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Stormwater modelling tools

a comparison and evaluation

Johanna Lind

Abstract

Stormwater modelling tools – a comparison and evaluation

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Stormwater is rain, melt and rinse water that temporarily runs off the ground surface. In cities with many impermeable surfaces large amounts of stormwater may be formed. Stormwater is diverted through conduits and ditches to recipients. If the diversion of stormwater is insufficient flooding can occur. Stormwater contains contaminants from the catchment surfaces such as nutrients, heavy metals, bacteria, organic compounds and oils. To study stormwater pollution and flows various stormwater modelling tools are used. The purpose of this thesis is to test, compare and evaluate four stormwater modelling tools and conclude their strengths and weaknesses. This was done by a literature study, a market research, definition of evaluation criteria and by testing the tools on a case study of an industrial and residential area in Scotland. The main developed evaluation criteria was model characteristics, required input, user friendliness, output and model application.

The four selected tools were StormTac, Infoworks CS, SuDS Studio and MUSIC. The case study included both flow and pollutants on a yearly basis and for a rainfall event. The results from the study were compared against observed values both before and after calibration. No model gave good model predictions for all parameters. The observed volumes of water were larger than modelled for all four models even after calibration. An intercomparison between the models however gave a better fit. Regarding pollutants, the model predictions compared with observed values varied between the tools and substances.

Strengths with StormTac are that it includes over 70 pollutants, includes the recipient and gave good model predictions for pollutant concentrations when compared with observed pollutants. A weakness is that StormTacs automatically calculated base flow was much smaller than observed in the case study and the tool is not suited for studies of single event rainfalls. Strengths with Infoworks CS are that it is fully distributed, a complete network is built up and the tool can be used for design of networks, flood predictions and flows over time. It is time consuming to build a model in Infoworks CS, few default pollutants are included and it gave poor model predictions for nitrogen concentrations in the case study. SuDS Studio is a unique tool for defining suitable options for retrofitting SuDS solutions and this is a strength as it is the only tool of its kind. SuDS studio gave large intervals for pollutant loads in the case study which can be difficult to interpret. A strength with MUSIC is that it is user friendly and can be used for comparing water quality pre and post treatment. It does however only include three default pollutants in the model, and only three pollutants can be modelled at a time.

Keywords: Stormwater modelling, StormTac, Infoworks CS, SuDS Studio, MUSIC

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Referat
Dagvattenmodelleringsverktyg – en jämförelse och utvärdering

Johanna Lind

Dagvatten är regn-, smält och spolvatten som tillfälligt avrinner på markytan. I städer med många hårdgjorda ytor kan stora mängder dagvatten bildas. Dagvatten avleds via ledningar och diken ut till recipient. Om avledandet av dagvatten inte är tillräckligt bra kan översvämning ske. Dagvatten innehåller föroreningar från de ytor de avrinner på som exempelvis näringsämnen, tungmetaller, bakterier, organiska föreningar och oljor. För att studera dagvattenföroreningar och flöden kan dagvattenmodelleringsverktyg användas. Syftet med arbetet var att testa, analyser och utvärdera fyra olika dagvattenmodelleringsverktyg samt bestämma verktygens styrkor och svagheter. Det gjordes genom en litteraturstudie, en marknadsanalys av dagvattenmodelleringsverktyg, definition av utvärderingskriterier samt modellering av en fallstudie med fyra valda verktyg från marknadsundersökningen. De fem framtagna huvudkriterierna var: modellegenskaper, nödvändig input, användarvänlighet, output och användningsområden.

De fyra valda verktygen är StormTac, Infoworks CS, SuDS Studio och MUSIC. Fallstudien utfördes för ett industri- och bostadsområde i Skottland och inkluderade både flöden och föroreningar på årsbasis och för ett specifikt regnfall. Resultaten jämfördes även med uppmätta data för kunna utvärdera modellernas prediktioner. Inget av de fyra verktygen gav bra prediktioner för samtliga parametrar. De uppmätta volymerna vatten var högre än modellerade volymer för samtliga modeller men modellerna gav en god överensstämmelse sinsemellan. För föroreningar varierade modellprediktionerna för de olika verktygen och substanserna.

