up. The concentration of pollutants is highest in the beginning of every rainfall event. As the sediment is washed off, the load of the remaining particles will decrease. This phenomenon is called first flush, and due to its higher pollutant concentration, this part of stormwater is the most important to treat (Li, Yin, He & Kong, 2007).

In addition to wash-off of sediment attached pollutants, substances can also be washed off from the land surface by being dissolved and transported in stormwater. The water solubility varies greatly between different substances. For instance, water solubility of metals ranges from being practically insoluble in water to being very soluble or even hydrolysed by water. Metals can exist in many different forms, which in turn affect its solubility in water. Metals in its pure form are practically insoluble, whereas several compounds of e.g. Cr, Cu and Zn with other elements are soluble or very soluble in water. Nutrients, such as different compounds of N and P, are either soluble or very soluble in water (Aylward & Findlay, 2008), whereas most hydrocarbons have very low solubility in water (Selva et al., 2008).

Dissolved pollutants in stormwater are often much more problematic than those attached to particles. Both because of their higher bioavailability, which is a measure of how well a substance is taken up in biological material, and because it is often much more difficult to treat dissolved substances. Stormwater ponds are, for instance, a common stormwater treatment method. This method is based on sedimentation of particles and therefore dissolved pollutants are not removed by this technique (LeFevre et al., 2015).

2.2. Event mean concentration (EMC)

EMC is often used to express stormwater quality. The EMC is calculated according to equation (1). If the catchment area is divided in several sub-catchments, the pollutant mass and stormwater volume from each sub-catchment are summarised to get the total mass and total stormwater volume for the whole catchment area (Peng, Liu, Wang, Gao & Ma, 2015).

$$EMC = \frac{\sum m}{\sum V} = \frac{\int C(t)\, V(t) dt}{\int V\,(t) dt} \tag{1}$$

C= pollutant concentration in stormwater at a given time
m=total pollutant mass in stormwater from the catchment area at a given time
V= total stormwater volume from the catchment area at a given time
t=time

When monitoring stormwater quality, several grab samples are commonly taken during each rainfall event. The concentration of each sample is analysed and multiplied with the total measured stormwater volume at the time the sample was collected. By doing this, the total pollutant mass in stormwater from the catchment area is obtained (Ahlman, 2006).

3. Stormwater models

In this chapter, the concept of stormwater models and the characterisation of them is presented. A brief description of the models is then provided. At the end of this chapter, the required input parameters of the models are also presented.

3.1. Types of stormwater models

There are several types of stormwater models available on the market. They differ depending on type of applications and their level of detail. For instance, different requirements of input data exist within the models and there is also some variation of available outputs. Which model suits best for a specific project depends on the aim of the project and what resources there are to carry out the project (Borris, 2019).

Stormwater models can be used to study both hydrology and hydraulics. Hydrology describes the water on the earth surface, e.g. its occurrence (i.e. liquid, solid or gas (SMHI, 2017)), the partitioning of water on the earth surface, the physical and chemical features of water (e.g. colour, smell and taste (NE, 2019)) and the water cycle (SMHI, 2019), whereas hydraulics concerns the flows and motions of liquids. Hydraulics can be applied to e.g. describing flows in pipes and channels (Hydraulics, 2019).

The stormwater models are divided into several categories due to their methodological approaches. For instance, a model can be either deterministic, which means that the same input data always give the same output value, or stochastic, which means that the model is based on statistical expressions and can generate different outputs with the same input value (Borris, 2019).

Furthermore, the methods are either static or dynamic. Static means that the simulation is constant over the whole period whereas dynamic methods mean that the simulation can change over time. To describe dynamic processes, input and output values are often expressed as time series (Ottenhag, 1999).

The representation of the catchment area, i.e. the area that contributes to stormwater into the recipient, can be lumped or distributed. A lumped catchment area is defined by one external system boundary. Within this boundary, several different land-use areas can exist. If the system boundary is further delineated, the catchment area is said to be distributed (Borris, 2019).

For simulating stormwater quality, there are several methods available. The land use method is one of the most common methods applied. Given standard concentrations for each substance and land-use category are adopted by this method (Borris, 2019). Another, probably even more common method, describes the physical processes that affect stormwater quality. At the land surface, pollutant build-up and wash-off processes are simulated. If a pipe network is included in the model, different transport processes through this network can also be simulated (Borris, 2019).

A less frequently used quality method is one based on the pollutant sources. With this method, sources for each substance are identified and the activities that give rise to the emissions are estimated. As an example, Cu in stormwater is derived from large metal surfaces, such as copper roofs. Corrosion is the main reason for the emissions from metal surface (Ahlman, 2006).

Stormwater quality can also be based on regression methods. The procedure is then based on relationships between observed parameter values, e.g. pollutant concentrations, and stochastic variables, e.g. rainfall intensity and the land-use (Borris, 2019).

3.2. Market survey of existing models for stormwater quality simulations

A market survey of available models for stormwater quality was carried out, based on a literature search. The purpose of this survey was to get an overview of different stormwater quality methods that are currently used. The models were selected to achieve a spread of different methods to investigate. During the market survey, the following aspects were considered:

- Number of predefined substances
- Required input parameters
- License price
- Applications
- Country where it was developed
- Outputs

The number of predefined substances provided by the model and the required input parameters were considered to give a hint on how detailed the model is. Applications and outputs were considered to express which type of project the model could be suited for. The country where the model was developed is also an important aspect since different geographical locations may provide different physical conditions.

The stormwater models, gathered from the market survey, and the required input parameters are briefly presented in the sections below. A summary of the considered aspects of the models are presented in Table 1.

Table 1. *Collected stormwater model aspects.*

Model	Pollutants	Minimum required input parameters	Price of license [SEK/yr]	Application	Country	Outputs
StormTac	>70	3	35000-60000	Long-term, Hydrology, Hydraulics	Sweden	C_i, m_i, V, RE, STF design, receiving water threshold values
SWMM		11	Free	Long-term and single events, Hydrology, Hydraulics	USA	C_i, m_i, V
MIKE URBAN	7	13	> 50 000	Long-term and single events, Hydrology, Hydraulics	Denmark	C_i, m_i, V, RE
MUSIC	3	10	(30 days free trial version)	Long-term and single event, Hydrology	Australia	C_i, V, RE, STF design
SEWSYS	20	14	20 500	Long-term and single events, Hydrology, Hydraulics	Sweden	C_i, m_i, V, pollutant sources

C_i=concentration of substance i [µg /L], m_i=mass of substance i [kg], V=runoff volume [m^3], RE=reduction efficiency [%], STF=stormwater treatment facility.

3.2.1. StormTac

StormTac was developed in Sweden in the PhD study "*Watershed-based design of stormwater treatment facilities: model development and application*" performed by Thomas Larm (2000). It is a static model based on a database with land-use specific concentrations and runoff coefficients, both measured during continuing long-time flow-based analyses from different types of land-use areas. The database includes standard concentrations for more than 70 different substances. StormTac only require three input parameters to be defined: land-use type and its total area and the annual average rainfall intensity (see table 2). The model can be used for both hydrological and hydraulic simulations. It can also be used to design stormwater treatment facilities (STF) and to investigate the condition of the receiving waters. Model outputs are defined as annual mean values of e.g. stormwater pollutant concentrations, stormwater pollutant load and stormwater flows. The cost of a StormTac licence can range between 35,000-60,000 SEK/yr.

3.2.2. SWMM

The most common stormwater model used worldwide is the Stormwater Management Model (SWMM), which was developed by the US environmental protection authority (EPA). This model is free to use. It is a dynamic model that uses physical-based processes to explain stormwater quality. The build-up and wash-off of pollutants can be described in the following environmental compartments: the atmosphere, the land area and groundwater. The stormwater quantity and quality are then simulated in the conduit network, which consist of e.g. pipes, channels and stormwater basins. To model stormwater quantity SWMM requires seven input parameters to be defined (table 2). As in all the other models a rainfall needs to be defined. Then the surface area, slope and imperviousness of the catchment area are required. Finally, a network needs to be defined and the Manning´s number of the pipes and the depression storage has to be given. Additional input parameters for each pollutant are then required to simulate stormwater quality (see table 3). The concentrations of the pollutant in air, land area and groundwater are required, and to simulate the pollutant removal rate, the substances decay constant must be given (Rossman, 2010).

3.2.3. MIKE URBAN

MIKE URBAN is a stormwater model powered by DHI. In addition to StormTac, it is one of the most applied stormwater models in Sweden. The price of a MIKE URBAN license varies with a minimum price of 50,000 SEK/yr. The model requires four general input parameters for simulation of stormwater quantity (table 2). It requires a map that states the geographical location of the catchment area, the total surface area and runoff coefficients. Then a rainfall needs to be defined. Several different surface runoff methods are available in MIKE URBAN and depending on which of these methods that is used, some more different input parameters are needed, which are presented in section 4.2. There are five different stormwater quality modules within MIKE URBAN, also these are presented in section 4.2. MIKE URBAN is the only model that can simulate biological processes within the conduit network. The surface runoff quality module is based on build-up and wash-off processes of sediment and sediment-attached pollutants. A conduit network can be defined by the user and then the transportation of dissolved and suspended substances in the network could be simulated. Transportation of dissolved and suspended substances in the conduit network are based on advection-dispersion processes. There are standard concentrations for seven different substances suggested in the MIKE URBAN user manual for the advection-dispersion (AD) module. Transportation of sediment in the network can also be simulated. The transportation of sediment can be simulated with one of the following four formulas: Englund-Hansen, Ackers-White, Engelund - Fredsøe – Deigaard or van Rijn (DHI, n.d.).

MIKE URBAN provides several different simulation possibilities. Depending on what the model is to be used for, the requirements for input parameters varies a lot. Required input parameters varies between five, when only stormwater quantity generated from the land surface is to be simulated, to 13 parameters, when both stormwater quantity from the land surface and in the network are to be simulated together with simulations of stormwater quality from the land surface and in the conduit network (DHI, 2017).

3.2.4. MUSIC

MUSIC "Model for Urban Stormwater Improvement Conceptualisation", is a model developed and mainly used in Australia. It is not sated on the MUSIC homepage how much a license cost. There is, however, stated that a free trial version on the MUSIC is available. The model requires nine input parameters for the simulation of stormwater quantity (table 2). A map over the catchment area is required together with the total surface area and width and slope of the area. The soil storage capacity, percentage of impervious area, field capacity and dominant soil type are also needed (eWater, n.d.).

The model can simulate stormwater quality for the following three substances: Total Suspended Solids (TSS), Nitrogen (N) and Phosphorous (P). The simulations are based on the regression method, which consists of an extensive literature review made by Duncan (1999). EMC´s are simulated through stochastic relationships between substance input parameter values and water quality autocorrelations, based on the review by Duncan (Montaseri, Hesami Afshar, & Bozorg-Haddad, 2015).

The model was developed for the purpose of managing stormwater and therefore several different STF´s are provided in the model. Pollutant reduction efficiencies (RE) for the following STF´s can be estimated in the model: sedimentation and detention basins, bioretention, infiltration and media filtrations systems, pollutant traps, buffer strips, rainwater tanks, vegetated swales and wetlands. The model also includes a cost-benefit module for the implementation planning of STFs (eWater, n.d.).

3.2.5. SEWSYS

SEWSYS was developed during the PhD study "*Modelling of Substance Flows in Urban Drainage Systems"* by Stefan Ahlman. The model is developed in Sweden and is performed in the software program Matlab-Simulink. To use SEWSYS a Matlab licence is required. The cost of a Matlab license is 20500 SEK/yr. For simulation of stormwater quantity, the following six input parameters (table 2) are required: rainfall, percentage of impervious area, temperature, road area, roof area and a lumped definition of "other areas". Unlike the other models, SEWSYS uses a lumped definition of the whole catchment area. The stormwater quality simulations are based on substance flow analysis (SFA). The SFA method is based on identifying the most important sources of the pollutants and thereafter estimating their emissions. The following eight input parameters (table 3) are required for simulation of stormwater quality: annual average daily traffic (AADT), percentage of heavy vehicles, percentage of Zn per road, roof and other areas and percentage of Cu per road, roof and other areas. SEWSYS provides 20 predefined substances, including e.g. metals, nutrients and suspended solids. Planning of pollutant source prevention are possible to perform in the model due to the pollutant source method that the model is based on (Ahlman, 2006).