Styrkor med StormTac är att det innehåller över 70 föroreningar, är användarvänligt, kräver få input data, gav god överensstämmelse med föroreningskoncentrationer i fallstudien på årsbasis samt inkluderar recipienten. StormTac är däremot ej lämpat för modellering av enstaka regnfall och dess automatiska beräkning av basflöde var mycket lägre än observerade basflöden. Infoworks CS styrkor är att ett komplett nätverk byggs i modellen och modellen kan användas för design, översvämningsstudier samt flöden över tid. Det är dock tidskrävande att bygga upp en modell i Infoworks CS, få föroreningar är inkluderade i modellen och Infoworks CS gav dåliga modellprediktioner för kvävekoncentrationer i fallstudien. SuDS Studio är unikt i sitt slag som verktyg för att identifiera platser för SuDS- lösningar då inget motsvarande verktyg finns. För fallstudien gav verktyget föroreningsmängder i stora intervall vilket kan göra resultaten svårtolkade. MUSIC har styrkan att det är användarvänligt och kan användas för studier av skillnader före och efter rening. MUSIC har dock endast tre föroreningar inkluderade i modellen och det går endast att modellera tre föroreningar i taget.

Nyckelord: Dagvattenmodellering, StormTac, Infoworks CS, SuDS Studio, MUSIC

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Preface

The MSc Thesis *Stormwater modelling tools – a comparison and evaluation* has been carried out as a finishing part of the Master Programme in Environmental and Water Engineering at Uppsala University. The thesis comprises 30 credits and was done at Atkins Sweden AB under the supervision of Denis Van Moeffaert. Subject reviewer at Uppsala University was Thomas Grabs - Senior lecturer at the Department of Earth Sciences, Program for Air, Water and Landscape Sciences. Examiner for the Master thesis was Fritjof Fagerlund- Senior lecturer at the Department of Earth Sciences, Program for Air, Water and Landscape Sciences.

I would like to express my gratitude to everyone who has supported me. First, I want to say thank you to my supervisor Denis at Atkins for the dedication, support, guidance and valuable suggestions. It has been a tremendous help. I would also like to express my appreciation to my subject reviewer Thomas for all your time, help and valuable advice and comments. I am very grateful for this.

Many thanks to Neil, Zorica and Tony for all the help and answers to my many questions about the software and about modeling. To the Väg, Gata & VA-group at Atkins, and the rest of the Nacka Strand office I want to say thank you for an enjoyable time at the office. I would also like to thank Thomas Larm for help and advice regarding StormTac.

Johanna Lind
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Popular Scientific Summary

A majority of the earth's population lives in cities and the urbanization is expected to keep increasing. The requirements for a functioning water and sewage supply in cities will therefore become even more important in the future. Stormwater is rain, melt and rinse water that cannot infiltrate into the ground and instead runs off on the ground surface. In cities, a large part of the land consists of impermeable surfaces such as roads, parking lots and roofs that prevent water from infiltrating into the ground and large amounts of stormwater can be formed. With growing cities more roads, parking lots and buildings are built and this will increase the amount of stormwater. Stormwater is discharged into lakes, oceans or other bodies of water through for example pipe networks or ditches. Flooding can occur if the disposal of stormwater is insufficient which may cause leakage from the waste water system as well as water filled basements and other property damages. Stormwater contains pollutants from the land surfaces it passes during its transportation to water bodies. These pollutants can come from e.g. traffic pollutions, atmospheric deposition, oil from vehicles, zink from roofs. When the pollutants follow the stormwater to lakes or the ocean it has a negative impact on the water environment.

To avoid flooding and high concentrations of pollutants in water bodies there is a need to study quantity and quality of stormwater. To do this computer-based stormwater modelling tools are being used for example by researchers, engineers and city planners. Today, there exists hundreds of computer-based stormwater modelling tools that are designed in different ways and have different objectives. They are therefore also suitable for different type of studies.

The objective in this thesis was to compare and evaluate four stormwater modelling tools with respect to different criteria such as the user friendliness, the field of application, the needed input data and quality of the results and conclude their strengths and weaknesses. A market research was done over stormwater modelling tools used worldwide. From this market research the four tools; StormTac, Infoworks CS, SuDS Studio and MUSIC were chosen for a more detailed analysis. To compare and evaluate the models, each model was set up for the same study area. The study area was an industrial and residential area in Scotland that drains to a small watercourse through a pipe system. Flows, volumes of water and the amount of pollutants simulated with the four modelling tools were studied and compared. The results from each tool were also compared to measured data for flows and pollutant concentrations to see how well the models portray reality. No model gave good model predictions compared with the measured data for all parameters. The observed volumes of water were larger than modelled for all four models. StormTac gave the best model predictions for pollutant concentrations.