3.2.6. Input parameters

Required input parameters for simulating stormwater quantity are listed in Table 2 whereas required input parameters for simulating stormwater quality are listed in Table 3.

Definition of a rainfall is required for all models and total catchment surface area are required for all models besides SEWSYS. More specific input parameters which describes the features of the catchment area are required for simulations in SWMM, MUSIC and SEWSYS. Those input parameters are the slope and width of the catchment area and the percentage of impervious area. The filed capacity to store precipitation is required in MUSIC, in SWMM this parameter is described as the “depression” capacity to store precipitation. Two additional input parameters that describes the features of the soil within the catchment area are required in MUSIC: soil storage capacity, i.e. the capacity of the soil to store precipitation and the dominant soil description, i.e. the dominant type of soils within the catchment area. A hydraulic network needs to be defined in SWMM before any simulations can be done in the model and the pipe roughness, which is described with the Manning´s number, is required. In MIKE URBAN and in MUSIC a GIS-map over the catchment area are needed to enhance the delineation process of the area.

Table 2. *Minimum required input parameters for simulating stormwater quantity*.

PARAMETERS	[UNIT]	STORMTAC	SWMM	MIKE URBAN	MUSIC	SEWSYS
TOTAL CATCHMENT SURFACE AREA	A [m^2]	✓	✓	✓	✓	
GIS-MAP OVER CATCHMENT AREA				✓	✓	
PRECIPITATION	p [mm]	✓	✓	✓	✓	✓
RUNOFF COEFFICIENT	ϕ [%]			✓		
SLOPE OF THE CATCHMENT AREA	[°]		✓		✓	
WIDTH OF THE CATCHMENT AREA	[m]				✓	
PERCENTAGE OF IMPERVIOUS AREA	A_{IP}[%]		✓		✓	✓
FIELD CAPACITY	[mm]				✓	
DEPRESSION STORAGE	[mm]		✓			
SOIL STORAGE CAPACITY	[mm]				✓	
DOMINANT SOIL DESCRIPTION					✓	
HYDRAULIC NETWORK			✓			
MANNING´S N	[sec/m$^{1/3}$]		✓			
AIR TEMPERATURE	T [C°]					✓
ROAD AREA	A_{road}[m^2]					✓
ROOF AREA	A_{roof} [m^2]					✓
OTHER AREAS	A_{others} [m^2]					✓
TYPE OF LAND USE AREA		✓				

There are no input parameters required to simulate stormwater quality in StormTac since standard values are given in the database. Several of the input parameters listed in table 3 can, however, manually be define in StormTac.

Table 3. *Minimum requiered input parameters for simulating stormwater quality.*

PARAMETERS	[UNIT]	STORMTAC	SWMM	MIKE URBAN	MUSIC	SEWSYS
POLLUTANT CONCENTRATION FROM THE LAND SURFACE	C* [mg/L]		✓	✓	✓	
POLLUTANT CONCENTRATION FROM AIR DEPOSITION	C_{Air} [mg/L]		✓			
POLLUTANT CONCENTRATION FROM GROUNDWATER	C_G [mg/L]		✓			
SUBSTANCE DECAY CONSTANT	[1/days]		✓	✓		
SEDIMENT BUILD-UP METHOD				✓		
SEDIMENT BUILD-UP RATE				✓		
ANTECEANT DRY WEATHER PERIOD (ADWP)	[Days]			✓		
POLLUTANT-SEDIMENT RATIO	PSR [%]			✓		
TYPE OF COMPONENT	Dissolved/Suspended			✓		
INITIAL CONCENTRATION	C_i [g/L]			✓		
SEDIMENT TRANSPORT METHOD	Englund-Hansen/Ackers-White/Engelund - Fredsøe – Deigaard/van Rijn.			✓		
TRAFFIC	AADI [vehicles/day]					✓
HEAVY VEHICLES	[%]					✓
ZN/ROADS	[%]					✓
ZN/ROOFS	[%]					✓
ZN/OTHER AREAS	[%]					✓
CU/ROADS	[%]					✓
CU/ROOFS	[%]					✓
CU/OTHER AREAS	[%]					✓

4. Method description and comparison

In this chapter, more detailed descriptions of StormTac, MIKE URBAN and SEWSYS are presented together with a comparison of the models. These three models were selected because of the different methods that the models are based on.

4.1. Method description of StormTac

StormTac is divided into the following modules: runoff, pollutant transport, pollutant treatment, receiving water and transport and flow detention. StormTac is a web-based model, where all work is done in the worksheet presented in Figure 1. This worksheet presents a flowchart of the various modules. The input parameter values can be handled by clicking the grey boxes. The transmission of the output values between the various modules is represented by the arrows that point from one module to the next (StormTac, 2018).

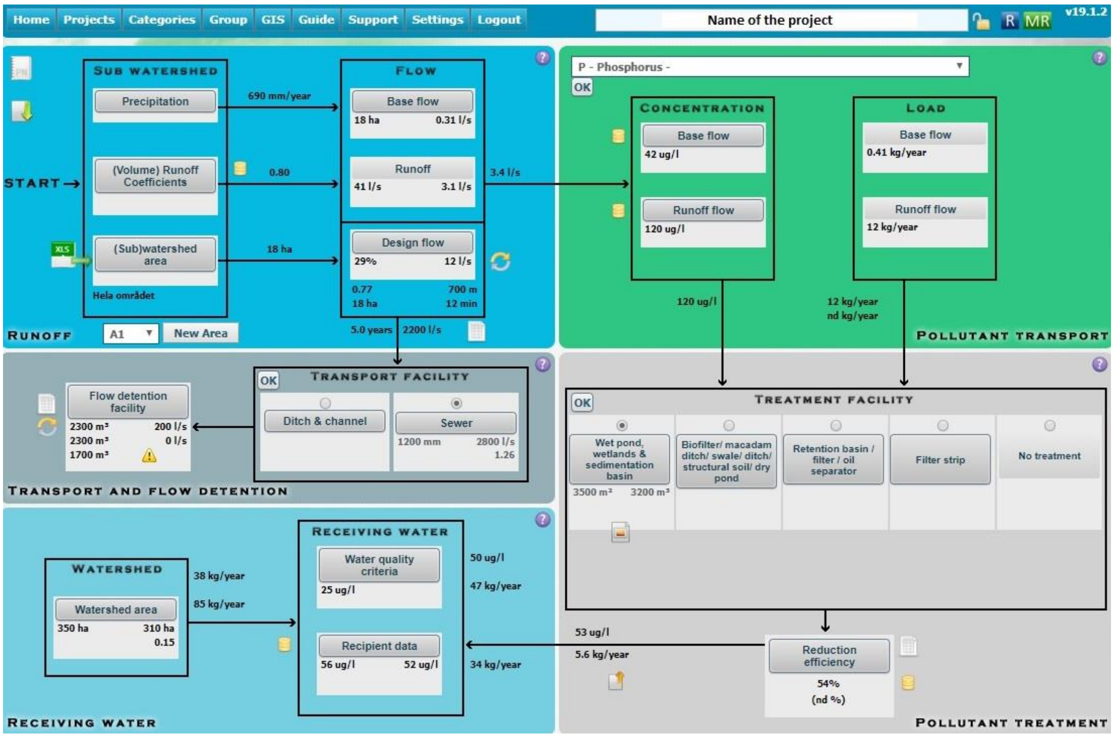

Figure 1. *StormTac worksheet (StormTac, n.d.).*

In the first module, stormwater flow (Q), given as L/s, is simulated by the following factors: annual average rainfall depth (p), given as mm/yr, catchment area (A), given as hectare, and land use specific runoff coefficient (φ), given as % of the precipitation that runs off from the specific land use area. The runoff flow is estimated for all sub-catchment areas and then summarised to get the total runoff flow, according to equation 2.

$$Q = 10p \sum \varphi A \tag{2}$$

The yearly baseflow can also be estimated, according to equation 3. The fraction (K_{inf}) of infiltrated water for all land-use areas are summarised and multiplied with the fraction (K_x) of infiltrated water that reach the baseflow (StomrTac, 2018).

$$Q_b = 10pK_x \sum ((K_{inf}A_b) / (365 \times 24 \times 3.6)) \qquad (3)$$

Q_b=Base flow, [m^3]
K_{inf}=Fraction of p that is infiltrated, [%]
K_x=Share of K_{inf} that reaches the base flow, [%]
A_b=Base flow area, [ha]

The volume of stormwater and baseflow are used in the subsequent pollution transport module to estimate yearly or monthly pollutant load (L), according to equation 4. The runoff volume from each sub-catchment is multiplied with land-use specific concentrations (C). The total load of a specific substance is obtained by summarising the load from all included sub-catchment areas (StormTac, 2018).

$$L = \frac{QC}{1000} \qquad (4)$$

The receiving water module includes threshold values for each substance. If the stormwater exceeding those values, stormwater management should be considered. Planning of stormwater management is done in the pollutant treatment module. The pollutant treatment module describes several types of STF and their reduction efficiencies (RE). Available STFs in StormTac are stormwater ponds, filter strips, wetlands, open ditches, swales, and detention basins. The REs for included STFs have been obtained by analysing concentrations in both inlet and outlet flow of the STFs, according to equation 5 (StormTac, 2018). The StormTac database includes obtained REs from several different experimental and literature-based studies (Larm, 2000). The average REs for each STFs are given in the database and are used for the stormwater management simulations in StormTac (Larm, 2000).

$$RE = 100 \frac{(C_{in} - C_{out})}{C_{in}} \qquad (5)$$

StormTac is based on a database of standard concentration for more than 70 substances, including 18 metals (the dissolved concentrations are available for seven metals), two metalloids, two nutrients, 26 organic substances, biological oxygen demand (BOD), chemical oxygen demand (COD), 14 pesticides, two bacteria, suspended solids (SS), total organic carbon (TOC), dissolved organic carbon (DOC) and oil. There are also more than 90 land-use areas included in the database. The standard concentrations are given as average, minimum and maximum values. The standard concentrations can be multiplied with a factor between 1-10 to modify the average standard values in cases that differ from the given standard conditions. Factor 5 is used for standard conditions, whereas a factor less than 5 is used if the study area has been graded to a less polluted area and a factor higher than 5 is used if the area is graded to higher pollution conditions (StormTac, 2018).

Hydraulic simulations are performed in the transport and flow detention module. The capacity of transporting stormwater in the conduit network and in ditches and channels can be estimated as well as the dimensions of the transport system. It is also possible to design detention facilities within the module. This procedure is based on the demand of the stormwater volume to be managed (StormTac, 2018).

4.2. Method description MIKE URBAN

MIKE URBAN is a stormwater model powered by DHI. The model can run simulations on both collection systems (CS) and water distribution systems (WD). For stormwater and wastewater simulations, the CS-module is used, and is therefore selected for this study. The hydraulic simulations in MIKE URBAN are either performed with the MOUSE calculation engine, developed by DHI, or by the SWMM calculation engine. Simulations with both SWMM and MOUSE are performed via a model manager where the network data is handled. In addition to the model manager, some additional modules are required to perform simulations with the MOUSE engine: (i) CS-Rainfall-runoff, (ii) CS-Pipeflow and (iii) CS- control (DHI, 2017).

The available options for stormwater quality simulations depend on what hydraulic calculation engine that is selected. The SWMM engine is provided with the same type of stormwater quality simulations as the SWMM software package described in section 3.2.2. have. If the MOUSE engine is selected, several elaborations by DHI for stormwater quality simulations are available (DHI, 2017). Both SWMM and MOUSE are based on the build-up/wash-off procedure. However, those processes are expressed in different ways in the two calculation engines (DHI, 2017). In this study, the MOUSE engine is selected for the evaluation. The method described in this section is therefore focused on the options of CS and MOUSE.