The final selection of a certain model highly depends on the scope of the study. StormTac is suitable for studies of pollutants and flows on a long term basis, treatment facilities and water quality in the receiving waters. It was considered as a user friendly tool that required few input data to build a model and gave a good model predictions for the stormwater pollutants in the case study. Infoworks CS was considered to be the suitable choice for studying flooding and designing networks but was time demanding to use as the implementation of the model was more complex and required many input data. SuDS studio was the only tool that can be used for defining options for sustainable urban drainage systems. As of 2013 no other similar tools existed.

MUSIC was considered user friendly, had a short learning period and could study pre and post treatment quality of the water. MUSIC should not be used for detailed design.

Populärvetenskaplig sammanfattning

En majoritet av jordens befolkning bor i städer och urbanisationen förväntas fortsätta öka. Kraven på funktionerande vatten- och avloppslösningar i städer kommer därför att bli än viktigare i framtiden. Dagvatten är regn-, smält- och spolvatten som ej kan infiltrera i marken och istället avrinner på markytan. I städer finns stora mängder hårdgjorda ytor såsom vägar, parkeringsplatser och tak som förhindrar att vattnet infiltrerar i marken och istället kan stora mängder dagvatten bildas. Med växande städer kommer fler vägar, parkeringar och byggnader att byggas och mängden dagvatten kommer därmed att öka.

Dagvatten avleds till sjöar, hav och andra vattendrag genom till exempel ledningar eller diken. Om avledningen av dagvattnet är otillräcklig eller feldimensionerad kan översvämningar ske med läckage från avloppssystem, vattenfyllda källare och andra skador på byggnader som följd. Dagvatten innehåller föroreningar som det får med sig från de ytor det passerar under sin väg till ett vattendrag. Föroreningarna kommer exempelvis från trafik, atmosfärisk deposition, olja från fordon och zink från tak. När föroreningarna följer med dagvattnet till vattendraget, sjön eller havet kan det ha en negativ påverkan på vattenmiljön.

För att undvika översvämningar och höga koncentrationer av föroreningar i vattendrag finns ett behov av att kunna studera dagvattenkvantitet och dagvattenkvalitet. För att göra det används databaserade dagvattenmodelleringsverktyg av forskare, ingenjörer och stadsplanerare. Idag finns det ett hundratal databaserade verktyg som är designade på olika sätt och har olika layout och fokus. Därför lämpar sig de olika verktygen också för olika typer av studier.

Målet med det här examensarbetet var att jämföra och utvärdera fyra dagvattenmodelleringsverktyg utifrån kriterier såsom användarvänlighet, användningsområde, nödvändig indata och kvalitet på resultat samt att dra slutsatser angående verktygens styrkor och svagheter. En marknadsundersökning utfördes över dagvattenmodelleringsverktyg som används i världen. Från marknadsundersökningen valdes fyra verktyg ut för en mer detaljerad analys; StormTac, Infoworks CS, SuDS Studio och MUSIC. För att jämföra och utvärdera verktygen användes varje modelleringsverktyg för att modellera en och samma fallstudie. Området som modellerades i fallstudien var ett industri- och bostadsområde i Skottland som avleds till ett litet vattendrag via ett ledningssystem. Resultaten från simuleringarna i form av flöden, volymer av vatten, föroreningsmängder och föroreningshalter studerades och utvärderades. Resultaten från varje verktyg jämfördes även med uppmätta data för flöden och föroreningskoncentrationer för att se hur bra modellerna överensstämde med verkligheten.

Val av modelleringsverktyg för en studie kommer att vara helt beroende av syftet för studien. Inget av verktygen gav goda resultat för samtliga parametrar vid jämförelsen med uppmätta data. Observerade volymer vatten var större än modellerat för alla fyra modeller.

StormTac var det verktyg som gav bäst förutsägelser för föroreningskoncentrationer. StormTac är passande för studier av föroreningar och flöden på lång sikt och ej för att studera en specifik regnhändelse. Det kan användas för studier av olika reningsanläggningar samt vattenkvalitet i mottagande vattendrag. StormTac bedömdes som ett användarvänligt verktyg som krävde lite indata för att bygga en modell och gav också bra resultat för dagvattenföroreningar i fallstudien. Infoworks CS bedömdes vara ett passande val av verktyg för att studera översvämningar och för att designa ledningsnät. Det var tidskrävande att implementera området i verktyget då det krävdes mycket indata för att bygga upp modellen. SuDS studio var det enda verktyget som kan användas för att identifiera områden för lämpliga hållbara urbana dräneringssystem, så kallades SuDS-lösningar (sustainable urban drainage systems). År 2013 existerade det inga andra sådana verktyg. MUSIC ansågs vara användarvänligt, hade kort inlärningsperiod och kan användas för att studera vattenkvalitet före och efter rening. MUSIC bedömdes ej vara ett lämpligt verktyg för detaljerad design av anläggningar och system.

Vocabulary

Stormwater	Rain, melt and rinse water that cannot infiltrate into the ground and instead runs off on the ground surface
Wastewater	Water from toilets, showers and washing machines.
Sewer	Conduits for diverting stormwater and/or wastewater
Combined sewers	Sewers with both stormwater and wastewater diverted in the same pipes
Recipient	The receiving waterbody
Catchment	The land area whose water drains into a particular watercourse
Time of concentration	The maximum time taken for a raindrop that falls farthest away in a catchment area to drain to the outlet point. The time of concentration depends on the distance and the water velocity
SWO	Stormwater Outlet
Invert levels	Inner bottom line of the pipes in the pipe networks.
Invert depths	The distance from the ground level and down to the bottom line of the pipe.
SuDS	Sustainable drainage systems such as for example permeable pavings, ponds and green roofs.
STF	Stormwater Treatment Facility
MUSIC	Model for Urban Stormwater Improvement Conceptualization
Infoworks CS	Infoworks Collection Systems

Table of contents

1 Introduction

1.1 Background

Water and sanitation is an essential part of a functioning society. Today, for the first time, a majority of the earth’s population live in cities. Urbanization is expected to keep increasing and in 2050 it is predicted that 70% of the earth's population will be living in cities. This means that the requirements for a functioning water and sewage supply in cities will become even more important in the future (World Health Organization, 2014.; Hellström, et al., 2013).

Stormwater is rain, melt or rinse water that temporarily runs off the ground surface (VA guiden AB, 2014). Stormwater is mainly formed by rainfall and snowmelt on surfaces where water cannot infiltrate into the ground and instead becomes surface runoff. In cities, a large part of the land consists of impervious surfaces like roads, parking lots and roofs. These impervious surfaces prevent water from infiltrating into the ground and large amounts of stormwater can be formed. Stormwater is diverted through pipes and ditches to water treatment plants, lakes, streams, oceans or other types of watercourses (Uppsala Vatten, 2014). Stormwater is diverted mainly in separate pipes or ditches. It can also be diverted in combined lines with wastewater and drainage water but it is not preferable (Svenskt Vatten AB, 2007).

If the disposal of stormwater is insufficient, flooding can occur with leakage from the waste water sewerage, water filled basements and property damage on buildings, power supply, infrastructure and sewerage systems as a result. Inundation often entails great economic costs. Some areas are more prone to flooding than others, and in those places, it is especially important to have a good stormwater management (Svenskt Vatten AB, 2007; SMHI, 2009). With larger and more densified cities, more stormwater can be formed and thus implies a greater demand for stormwater management.

Stormwater often contains pollutants from the surfaces it passes during an event. Pollutants can be nutrients, heavy metals, bacteria, organic compounds and oils. These contaminants may originate from for example traffic pollutions, sewage systems, atmospheric deposition and oil leakage from vehicles. (Larm, 2010). The pollutants are discharged to the recipients along with the stormwater. In the recipients they can cause a deterioration of the aquatic environment by having a toxic effect on plants and animals and contribute to eutrophication. Therefore, stormwater might need to undergo treatment before it is discharged into receiving waters. Treated means that some action is used to reduce the emission, and it can involve both preventative actions to reduce the source of the pollutant and direct actions like letting the stormwater pass through a wastewater treatment plant (Stockholm Vatten, 2001a).