The CS simulation in MIKE URBAN is divided in two steps: First, a surface runoff simulation is carried out and then a simulation of the conduit network follows. There are four different methods available to describe surface runoff in MIKE URBAN:

- Time-Area (T-A) method
- Kinematic wave theory (KWT) method
- Linear reservoir (LR) method
- Unit hydrograph method (UHM)

There are some general inputs required for each of these surface runoff methods. First, a geographical coordinate system is stated, to be able to specify the geographical location of the study area. Then a catchment area is drawn within the MIKE URBAN software. Background layers, e.g. map over the study area and network drawings, are used to facilitate this process. The whole catchment area can then be split into several sub-catchment areas. Calculation of the area is performed automatically during the drawing process (DHI, 2017).

To estimate how much of the catchment area generates surface runoff, rainfall data and land use specific runoff coefficients are given for each sub-catchment. The rainfall is described as time series where e.g. Excel-sheets can be used to present data for each included time step (DHI, 2017).

The T-A method is a simple surface runoff method based on a time-area curve and the "time of concentration" parameter. The curve represents the shape of the catchment area. There are three pre-defined time-area curves within the software. The "time of concentration" describes the time it takes for the water to flow from the most distant part of the catchment to the outflow from the catchment area. MIKE URBAN provides default values for all specific input parameters for this method. The parameters can be edited if wanted. The specific input parameters for the T-A method, in addition to the T-A curve and the time of concentration, are initial loss, which describes the depth of rainfall required for runoff to start, and hydrological reduction factor, which account for hydrological losses in form of e.g. evapotranspiration (DHI, 2017).

The KWT method is based on the Manning's equation. This method simulates the runoff by assuming an open channel flow. The gravitational and frictional forces are accounted for with this method. The method specific input parameters are the length and slope of the catchment area, the type of the catchment surface in form of e.g. "impervious steep", "impervious flat" or "pervious (small/medium/large) impartibility", together with the percentage of each surface type, wetting and storage loss of water, start and end infiltration, which describes the maximum and minimum rate of infiltration, Horton´s exponent that describes the rate reduction over time due to infiltration capacity during a rainfall event and the Manning's number (DHI, 2017).

The LR method simulates the runoff based on the routing of a linear reservoir, which means that the runoff is proportional to the water depth on the catchment surface. There are two options for this method: (i) Model C1, which is based on effective area describing the percentage of the catchment area that effectively contributes to the formation of runoff and (ii) Model C2, which is based on the percentage of impervious area. Model C1 require the following input parameters: initial loss, time constant that define the shape of the hydrograph (i.e. runoff volume generated over time), maximum and minimum infiltration capacity and time coefficient (same as Horton´s exponent) for both dry and wet weather. Following input parameters are required for model C2: length and slope of the catchment area, hydrological reduction factor and the time constant (DHI, 2017).

The UHM method can be used to simulate the excess precipitation from single rainfall events and is based on a linear runoff model. There are four different methods to simulate the excess precipitation, all using a lumped description of the catchment area. All four methods require an "area adjustment factor" that describes the non-uniform spread of the precipitation over the catchment area. The rational method also requires a runoff coefficient. The "fixed initial loss" and the "constant loss" methods require the following input parameters: excess precipitation accumulated since start of the rainfall event, initial loss and constant loss rate and the time the rainfall event last. The fourth and last method is the "soil conservation service (SCS) loss model". This model requires the initial loss parameter and the maximum potential retention of precipitation (DHI, 2017).

The T-A and LR methods require the least input data, whereas KW requires the most. Due to limitations within this study the T-A surface runoff method has been selected. The four surface runoff methods generate discontinuous hydrological measurements, i.e. the flow is assumed to start and end in connection with individual rainfall occasions. Continuous and long-term simulations of surface runoff can be performed if the additional "rainfall dependent inflow and infiltration model" (MIKE RDI) is used. The four surface runoff methods can either be used separately or in combination with MIKE RDI. If one of the surface runoff methods, except the UHM, is used in combination with MIKE RDI, the base flow can also be included in the simulation. (DHI, 2017)

After all required input data are given, the surface runoff flow (Q) can be estimated. The flow is then used to estimate stormwater quality. For stormwater quality, the following modules are included in MOUSE:

- Surface runoff quality (SRQ)
- Pipe sediment transport (ST)
- Pipe advection-dispersion (AD)
- Biological processes (BP)
- Stormwater quality (SWQ)

Each module can be used either independently or in conjunction with the other modules. The BP, however, is required to be run simultaneously with the AD module (DHI, 2017). An overview of the stormwater quality modules and the connection between them are illustrated in Figure 2.

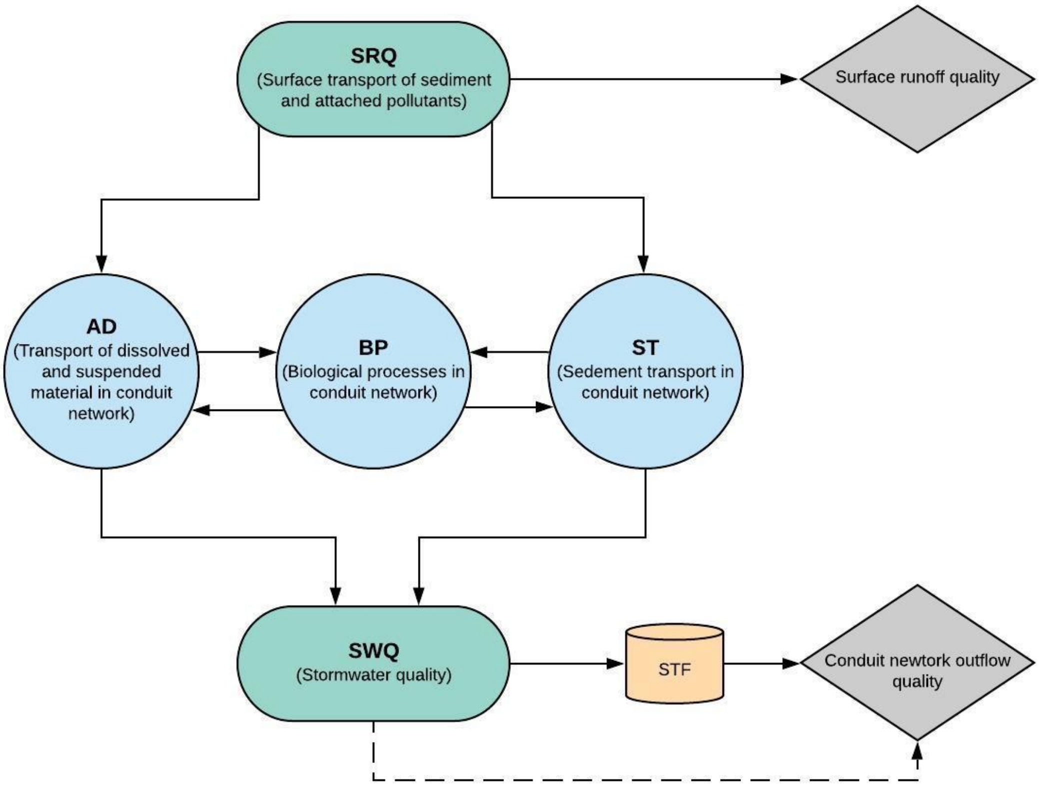

Figure 2. *Stormwater quality modules in MIKE URBAN and the interconnection between them (Developed based on information from DHI, 2017).*

SRQ is used to simulate the physical processes of build-up and wash-off of sediment. The build-up of sediment can be expressed either as linear or exponential. The exponential sediment build-up process is specified in equation 6 (DHI, 2017):

$$\frac{dM}{dt} = A_C - D_{rem} \times M \tag{6}$$

M=The accumulated mass of particles at time (t) [kg]
A_c=The daily accumulation rate [kg/ha/day]
D_{rem}=Removal coefficient [/day]

The daily accumulation rate and the removal coefficient can be obtained by performing experimental studies (DHI, 2017).

The build-up of pollutants is then estimated based on the pollutant partition concept (PPC), described in chapter 2. The mass of accumulated pollutants is estimated according to equation 7. This equation is applied on both fine and coarse sediment particles (DHI, 2017).

$$M = TP \times S \tag{7}$$

M=Mass of attached pollutant to sediment particles [g]
TP= Pollutant per liter of wet sediment [kg/L]
S=Sediment transport [m3/s]

The wash-off of sediment is thereafter calculated with respect to the area covered by the sediment particles and the rate at which the particles are washed off by rain. These two parameters are established by experimental studies (DHI, 2017).

The ST, AD and BP can be used to simulate stormwater quality processes in the network. ST is used to simulate how the sediment affects the hydrodynamics in the conduit network. For transport of dissolved and suspended material in the conduit network, AD is used. The transport mechanisms included in the AD module are advection, which is the transport with the mean flow velocity, and dispersion, which is the transport due to concentration differences. The biological processes that occur due to oxygen-consuming materials, e.g. BOD and COD, and microorganisms, e.g. bacteria and algae, are treated in the BP module (DHI, 2017).

The conduit network in which the stormwater is transported consists of e.g. pipes and wells. The dimensions of each part of the network must be specified. If stormwater quality is simulated in the conduit network, the SRQ result file needs to be included before the network simulation module is run (DHI, 2017).

The outcomes from SRQ can be used in conjunction with the AD and ST modules to explain how the pollutants first are transported from the catchment area and then through the conduit network. The stormwater quality is then simulated in the SWQ module, where concentrations of included pollutants are calculated. The SWQ module also includes the opportunity to simulate stormwater treatment in e.g. ponds and infiltration facilities (DHI, 2017).

Standard concentrations for three metals: Cd, Cu and Zn, TSS, BOD and the nutrients nitrogen and phosphorous are given in the user manual of MIKE URBAN (Table 4). The values are presented as normal, low and high concentrations (Larsson, Larm, Lindfors, 2014).

Table 4. *Standard concentrations given in MIKE URBAN User Guide [μg/L].*

Substance	Normal concentration	Low concentration	High concentration
TSS	100×10^3	30×10^3	400×10^3
Cd	0.5	0.15	1.5
Cu	30	15	100
Zn	130	50	400
N_{tot}	1.8	0.6	3.5
P_{tot}	100	25	300

Guidelines for which pollutant levels to use in the simulation, from Svenskt Vatten P105, are recommended by DHI (see Table 5).

Table 5. *Pollutant levels for different land use areas recommended by Svenskt Vatten P105.*

Land use area	Pollutant levels
Residential areas, incl. local streets	Low-Normal
Small house areas, incl. local streets	Low
Parking lots	Normal-High
Local streets	Low
Roads	Low-Normal
Thoroughfares	Normal-High
Parks and uncultivated	Low

4.3. Method description SEWSYS

SEWSYS is a source-based model. It means that stormwater quality is estimated by calculating the emissions directly from its source. The most important sources of pollutants in urban stormwater is traffic and roofs (Ahlman, 2006).

Substance flow analysis, on which SEWSYS is based, is an analysis of substance flows within a given system over a given time. When performing an SFA, a system is defined and the substance flows and stocks within that system are then estimated (van der Voet, 2000). SEWSYS is based on a conceptual model over a stormwater system. The system boundaries are defined by the catchment area and the pipe network. It is also possible to include stormwater ponds and infiltration facilities within the system. Major sources of studied pollutants are then defined. The model includes 20 predefined substances. For instance, nutrients, heavy metals and suspended solids are included (Ahlman, 2006). The stormwater model has also been extended with a few organic pollutants during a Phd study "*Sources and Fluxes of Organic Contaminants in Urban Runoff*" performed by Karin Björklund (2011).