Climate change will likely affect precipitation and snowmelt in the future, and most forecasts indicate that the amount of precipitation will increase. An increased amount of precipitation will give a larger amount of stormwater to seize and divert and this should be accounted for in stormwater planning (Svenskt Vatten AB, 2007).

There is a need to study and calculate stormwater quantity and stormwater quality. To do this stormwater models are being used. There exists both simple stormwater models, which can be used for manual calculations, as well as more advanced computer-based stormwater modelling tools. Computer-based hydraulic and hydrological modelling tools are used by engineers around the world to analyze, simulate and design storm water systems. Models are used to calculate and study changes in time and space and are a great way to test hypotheses and make predictions about the future (Beven, 2005). Modelling tools can help comparing the effectiveness of different stormwater scenarios in urban and regional planning.

Today, there exists hundreds of computer-based stormwater modelling tools to model stormwater quantity as well as stormwater quality. These modelling tools are constructed in various ways, require different input data and produce different output. Some modelling tools only include stormwater systems while others are more comprehensive and include other systems such as drinking water systems, wastewater systems, and river systems. Since the modelling tools are designed in different ways, they are also suitable for different fields of applications and different objectives. Which model that is appropriate to use depends on the type of problem the user is interested to solve or analyze (Beven, 2005; Zoppou, 2000).

1.2 Purpose and objective

The purpose of the MSc. Thesis has been to compare and evaluate currently used computer based stormwater modelling tools and their predictions of stormwater quantity and stormwater quality. For stormwater quality the modelling tools are evaluated from their predictions of Phosphorous (P), Nitrogen (N), Lead (Pb), Cupper (Cu), Zink (Zn), Cadmium (Cd), Chromium (Cr), Nickel (Ni), Mercury (Hg), Suspended solids (SS), Benso(a)pyrene (BaP) and oil from a mixed Industrial and Residential area in Scotland. The following milestones were set up to achieve this purpose.

- Conduct a market research to identify currently used stormwater modelling tools and select four tools for a more detailed comparison.
- Develop evaluation criteria that will be used to evaluate and compare the modelling tools and give a comprehensive picture of the tools strengths and weaknesses
- Test the four selected modelling tools on a case study. Make an intercomparison of the results and also compare the results with observed values for both stormwater quantity and quality.

The goal is to give clear recommendations regarding the modelling tools strengths and weaknesses based on the test, analysis, evaluation and comparison.

As computer based stormwater modelling tools are developed rapidly there is a need for a comparative study of currently used tools and the current state of the art in the field.

1.3 Limitations

Stormwater modelling tools often uses default values for many model parameters to calculate the loads and concentrations of pollutants in stormwater from different land use classes in a catchment. These default values can often be changed or adjusted depending on the area of the study. In this thesis the default values for the land use classes are used.

The numbers of predefined pollutants varies between the tools. In some modelling tools it is possible to define and implement more pollutants than the predefined ones. In this thesis only the default values for all pollutant parameters are used. When the tools are tested on their model predictions of water quantity, they are only evaluated from the predefined pollutants that have Swedish guidelines.

2 Theory

In this chapter general information regarding stormwater is presented with regards to catchment, pollutants, treatment, flows, disposal and general design criteria. The importance of stormwater management is also enlightened and the Swedish guidelines and European water framework directive is described.

2.1.1 Stormwater modelling and management Catchment area

Precipitated water that does not infiltrate in the ground or is intercepted by vegetation may become surface runoff (Ven Te Chow, 1988). Precipitation includes both liquid and solid water particles, such as rain, snow or hail.

When stormwater is formed as a result of rainfall or snowmelt it runs off to a recipient. The land area whose water drains into a particular watercourse is called the catchment of the watercourse (Hendriks, 2010). Principally all rainwater that rains into a catchment, which does not evaporate or is absorbed by plants, will eventually drain into the same watercourse (figure 1) (SMHI, 2009).The size of the catchment affects how much water will be present in the watercourse. Emissions of pollutants in the catchment area will likely have an impact on the recipient. Two catchments are separated by a water divide and a catchment can be divided into sub-catchments (SMHI, 2013).

Figure 1; A catchment area that drains to a recipient in the bottom right corner of the picture.

2.1.2 Importance of stormwater management

Development of natural areas and densification of cities increase the percentage of impervious surfaces and at the same time vegetation and permeable surfaces decrease which affect the natural water balance (Svenskt Vatten AB, 2004). In forested areas, often only a few percent of the precipitation becomes surface runoff, while in an urban area with a high proportion of impervious surfaces the surface runoff can be up to 80-90% of the precipitation (Adielsson, 2012). When rain falls over an urban area large amounts of stormwater are formed and the runoff occurs faster than for example in a forested area (figure 2) (Svenskt vatten AB, 2011a).

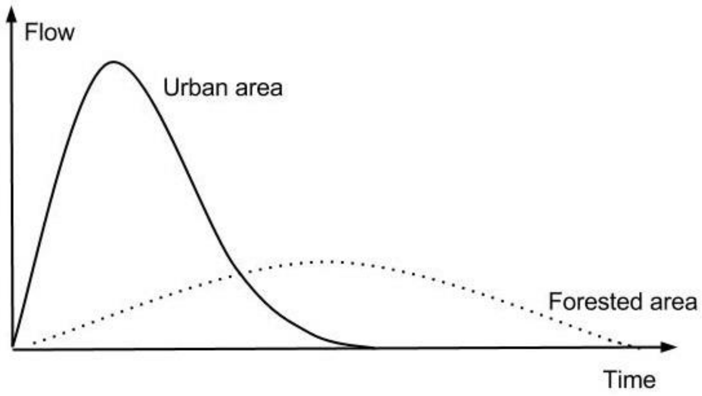

Figure 2; The difference in stormwater runoff between a rainfall in a forested and urban area. Modified from Svenskt Vattens publication M134 (Svenskt vatten AB, 2011a)

When developing or redeveloping an area it is therefore important for land use planning to investigate how the change might affect the stormwater flows and the stormwater quantity. An assessment can then be made regarding the capacity of the existing stormwater system and if the system is in need of an expansion or modification.

The amount of pollutants on the surfaces that the stormwater passes during the runoff will determine how much pollution the water will contain, and different surfaces can contain different amounts and types of pollutants. For example, a small country road with a small amount of traffic will contribute with less pollution than a highway with heavy traffic (Persson, et al., 2009). It is therefore also important to study how changes in land use in an area may affect the amount of pollutants in the stormwater.

2.1.3 Flows, pollutants and regulations

In Svenskt Vattens publication P90 (Svenskt Vatten AB, 2004) three functional requirements for storm sewers are presented.

1. The most vulnerable properties should not be affected by flooding more frequently than with a return period of 10 years. In a stormwater system that means that the hydraulic grade line in a service line shall not be higher than the ground surface, and in a combined system it may not be higher than the basement floor level more often than with a return period of 10 years.
2. The second functional requirement is that the risk of backflow should be minimal in dewatering.
3. Stormwater from polluted surfaces may need to undergo treatment before it reaches the recipient (Svenskt Vatten AB, 2004).

The sources of the pollutants are for example traffic, agriculture, leakage from the ground, long-range atmospheric deposition as well as roofs and other construction materials. In Stockholm, the greatest source for stormwater contaminants is traffic. Direct emissions from traffic can be suspended material from the road surface and oil from combustion in the engines. Indirect emissions are pollutants that reach the ground through atmospheric deposition, both dry and wet deposition. Long-range atmospheric deposition contributes to both metals and nutrient transport. Zinc and copper roofs contributes to metal contaminations in the stormwater when the roofs are corroding and thereby emitting copper and zinc to the water. In table 1, 12 substances that are common to find in stormwater and also have Swedish recommended guidelines (see section 2.1.4) are presented along with their main sources and the effects they can have on the environment. Traffic is one of the main sources for all of these 12 substances.