The land uses included in SEWSYS are roads and roofs, the rest is then defined as "other areas". The stormwater quality is estimated by build-up/wash-off processes. The build-up process is defined by the substance generation rate (C), which is specific for each substance and source and is assumed to be constant over time, and the removal rate constant (k_a), which is also specific for each substance. Equation 8 describes this process as the change in time of accumulated load (L) of substances:

$$\frac{dL}{dt} = C - k_a \times L \qquad (8)$$

The build-up of pollutants occurs during dry weather periods, whereas the wash-off off substances occurs during rain periods. The wash-off process describes how the accumulated pollutant (P) is washed out by the rain (r) with a speed defined by a wash-off rate constant (k_w), as in Equation 9.

$$\frac{dP}{dt} = -k_w \times r \times P \qquad (9)$$

The generation of substances is based on different processes occurring at the source of the pollutant. For instance, metal roofs accumulate corrosion products of the metal at a constantly defined corrosion rate. The wash-off off the corrosion products by rain is then assumed in SEWSYS to be 50 %. Emissions generated on roads comes from e.g. tyre brake and road wear and depend on the total kilometres driven per day. It is assumed that 70 % of those emissions finally end up in the stormwater. Input-files over i.e. corrosion rates for different metals and road emissions are provided in the model (Ahlman, 2006).

SEWSYS is developed and running in the software program MatLab-Simulink. Input parameter values are inserted through the program main window, shown in Figure 3. For stormwater simulations, the catchment area and rain data are defined. If the catchment includes roads, the total driven kilometres per day and the number of heavy vehicles also need to be defined (Ahlman, 2006).

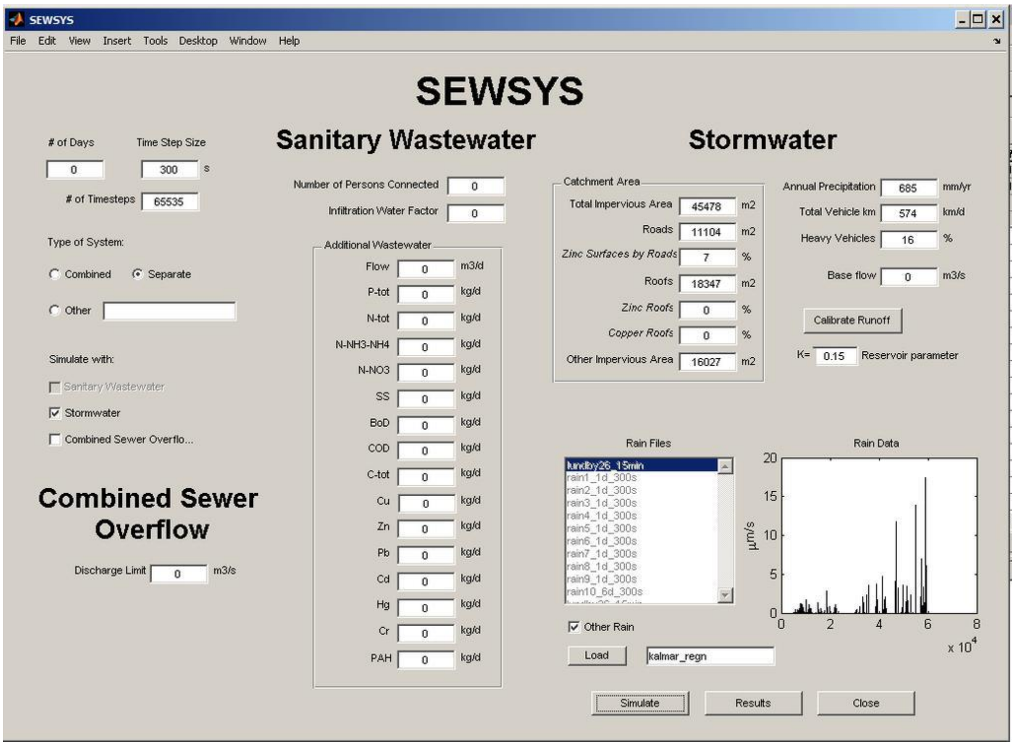

Figure 3. *Main window in SEWSYS (Ahlman, 2006).*

When all input values have been added into the main window, the Simulink model can be run. The results can then be viewed as graphs in MATLAB or exported and viewed in e.g. Microsoft Excel.

4.4. Model comparison

In this section, each methodological step in StormTac, MIKE URBAN and SEWSYS is compared. There are essentially three different steps that differ within the models: (i) How to express the rainfall; (ii) how to estimate stormwater quantity and (iii) how to estimate stormwater quality.

4.4.1. Rainfall

The rainfall is described in different ways in StormTac, MIKE URBAN and SEWSYS. The two later models have a more detailed description of the rainfall. In these models the rainfall is expressed as time series, usually divided in timesteps of minutes or in intervals of e.g. 15 minutes. At every time step, the rain depth is stated. This dynamic method of describing the rainfall considers the fluctuations that occur within the study period. StormTac, on the other side, describes the rainfall as yearly, or monthly, mean values. Figure 4 illustrates an example of the differences between these two methods.

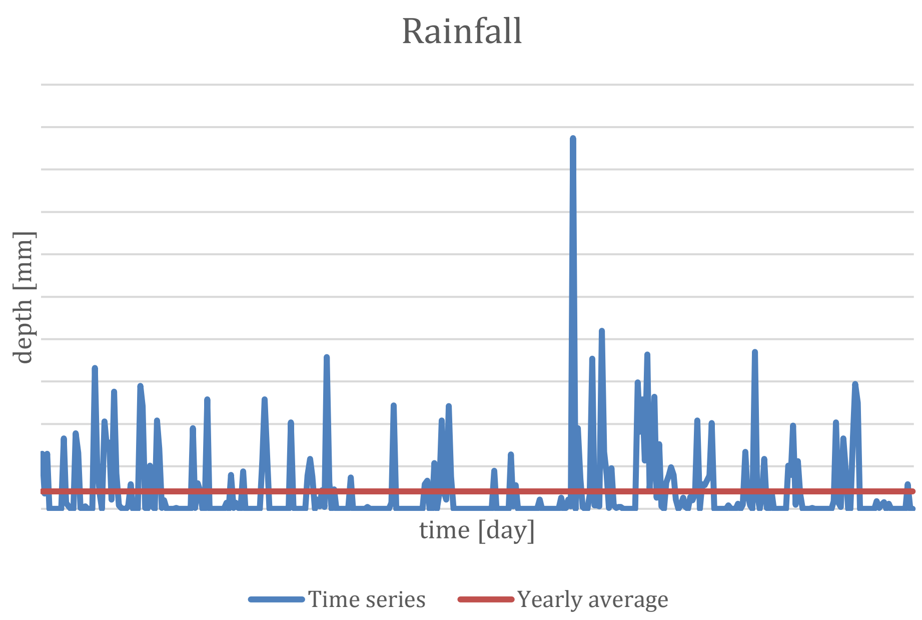

Figure 4. *Illustration of rainfalls, as time series and yearly average (Data from SMHI).*

4.4.2. Stormwater runoff quantity

The quantity of stormwater is estimated based on rainfall intensity and the imperviousness of the study area, in all three models. The imperviousness is expressed in a runoff coefficient, ranging between 0-1. The more impervious the surface is the more water will consequently run off from the surface. A value of 0 means that the surface will infiltrate all precipitation, whereas a value of 1 means that all precipitation will run off from the surface. There are recommendations available from e.g. Svenskt Vatten for runoff coefficients. In addition to the runoff coefficients, the slope of the catchment area can affect how much water that runs off. This concept is common for all three models.

Depending on whether the rainfall is described as static or dynamic, the stormwater quantity will also be statically or dynamically described. Static rainfall will generate static stormwater flows, whereas a dynamic rainfall will consider all peak and zero flows over the period.

4.4.3. Stormwater runoff quality

The characterisation of the three different models: StormTac, MIKE URBAN and SEWSYS is listed in Table 6.

Table 6. *Characteristics of stormwater quality simulations in StormTac, MIKE URBAN and SEWSYS.*

	Quality methods	**Description over time**	**Mathematical approach**	**Spatial representation**
StormTac	Land use-based	Static	Deterministic	Distributed
MIKE URBAN	Build-up/Wash-off, Land use based	Dynamic	Deterministic	Distributed
SEWSYS	Source based, Build-up/Wash-off	Dynamic	Deterministic	Lumped

StormTac estimates stormwater quality based on monitored pollutant concentrations collected from all over the world. Various land-use areas generate different pollutant concentrations. In the database of StormTac, standard concentrations are hence based on different land-use. Monitoring of same land-use category has, in most cases, been carried out in several places to also include geographical differences of pollutant concentrations. The method is often called "Land use-based method". Standard concentrations should preferably be measured over a longer period with several rainfall events included (Larm, 2000). Since the conditions for every individual rainfall event can differ considerably, just including one event should not be general enough to use as a standard. This is the main reason why this method is based on annual (or monthly) rainfall depth.

MIKE URBAN describes physical build-up and wash-off processes to measure stormwater quality. This method enables simulations for unlimited time ranges. The land-use based method can also be used in MIKE URBAN. When simulating stormwater quality in the conduit network the MIKE URBAN user guide recommend standard concentrations for seven pollutants based on the land-use categories.

SEWSYS is, unlike the other two models, based on pollutant sources instead of entire land-use areas. The representation of the catchment area is therefore lumped instead of distributed. The model describes the physical and chemical build-up processes occurring at the source of the pollutants. Corrosion of metal surfaces and emissions form traffic are examples on such processes.

5. Case study

Both StormTac and MIKE URBAN were used on a case study with monitoring data provided. The SEWSYS model was no longer compatible with current software updates and hence the model was not applied on this case study.

The conditions for StormTac and MIKE URBAN were as similar as possible to make a fair comparison of the two models. Required input data found in a PhD study of a stormwater pond and connected catchment area, performed by Thomas Pettersson (1999), is used to run and evaluate the models. The monitoring data is retrieved from Pettersson´s study and the simulated outputs are compared to these results.

5.1. Study area

The study area is approximately 480 ha and is located 5 km outside the city centre of Gothenburg (Figure 5). The area is connected to the Järnbrott pond. This stormwater pond has been the study object to several research projects, among them a PhD study "Stormwater Ponds for Pollution Reduction" performed by Thomas Pettersson. In this study, both stormwater quantity and quality into the pond was measured for 65 individual rainfall events between the period of August 1997 until July 1998. Since StormTac requires annual average input data and there is limited access of previous stormwater quality studies performed over longer time periods, the monitoring data from Peterssons study are used. The results from this study were also used to evaluate the outcomes from StormTac and MIKE URBAN.

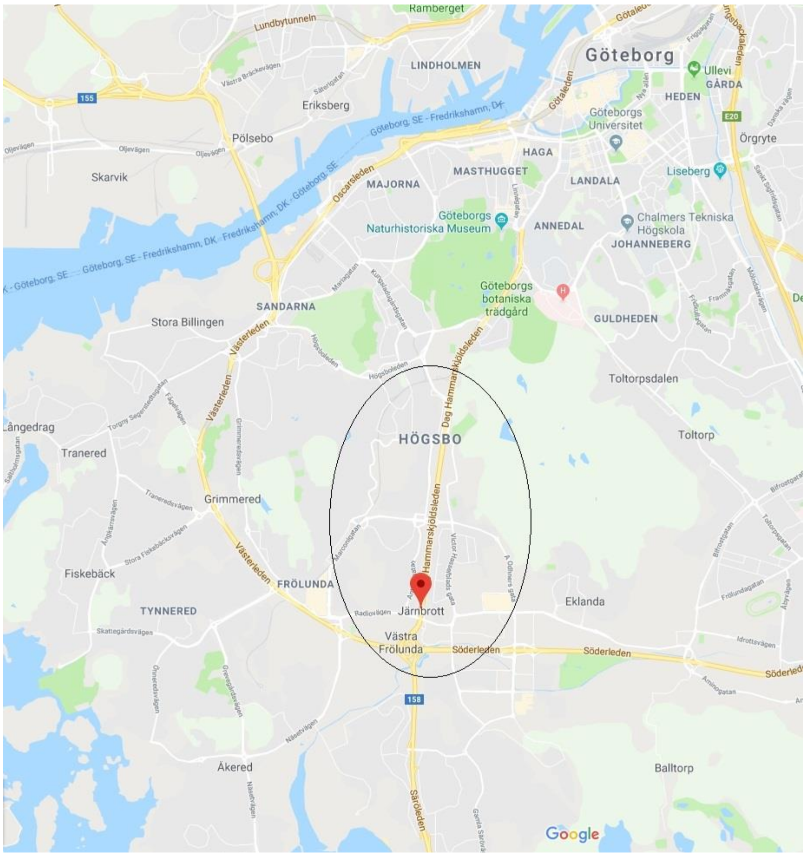

Figure 5. *Map with encircled study area (Google maps, 2019).*

The catchment area consists of residential, industrial, forest, highway and single-family housing land-use areas. The distribution of the land-use area is presented in Figure 6. The percentage partitioning of the land-use is based on an orthophoto over the area, where each category is drawn and calculated in MIKE URBAN.

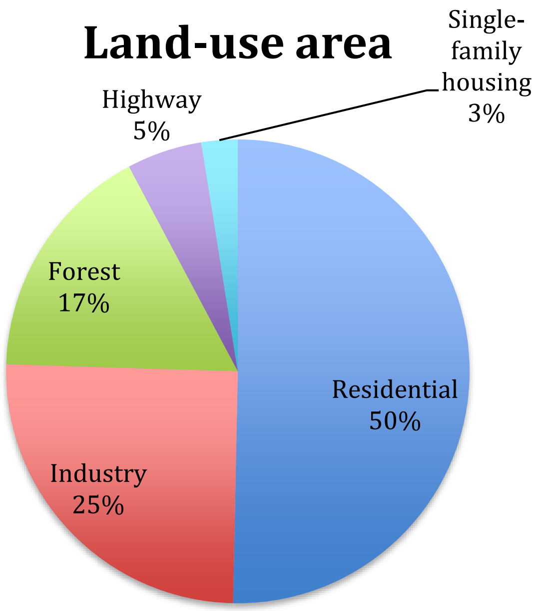

Figure 6. *Partitioning of land-use areas.*

5.2. Pollutants

The examined pollutants are those included in the study of Thomas Pettersson: TSS, Cu, Zn, Cd, Pb, P and N. TSS occurs on all types of surfaces and largely affects the transport of the other contaminants by acting as a sorbent.

5.3. Monitoring data

Monitoring data over the case study are available from the PhD study by Thomas Pettersson (1999). The observations were performed during two separate periods. The first period extended over six months between August 1997 and February 1998, whereas the next period extended over three months between April 1998 and July 1998. Together these two periods consist of 65 individual rainfall events.

Stormwater samples were collected at the inlet to the Large Järnbrott pond. The sampling equipment existed of 24 bottles made of polyethylene. The sampler was provided with a flow meter that enabled flow-weighted sampling. A rain gauge was also installed at the study area.

All sampling bottles were taken to a test laboratory at the department of Sanitary Engineering at Chalmers University of Technology, where the pollutant content was analysed.

All raw data was processed in the software program "Analys95", which calculated rain intensity, flow volumes and pollutant masses. The total mass of pollutant was calculated by multiplying the analysed concentration with the associated stormwater volume.

5.4. Calibration and validation

Calibration and validation of stormwater models are often recommended. The calibration involves comparing the different simulation steps with monitoring data. An iterative process of adjusting the input parameters to fit monitoring data follows. After the calibration process, validation is recommended. The calibrated model is applied on two or three other case studies with previous monitoring data to validate the adjusted input parameters (Peter & Singhofen, 2001).

Calibration and validation are often complex to perform due to the many input parameters included in a stormwater model (Peter et al., 2001). In some models, the calibration process has been automatized (Barco, Wong & Stenstrom, 2008).

In this study, the model outcomes from StormTac and MIKE URAN have been compared with each other and with monitoring data, without any following calibration and validation process.

5.5. Case study simulation in StormTac

In StormTac, the study area is divided into five different sub-catchments based on their land use. Each sub-catchment and its total area are listed in Table 7. In addition, the runoff coefficient and its corresponding reduced area, i.e. the area multiplied with its runoff coefficient, are listed in the table.

Table 7. *Input parameter values of land-uses in the case study area in StormTac.*

	Area [ha]	**Runoff coefficient***	**Reduced area [ha]**
Highway (30 400 vehicles/d)	25.0	0.80	20.0
Single-family housing	12.1	0.30	3.63
Residential	240	0.60	144
Forest	79.8	0.10	7.98
Industrial (less polluted)	120	0.70	84
Total	480	0.54	259

**Runoff coefficients from Svenskt Vatten, P110.*

In StormTac there are default values for the runoff coefficient for different land-use areas, based on recommendations from Sveskt Vatten, P110.

The rain is expressed as annual average rainfall depth, in mm/yr. The average rainfall intensity in Gothenburg between the year of 1997-1998 was 700 mm/yr (Pettersson, 1999).

In Table 8, the substances that are included in this study are listed. Standard concentrations are given in the pollutant transport module. All standard concentrations are given a certainty classification depending on their coefficient of variation (CV). CV is calculated by dividing the standard deviation with the mean value, which explains the dispersion of data points around the mean value (CFI, n.d.). All factors have been set to 5 as the study area is considered not to be either less or higher polluted than standard conditions. The average daily traffic in the year 1997 was estimated to be 30400 vehicles/d (Göteborgs stad, n.d.). The standard concentrations for the road are therefore multiplied by a factor of 30, since the standard value of Annual Average Daily Traffic (AADT) is set to 1000 vehicles/d in StormTac.

Table 8. *Standard concentrations [µg/L] in StormTac.*

	Factor*	TSS	Cu	Zn	Cd	Pb	P	N
Road (30 400 vehicles/d)	30	130000	49	240	0.48	25	220	2400
Single-family housing	5.0	45000	20	80	0.50	10	200	1400
Residential	5.0	70000	30	100	0.70	15	300	1600
Forest	5.0	34000	6.5	15	0.20	6.0	17	450
Industrial (Less polluted)	5.0	80000	35	210	1.1	25	290	1600

**Factor:*
Roads: 1000 vehicles/d × AADT
Others: Given in intervals of 1-10, 5=Standard conditions, <5=Less polluted, >5=More polluted
Certainty classification: High (CV<0.5) Medium (0.5<CV<1.25) Low CV>1.25

5.6. Case study simulation in MIKE URBAN

In MIKE URBAN, the study area is divided based on land-use, into seven sub-catchments (Table 9). A background layer gathered from the geographical information system (GIS), called ArcMap, is inserted in the model. This layer serves as a base for the delineation process of each land-use category.

Table 9. *Input parameter values of land-uses in the case study area in MIKE URBAN.*

	Area [ha]	Runoff coefficient*	Reduced area [ha]
1.Highway (30 400 vehicles/d)	25.0	0.80	20.0
2.Single-family housing	12.1	0.30	3.63
3.Residential 1	59.9	0.60	35.9
4.Residential 2	179	0.60	107
5.Forest 1	6.20	0.10	0.62
6.Forest 2	73.6	0.10	7.36
7.Industrial	120	0.70	84
Total	480	-	259

**Runoff coefficients from Svenskt Vatten, P110.*

Background layer and the division of each sub-catchment are shown in Figure 6. Each sub-catchment is numbered as in Table 9.

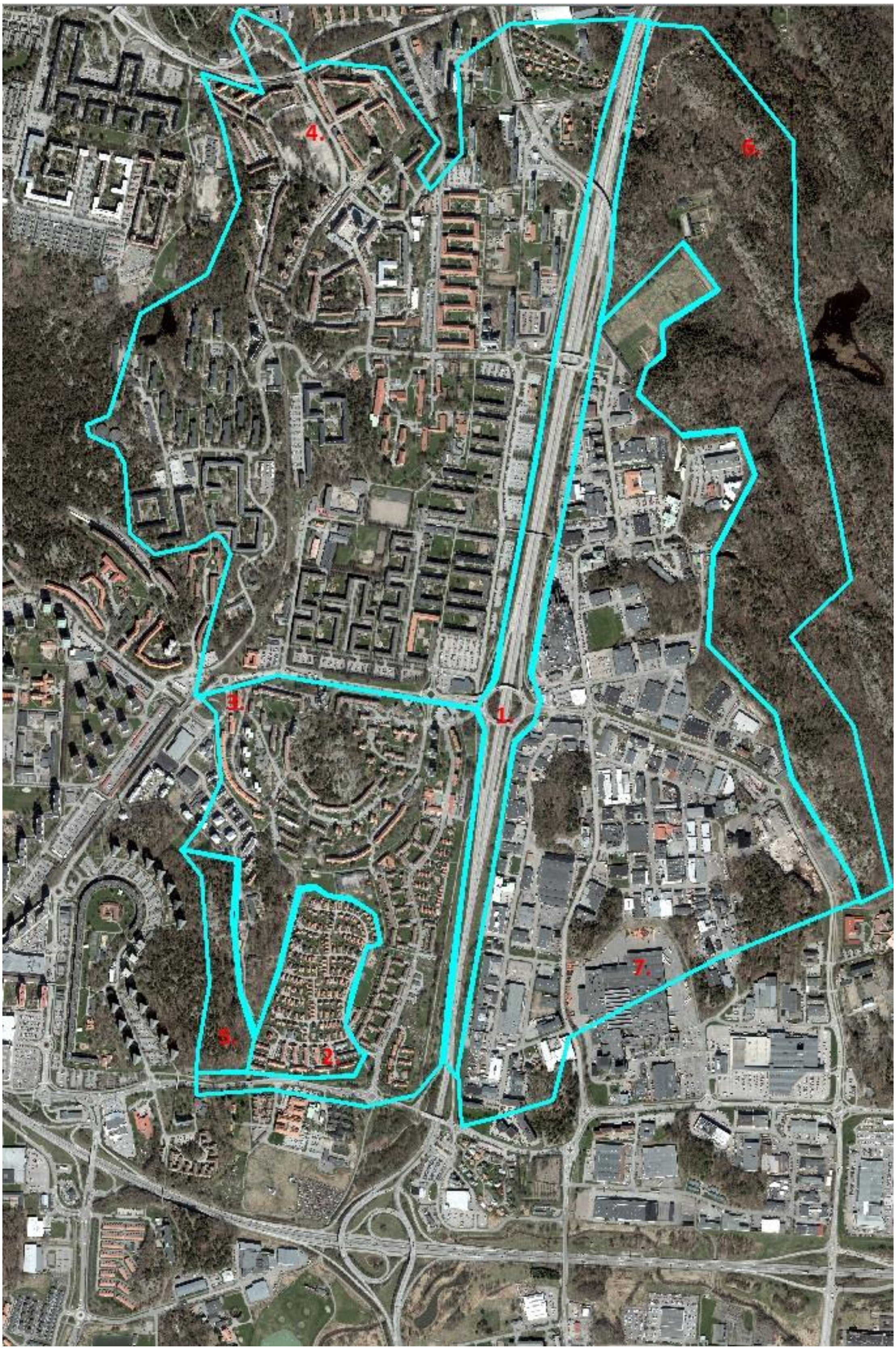

Figure 6. *Total catchment area delineated in its land-use categories. The land-use areas are numbered between 1-7.*

The rain period is divided as in the experimental study performed by Thomas Pettersson. The first period is between August 1997 and February 1998 and the second period between April 1998 and June 1998. The rainfall data has been collected from the Swedish Meteorological and Hydrological Institute (SMHI), where the data are gathered from a gauging station placed at the city centre of Gothenburg. The rainfall time series included in MIKE URBAN are expressed as rainfall intensity, in mm/d (Figure 7). SMHI also provides rainfall data of 15-minute intervals, with this resolution though, there are several data gaps for the actual period. Due to those data gaps, daily interval is selected despite its lower resolution.

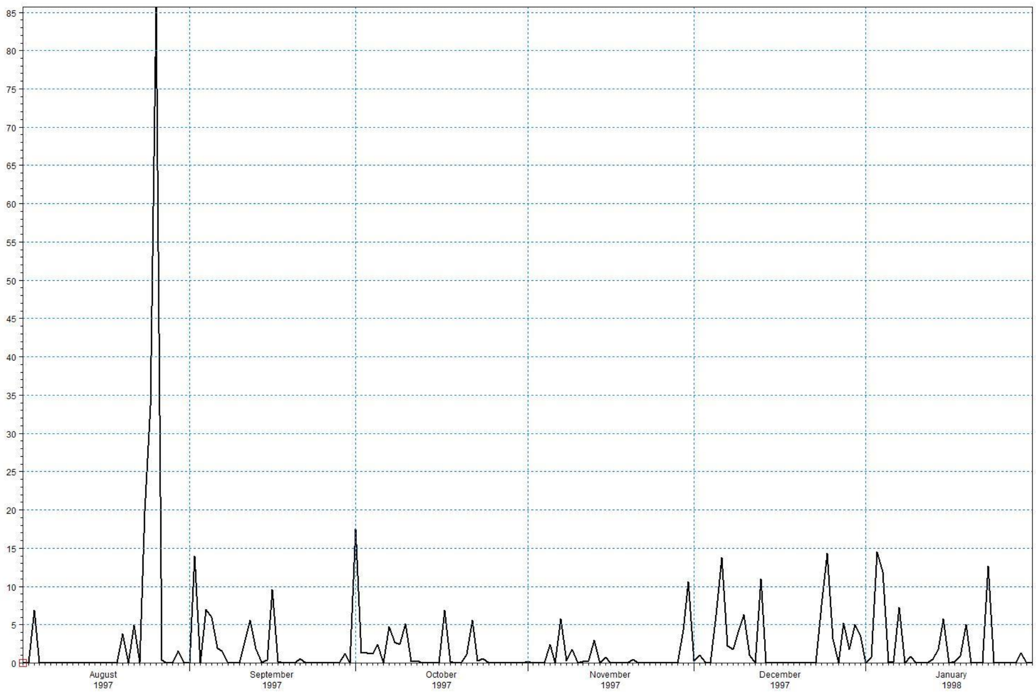

Figure 7. *Rainfall period 1 (August 1997-February 1998), expressed as (mm rain/day). (Data from SMHI).*

The SRQ-module is used for the stormwater quality simulation. This module is chosen to test the build-up and wash-off method. Table 10 and 11 list the input parameters for the SRQ-module. The build-up process of surface sediment is expressed by the build-up rate parameter and can be expressed either as a linear or exponential build-up process. There is no universal method to express this process (DHI, 2017), the exponential build-up method is typically used for water quality simulations though (Liu, Egodawatta, Kjoelby & Goonetilleke, 2010). In this study, the exponential build-up process was therefore selected. The sediment build-up rate can only be set as a lumped description over the whole catchment area. This parameter has been analysed and collected in a study by Chow, Yusop & Toriman (2012). Analyses were conducted in five different countries: Malaysia, Spain, Italy, Estonia and Australia. Of these five countries, Italy and Estonia are in the same climate zone as Gothenburg (Klimat och Väder, n.d.). Furthermore, the study in Estonia was carried out in an urban area while the study in Italy was carried out in a residential area. Based on this, the Estonia study has been considered to have the most similar physical conditions as the study area in Gothenburg and therefore the build-up rate analysed in Estonia was selected for this input parameter value. The ADWP are estimated from the rainfall time series and are counted as number of days between two rainfall events. Detachment rate are expressed by the "detachment coefficient by rainfall" and the wash-off exponent. The wash-off exponent, with the default value 2, expresses the power of rainfall intensity divided by the rainfall intensity constant (DHI, 2017). Detachment coefficient by rainfall, wash-off exponent and the sizes of fine and coarse sediment particles are given default values recommended in the software program.

Table 10. *Input parameter values for SRQ in MIKE URBAN. Build-up/wash-off and Attached pollutants.*

	Unit	**Parameter value**	**Reference**
Build-up Method	-	Exponential	Liu, Egodawatta, Kjoelby & Goonetilleke (2010)
Build-up rate	kg/ha/d	25	Chow et. al. (2012)
ADWP	d	3.2 (Period 1) and 3.1 (Period 2)	SMHI
Detachment coefficient by rainfall	m/h	0,001	Default
Wash-off exponent	-	2	Default
Size fine particles	mm	0.1	Default
Size coarse particles	mm	1	Default
Density fine particles	kg/m^3	1760	The Engineering Toolbox
Density coarse particles	kg/m^3	2000	The Engineering Toolbox

The build-up of attached pollutants to sediment particles can be simulated if the pollutant-sediment ratio (PSR) is available. This parameter is expressed as grams of pollutant per litre of wet sediment. Since TSS is defined as the total amount of solid particles suspended in stormwater, and the sediment is defined as the total amount of particles on surface, the PSR for TSS has been assumed to be described with the following relationship (Equation 10):

$$PSR_{TSS}=(FR_{fine}\times\rho_{fine}) + (FR_{coarse}\times\rho_{coarse}) \quad (10)$$

FR=Fraction of particle size
ρ=Particle density

Table 11. *Input parameter values for build-up of TSS in MIKE URBAN. PSR and sediment fractions.*

	Unit	Parameter value	Reference
PSR	g/L wet sediment	1856	See equation 10
Fine sediment fraction	%	60	Default
Coarse sediment fraction	%	40	Default

6. Results and discussion

The presentation of the results and related discussion is divided into two sections: first a comparison of stormwater models regarding their pros and cons are discussed and then the outcomes from the case study simulations in StormTac and MIKE URBAN are presented and discussed.

6.1. Comparison of stormwater models

The market survey resulted in a collection of five different stormwater models: StormTac, SWMM, MIKE URBAN, MUSIC and SEWSYS. StormTac is relatively easy to use and it requires the least number of input data of all models. StormTac is also the only model where the quality conditions of receiving waters are possible to investigate. The limitations of StormTac is that it is only possible to simulate average pollutant concentrations over longer periods of time. This means that specific rainfall events cannot be examined in the model. If maximum concentrations need to be investigated, StormTac cannot be used. Maximum concentrations are of interest if the risk for acute adverse effects on aquatic life are to be considered. The long-time simulation makes it also difficult to validate the model, since measurements of stormwater are usually carried out on individual rainfall occasions and not for long periods of time.

SWMM is free to use, but on the other hand it requires more work from the practitioner, compared to e.g. StormTac. Together with SEWSYS and MIKE URBAN, SWMM has the highest number of required input parameters of all models. Since there are no predefined pollutants in this model, all substances are described manually.

MIKE URBAN has the highest number of required input data compared to all other models. MIKE URBAN does not include any predefined pollutants. However, the user manual provides standard concentrations of seven different pollutants, which can be implemented in the AD module. There are almost unlimited possibilities regarding stormwater quality simulations within MIKE URBAN. To perform more detailed simulations, on the other hand, high technical and scientific pre-knowledge is required.

MUSIC contains the highest number of STFs of all models. There are 12 different STFs described in MUSIC. It is also the only model where cost-benefit analysis of stormwater treatment is possible to perform. A free trial version of MUSIC is available, and the model can hence be freely tested. The disadvantage of this model is the limited number of pollutants possible to examine. For instance, neither metals or organic pollutants can be simulated in the model. Since the model is based on the regression method, there is no possibility to define pollutants manually.

Unlike the other models, SEWSYS is based on calculations of pollutant sources and can therefore be used to investigate where the pollutants originally come from. This quality method facilitates planning of source-based prevention of pollutant transport instead of treating the contaminated water afterwards. According to Björklund (2011), this model is not well suited for simulations of organic pollutants.

Table 12. *Pros and cons of the various stormwater models.*

	StormTac	SWMM	MIKE URBAN	MUSIC	SEWSYS
PROS	+ User friendly + Large number of predefined substances +Large number of land-use areas +Investigation of receiving waters	+Free +Able to simulate peak concentrations	+Almost unlimited possibilities of modelling stormwater quality +Able to simulate peak concentrations	+Large number of STFs included +Cost-benefit analysis of stormwater treatment +Free trial version	+Planning of source-based prevention of pollution +Able to simulate peak concentrations
CONS	-Hard to evaluate simulated pollutant concentrations -Not able to simulate peak concentrations	-No predefined substances	-High knowledge requirements	-Limited number of substances to examine	-Not well suited for simulations of organic pollutants.

6.2. Case study simulations

In this section, results from the case study simulations in StormTac and MIKE URBAN is provided. First, the stormwater quantity results are presented and discussed, and thereafter the stormwater quality results.

6.2.1. Stormwater quantity simulations

The average yearly stormwater runoff flow is estimated to 58 L/s in StormTac, which gives a total yearly stormwater runoff volume of 1,800,000 m^3/yr. Compared to the measured volume in 1997-1998 (Pettersson, 1999), the simulated volume is approximately three times higher (Figure 8). However, the measured volume is only for a total of 9 months. Monitoring data for February, Mars and July 1998 are missing. The precipitation parameter in StormTac is given for 12 months. To explain the large difference between measured and simulated runoff volume though, the runoff volume generated in these three months has to count for 97 % of the annual runoff volume. According to rainfall data from RL (2019) there was no such rainfall event during these three months that could generate this extensive runoff volume. Therefore, the difference between simulated and measured volumes could not be explained by the gap in monitoring data.

In MIKE URBAN the total stormwater runoff volume in period 1, between August 1997 and February 1998, is estimated to 100,000 m^3 and to 50,000 m^3 in period 2, between April 1998 and June 1998. The total volume for both periods is then estimated to 150,000 m^3. Compared to the measured volume this result is three times lower.

In Figure 8, the total runoff volume measured in Pettersson's study and the simulated volumes in MIKE URBAN and StormTac are shown. Since only annual rainfall data can be specified in StormTac, the annual average runoff simulated in StormTac has been divided by 12. This simplification of monthly volumes has been used to estimate the total runoff over a 9-month period in order to compare StormTac with MIKE URBAN and to measured volumes. The total 9-month volume simulated with StormTac has been estimated to 1,350,000 m^3.

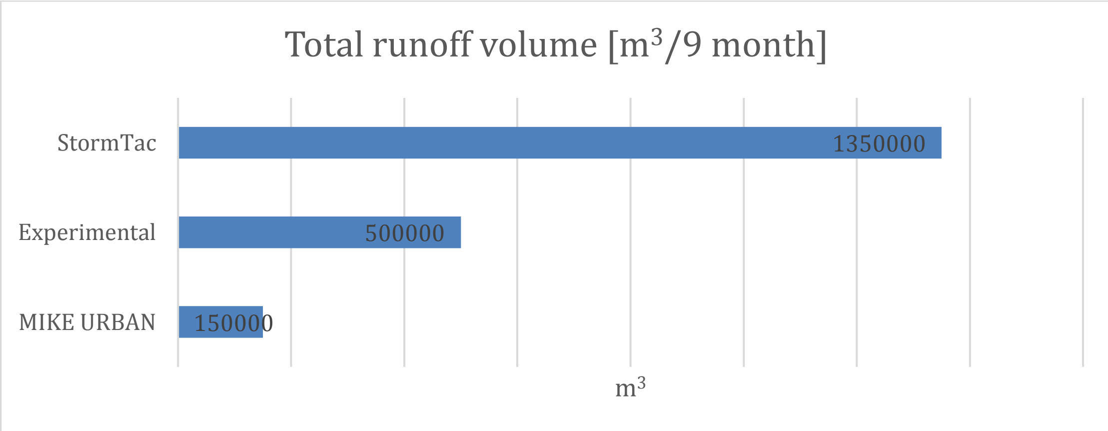

Figure 8. *Total runoff volume estimated from experimental measurements and simulations in StormTac and MIKE URBAN within a 9-month period.*

The measured volume from the study by Pettersson (1999) was based on water flows at the inlet to the stormwater pond. However, the flow into the pond only accounts for part of the total runoff from the catchment surface. The pond inlet is designed for a maximum flow of 700 L/s. Pettersson (1999) used the MOUSE calculation engine to estimate the annual volume overflow (Table 13). This overflow counts for 23 % of the total runoff volume.

Table 13. *Annual runoff volume [m^3] measured in Pettersson's study, simulated annual overflow and simulated annual runoff volume in StormTac.*

	StormTac	Simulated overflow by MOUSE	Experimental measured volume into the pond	Experimental, measured volume into the pond+ simulated overflow
12-month period	1,800,000			
9-month period	1,350,000	113,800	378,700	492,500

What distinguishes the simulated values in StormTac and MIKE URBAN compared to the measured values is partly due to the different procedures used for calculating them. The simulated values are based on theoretical methods, while the measured values are based on experimental methods. According to a study about uncertainties in water flow measurement by Dias, Dalfré Filho & de Lucca (2013) there are essentially three types of errors when measure water flow: (i) random errors, (ii) systematic errors and (iii) spurious errors caused either by errors in the device or by human errors. This study also concludes that random errors in flow meters based on velocity constantly increase with an increased velocity (Dias et al., 2013). Uncertainty in model input data may also be an explanation why the simulated values deviate from actual values. For instance, the reduced area for simulations performed in MIKE URBAN and StormTac was calculated to 259 ha. This automatically calculated reduced area is 38 % higher than the impervious area estimated by Pettersson (1999). The method Pettersson used for estimating the impervious area is not stated in the Phd thesis. However, the reduced area calculated in MIKE URBAN and StormTac is based on the total catchment area and runoff coefficients. It is also likely that the reduced area has changed since 1997/98.

The rainfall can deviate depending on location. The rainfall data used in MIKE URBAN was taken from SMHI. This data was measured approximately 8 km away from the study area (Google maps, 2019). The rainfall data used in Pettersson's study was measured in direct connection to the Järnbrott pond. Rainfall data used in StormTac was based on Pettersson's monitoring data. In StormTac the rain is expressed as annual average rainfall depth, whereas in MIKE URBAN the rainfall is expressed in time series of daily rainfall depth.

6.2.2. Stormwater quality simulations

In Table 15, annual EMC´s simulated in StormTac are listed. The differences in EMC between the land-use areas are presented in the table. In the rightmost column, experimental values from the study by Pettersson (1999) are listed. The values within the parenthesis presents the minimum and maximum measured values.

Table 15. *Annual EMC [µg/L] simulated in StormTac, including values for the total catchment area and for each land-use category. Experimental average EMC [µg/L] from Pettersson (1999) are listed in the rightmost column. (Minimum and maximum values are presented within the parenthesis)*

	Forest	Single-family housing	Road	Industry	Residential	Total	Experi-mental
TSS	34,000	45,000	130,000	80,000	70,000	76,000	55,000 *(6300-820,000)*
N	450	1,400	1,600	1,600	2,400	1,600	2,000 *(630-5,300)*
P	17.0	200	220	290	300	280	70.0 *(20-560)*
Zn	15.0	80.0	240	210	100	140	120 *(42-520)*
Cu	6.50	20.0	49.0	35.0	30.0	32.0	53.0 *(16-210)*
Pb	6.00	10.0	25.0	25.0	15.0	19.0	13.0 *(2.10-77)*
Cd	0.20	0.50	0.48	1.10	0.70	0.79	0.55 *(0.15-1.30)*

The total EMC for TSS, N and metals in StormTac are rather close to the average experimental EMC´s. For TSS, Zn, Cd and Pb, the simulated EMC´s are higher compared to average experimental EMC´s, whereas Cu and N are lower. Since simulated EMC´s are both higher and lower compared to measured EMC´s, random errors may explain the variations. Uncertainties in both experimental and simulated EMC´s exist. There is no analytical method that can measure exact concentrations. Uncertainties in experimental measured EMC´s are for instance sampling errors. The accuracy of analytical measurements depends on many different parameters: e.g. how the sample is taken and transportation and pre-treatment of the sample. In addition, it can also exist matrix effects in a sample and uncertainties within the analytical devices exists (De Bievré & Günsler, 2003). Simulated EMC´s in StormTac are based on stormwater quantity and standard concentrations from previous experimental and theoretical studies. Uncertainties in stormwater quantity has been discussed in the previous section and regarding the standard concentrations, measurement uncertainties exists (StormTac, n.d.). In Table 8, certainty classification for all standard concentrations used in this study are stated. Only five out of 35 standard concentrations are of high certainty. Standard concentrations for TSS and P from roads, P and N from single-family housing and P and N from residential areas are assessed to have high certainty. 13 standard concentrations are of low certainty, all pollutants from industrial areas, TSS, Cu, Zn, Cd and P from forest and TSS from single-family housing.

EMC of P differs much between the simulated and experimental values. StormTac simulate four times higher EMC of P than the measured EMC. All land-use categories within this study area has standard concentrations between 200-300 µg/L except the forest area which have a standard concentration of 17 µg/L (see Table 8). According to the Swedish environmental protection agency, agricultural land was the major source of P in Sweden, counted for the years 1995-2000. It contributes to 49 % of the P emissions to water. Stormwater was estimated to account for only 4 % of the emissions of P to water (Naturvårdsverket, 2004). Agricultural land is given the standard concentration of 220 µg/L in the StormTacs database. With agriculture as reference, the standard concentrations of the land-use categories within this case study seems too high. For instance, the industry accounted for 11 % of the emissions of P (Naturvårdsverket, 2004), yet the industry is given a standard concentration of 290 µg/L in StormTac, i.e. 70 µg/L higher than agricultural land. It is not stated though from where the 4 % of the P in stormwater are from. If the contaminated water from agriculture would consist mostly of other than stormwater while the majority of contaminated water from industries would consist mostly of stormwater, the source distribution of P in stormwater could deviate from the distribution presented above. However, it can be assumed that large part of the contaminated water from agricultural areas consists of stormwater. Agricultural land is often open to the atmosphere and the runoff can therefore exist of i.e. precipitation and irrigation water, while polluted water from industries largely consists of wastewater.

The stormwater quality results from StormTac can, in addition to only determining the total EMC from a catchment area, be used to obtain the most problematic land-use area regarding the stormwater pollution within a defined study area. The percental contribution of a pollutant per land-use area can be investigated in order to obtain how much each land-use category contributes to the highest pollutant concentration. This procedure has been applied to Cu to serve as an example. The percental contribution of Cu due to the land-use area (% per land use area) from this study is shown in Figure 9.

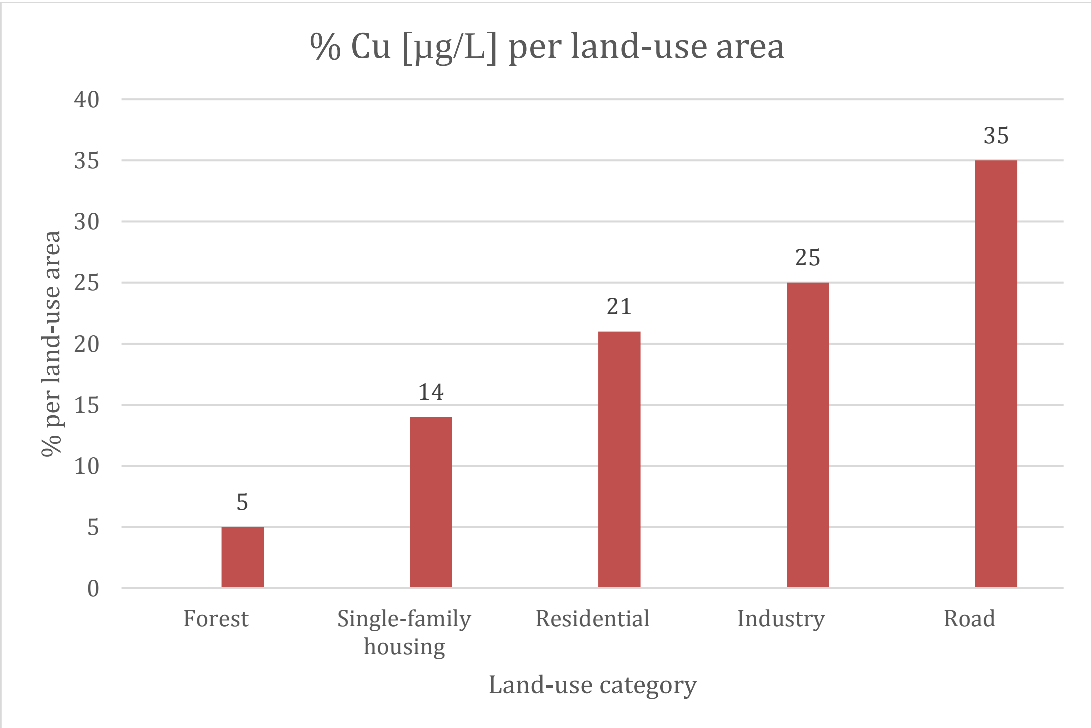

Figure 9. *The contribution of the land-use areas to the concentration of Cu within the total catchment area.*

It can be seen from Figure 9 that the biggest source of Cu within the study area is the road. Even though the small share of the road compared to the other land-use areas are considered, the road is still the largest source of Cu. This could be explained both due to the high standard concentrations of Cu on roads and by the high imperviousness of asphalt. According to the Swedish Environmental Protection Agency, it is in fact true that the largest source of Cu in nature comes from road traffic (Naturvårdsverket, 2018). The biggest reason why traffic emits Cu is because brake linings in vehicles are often plated with Cu (Naturvårdsverket, 2018).

The EMC´s simulated in MIKE URBAN are listed in Table 16. TSS is the only substance that has been simulated in MIKE URBAN. Input data for the other pollutants has not been found. EMC of TSS is estimated based on total washed off mass of TSS divided by the total runoff volume, for the two time periods. EMC of TSS for the whole period is estimated based on total washed-off mass of TSS divided by the total runoff volume from period 1 and period 2. In Appendix 1, the calculation procedure of converting the outputs in MIKE URBAN to its corresponding EMC is provided.

Table 16. *EMC of TSS [µg/L] simulated in MIKE URBAN. Experimental average EMC [µg/L] from Pettersson (1999) are listed in the rightmost column. (Minimum and maximum values are presented within the parenthesis)*

	Forest	**Single-family housing**	**Road**	**Industry**	**Residen-tial**	**Total**	**Experi-mental**
Total EMC	167,000	167,000	167,000	167,000	167,000	167,000	55,000 *(6300-820,000)*
EMC Period 1	158,000	158,000	158,000	158,000	158,000	158,000	
EMC Period 2	184,000	184,000	184,000	184,000	184,000	184,000	

Since the input parameters for the build-up and wash-off processes are not land-use specific, the EMC is equal for all land-use categories. This is a rough simplification of the reality. For instance, the sediment build-up rates obtained in the study by Chow et. al. (2012) differentiate with a factor of 7 between residential and urban areas. According to a compilation in the "Minnesota stormwater manual", land-use categories highly affects the concentration of TSS (Minnesota stormwater manual, n.d.).

What affects EMC in the SRQ-module in MIKE URBAN is, for instance, the length of the ADWP. This parameter differs between period 1 and period 2. The washed off stormwater volume also affects the concentrations of pollutants. Table 16 shows that EMC is higher in period 2 (184 mg/L) than in period 1 (158 mg/L). Period 1 consists of an average of 3.2 dry days whereases period 2 consists of an average of 3.1 dry days. With longer ADWP, the TSS had a longer time for the build-up process and the particle mass would, therefore, be greater compared to a rainfall event with a lower ADWP. In this case, however, the average rainfall intensity is also lower in period 2 than in period 1. With lower rainfall intensity, the generated stormwater volume will consequently be smaller and therefore the mass of TSS per volume of stormwater is higher in period 2 than in period 1, despite the lower ADWP.

In Figure 10, the total mass of TSS washed off by stormwater is illustrated. Each coloured line represents the wash-off from one of the individual sub-catchments included in the model. The zoom-in shows the different steps of dry and wet periods. At dry weather periods, there is no stormwater that can transport substances and hence the slope is zero during those periods. During rainfall events, the total washed off mass increases constantly until the next dry period.

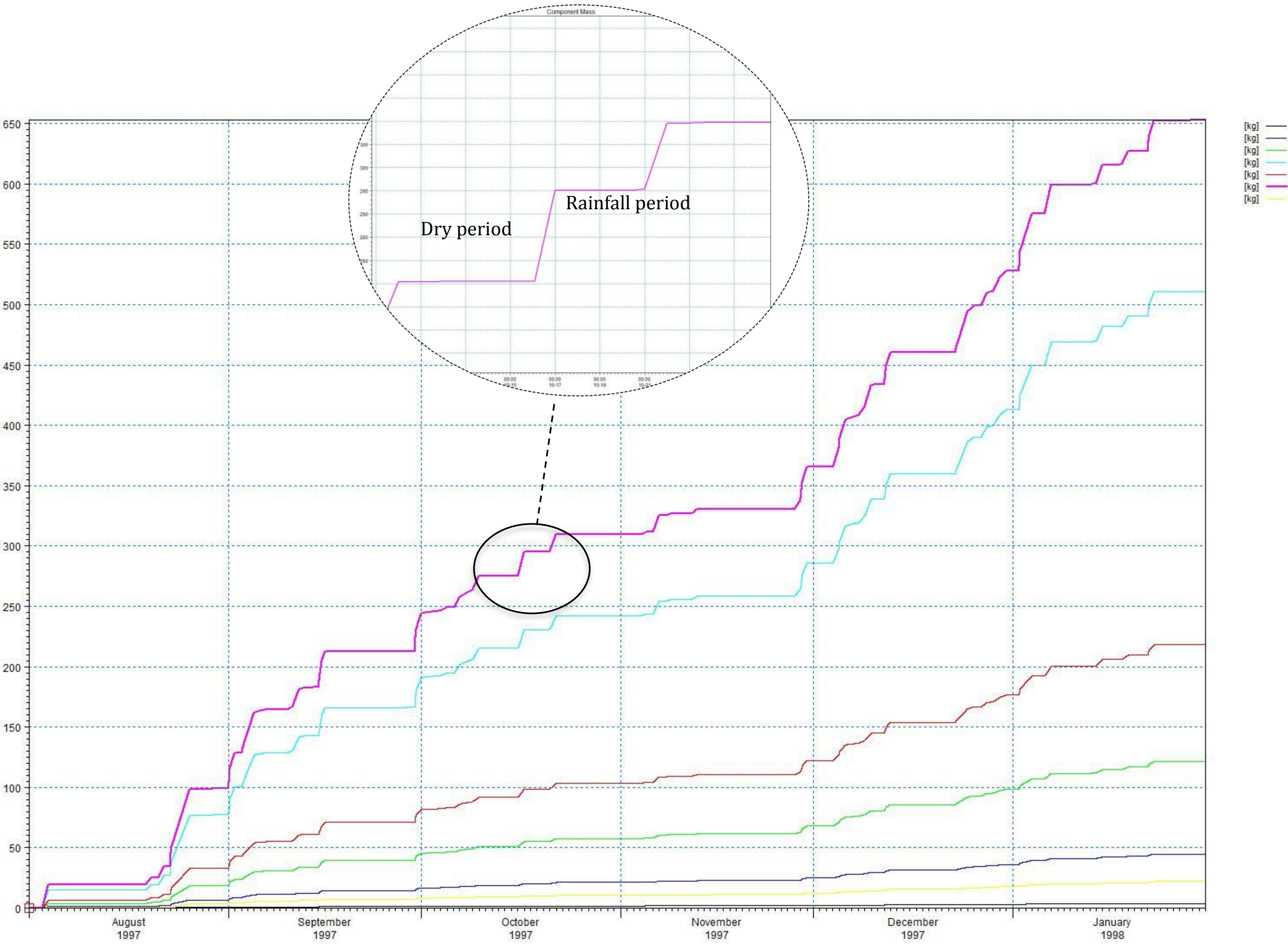

Figure 10. *Total mass of TSS washed off by stormwater, expressed as (kg TSS/time and land use area). (-Forest1 -Forest2 -Highway -Industry -Residential1 -Residential2 -Single-family housing)*

The comparison between StormTac, MIKE URBAN and experimental measured EMC of TSS can be seen in Figure 11. The EMC estimated in StormTac is around 1.4 times higher than the experimental concentrations, whereas the EMC estimated in MIKE URBAN is around 3.1 times higher.

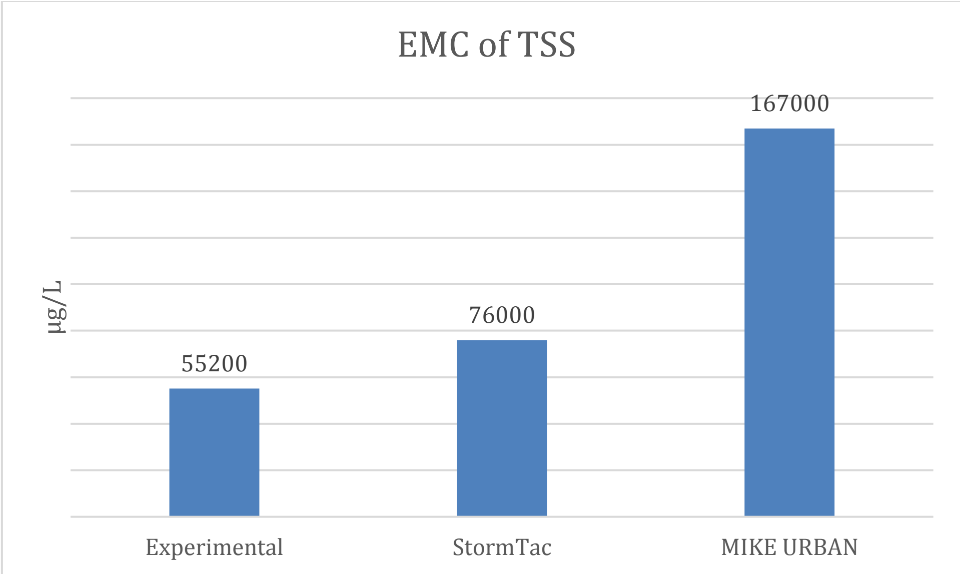

Figure 11. *EMC of TSS from experimental and modelled measurements in StormTac and MIKE URBAN.*

6.3. Suggested model improvements

Based on the performed literature review and the case study results, some model improvement for MIKE URBAN and StormTac are suggested.

6.3.1. Improvements of stormwater quantity simulations

The reduced area estimated in MIKE URBAN and StormTac largely deviates from the reduced area estimated in the study by Pettersson (1999). It is not stated though in the Phd thesis by Pettersson how the reduced area was estimated. The difference between the reduced areas could be due to calculation of the total catchment area and the delineation of the sub-catchment areas. The difference can also be due to the estimation of the imperviousness and the runoff generation. The delineation process has been manually proceeded in this case study. However, this process can be done automatically in MIKE URBAN. It should be highly recommended to perform the delineation process automatically since this procedure would generate more precise delineation of the catchment area.

Both MIKE URBAN and StormTac recommends using runoff coefficients from Svenskt Vatten, P110. Since the runoff coefficients highly affects the reduced area, those parameters should be given adequate attention. A study performed by Chen, Krajewski, Helmers & Zhang, investigated “spatial variability and temporal persistence of event runoff Coefficients for cropland hillslopes” and found that the input parameter that gives rise to the highest runoff coefficient variability was the slope. It is possible to specify the slope in both MIKE URBAN and in StormTac. This parameter should, however, be given higher attention. Currently, it is not obligatory to specify the slope in either MIKE URBAN nor in StomrTac. Runoff coefficients around 0.48 in the study by Chen et al. had the highest standard deviation. It was also found that the coefficient of variability decreases as the runoff coefficient increases. According to this finding, it should be recommended to pay extra attention to runoff coefficients with a value around 0.48 or lower. It should be stated though that the study by Chen et al. are only valid for arable land-uses. On the other hand, the findings from this study should spread light on the importance to investigate the variability of runoff coefficients.

The only input parameter that differ between the stormwater quantity simulations performed in MIKE URBAN and StormTac in this case study was the rainfall. The simulated total runoff volume differentiates much between those models and therefore this input parameter should be paid special attention. The rainfall data should be measured in direct connection to the study area since the rainfall is highly dependent on the spatial location (SMHI, n.d.).

6.3.2. Improvements of stormwater quality simulations

The standard concentrations in StormTac are constantly updated as new reliable monitoring data are available (StomTac, n.d.). This is needed since there is only few standard concentrations that have been classified with high certainty in StormTacs database. The EMC of P in this case study deviate much from the monitoring data and therefore the standard concentrations for this pollutant is specially recommended to be investigated.

The sediment build-up rate in MIKE URBAN is currently not possible to be land-use specific. Since it has been shown in previous studies that the sediment build-up rate vary depending on land-use area and geographical location (Chow et al., 2012), this feature should be included in the model. The build-up rate of other pollutants in MIKE URBAN is only estimated based on the PSR. The PSR can only simulate the amount of transported pollutants. To describe the build-up of pollutants, other than sediments, a land-use based method or pollutant source-based method should also be included in the SRQ module of MIKE URBAN.

7. Conclusions and recommendations

Four different methods for simulating stormwater quality are available: (i) Land-use based method, (ii) Physical process-based method (iii) Pollutant source-based method and (iv) the Regression method. There are essentially three different parts that distinguishing the different methods from each other: (i) how to express the rainfall, (ii) how to simulate stormwater quantity and (iii) how to simulate stormwater quality. The simulations can vary on several different aspects. For example, mathematical approach, spatial representation and description over time varies between the different methods.

When compared to measured volume from monitoring data, the simulated runoff volume estimated in MIKE URBAN is approximately three times lower, whereas the simulated runoff volume in StormTac is around three times higher. EMC´s simulated in StormTac are within the measured interval for all compounds included in the case study. The EMC of TSS simulated in MIKE URBAN is close to the maximum measured EMC.

There are some suggestions given to improve StormTac and MIKE URBAN, based on this study. It is important to continue to update the standard concentrations in StormTac since the certainty classification is low for many of the included substances and land use categories. The delineation process of the catchment area should be recommended to be automatically performed. It should also be recommended to specify the slope of the area, since this is the parameter that affect the runoff coefficient the most. Finally, the sediment build-up rate in MIKE URBAN should be land-use specific.

Based on the comparison and evaluation of StormTac and MIKE URBAN in this study, StormTac is recommended for simulating long-term EMC´s of pollutants. StormTac is much more user friendly and, at least for TSS, this model simulates EMC closer to measured data. If single rainfall events are to be simulated, StormTac can, however, not be used. Acute effects can, for instance, not be investigated in StormTac.

7.1. Recommendations for future research

In future research, it would be interesting to apply this case study to stormwater models based on the pollution source method and the regression method in order to compare also these two quality methods with monitoring data. It would also be valuable to study dissolved and bioavailable pollutants in stormwater more frequently. This part of stormwater pollution is the most problematic considering acute toxic effects on living organisms. In StormTac, for instance, dissolved pollutants are currently not possible to simulate. There are some data for dissolved pollutants included in the database of StormTac. Still, more monitoring data is needed to ensure reliable modelling results.

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Appendix

Appendix 1 - Calculation of EMC of TSS from the results in MIKE URBAN

The results from MIKE URBAN can be presented in for of time series of, e.g. volume of stormwater that run off from each land-use per second and mass of TSS that is washed off from each land-use area per second. From these time series, total runoff volume and washed off TSS for the whole period and the whole catchment area was measured. The EMC was then calculated according to equation A1:

$$EMC = \frac{m(tot)}{V(tot)} \tag{A1}$$

All included parameter values for the calculation of EMC of TSS are listed together with resulting EMC in Table A1.

Table A1. *Total runoff volume and total washed-off TSS simulated in MIE URBAN. EMC of TSS calculated according to equation A1.*

	Forest 1	Forest 2	Highway	Industrial	Residential 1	Residential 2	Single-family housing	Total catchment
Period 1								
Total runoff volume [m^3/yr]	39.79	472.4	512.2	5393	2304	7698	232.1	16650
Total washed off TSS [kg/yr]	6.283	74.59	80.87	851.7	363.8	1215	36.65	2629
EMC [µg/L]								157898
Period 2								
Total runoff volume [m^3/yr]	19.60	232.6	252.2	2656	1135	3791	114.3	8201
Total washed off TSS [kg/yr]	3.609	42.85	46.45	489.2	209.0	698.1	21.05	1510
EMC [µg/L]								184141
Period 1+ Period 2								
Total runoff volume [m^3]								150000
Total washed off TSS [kg]								25000
EMC [µg/L]								167000