Table 1; Substances that are common to find in stormwater along with their main sources and the environmental effects (Stockholm Vatten, 2001; Jacobs, et al., 2009)

Substance	Main Sources	Environmental effects
Nutrients		
Phosphorus (P)	Traffic, Agriculture, Leakage from the ground.	Eutrophication of lakes
Nitrogen (N)	Traffic, Agriculture, Leakage from the ground. Atmospheric deposition (long-range)	Eutrophication of oceans and lakes
Metals		
Lead (Pb)	Traffic	Toxic for humans and animals
Copper (Cu)	Traffic, Roof and other construction material.	Toxic for aquatic animals and vegetation
Zink (Zn)	Traffic, Roof and other construction material.	Toxic in high concentrations for aquatic organisms
Cadmium (Cd)	Traffic, Roof and other construction material. Atmospheric deposition (long-range)	Very toxic and can prevent growth for aquatic vegetation
Chromium (Cr)	Traffic, Atmospheric deposition (long-range)	Carcinogen and toxic for animals
Nickel (Ni)	Traffic	Carcinogen and toxic for some animals and plants
Mercury (Hg)	Traffic	Toxic
Other substances		
Oil	Traffic	Toxic for aquatic animals and vegetation
Benso(a)pyrene (BaP)	Traffic	Carcinogen and can be bio accumulated
Suspended material (SS)	Traffic	Changes the turbidity and light and this can cause death for aquatic animals.

Stormwater pollutants can be in particulate form or attached to suspended solids. Metals are often found in dissolved form in the water as they for example corrode from roof surfaces. The greatest concentration of pollutants in stormwater usually occurs at the beginning of a rain and is called the "first flush" effect. The first flush effect assumes that pollutants have accumulated on the surfaces during dry periods and are washed off the surfaces in the beginning of the rainfall event (Stockholm Vatten, 2001a).

2.1.4 EU Water Framework Directive, Swedish guidelines and regulations

The countries in the European Union adopted the Water Framework Directive, WFD in 2000. The objective of the WFD is that all inland, coastal and groundwater should have good water status by 2015 with respect to both ecological and chemical status. The watercourses that do not achieve good status, have to be improved, and the watercourses that are already in good water status shall keep it. The directive includes a number of priority substances that are of significant risk to the aquatic environment. To reduce the presence of the substances included in the WFD, Sweden has Environmental Quality Standards, EQS. The EQS contain limits for the substances in surface water in form of maximum allowable concentrations and allowed yearly mean concentrations (Svenskt vatten AB, 2011a).

Today, there are no regulations for treatment of stormwater in Sweden. However, there are guidelines regarding pollutant concentrations in stormwater. These guidelines are usually expressed as maximum allowed yearly average concentrations and can not be compared directly to the EQS for surface waters. This is due to the fact that stormwater often contains much higher levels of pollutants than the recipient as there is dilution of the concentration of pollutants in the recipient (Larm, 2011). There are no national guidelines for stormwater pollutants (Alm, et al., 2010) but there are guidelines or guideline proposals for some counties in Sweden. *Regional stormwater network in Stockholm county* prepared a proposal in 2009 with guidelines for Stockholm county which includes 12 substances. These are the substances that will be included in the comparison between modelling tools in this thesis.

The guidelines for discharge to small lakes, watercourses and coastal bays are presented in table 2 where. For example, the concentration of phosphorous in stormwater that is discharged directly to a recipient shall, according to the guidelines, not exceed 160 µg/l. If it is not discharged straight to a recipient the guideline value shall not exceed 175 µg/l (Jacobs, et al., 2009). There are other guideline values for larger watercourses and discharge from operators, which can for example be discharged from an industrial area that is connected to a stormwater system but does not discharge straight to a recipient.

Table 2; Proposed guidelines for stormwater discharges to small watercourses from Regional Stormwater network in Stockholm county (Jacobs, et al., 2009).

	Small lakes, watercourses and coastal bay	
	Discharge directly into recipient	**Not discharged directly into recipient**
Substance		
P [µg/l]	160	175
N [mg/l]	2.0	2.5
Pb [µg/l]	8	10
Cu [µg/l]	18	30
Zn [µg/l]	75	90
Cd [µg/l]	0.4	0.5
Cr [µg/l]	10	15
Ni [µg/l]	15	30
Hg [µg/l]	0.03	0.07
Oil [mg/l]	0.4	0.7
BaP [µg/l]	0.03	0.07
SS [mg/l]	40	60

2.1.5 Stormwater treatment

If stormwater is discharged in a combined system it is treated along with the wastewater in treatment plants. This is not preferable since the volume water to the wastewater treatment plants will be very high during heavy rainfall events (Alingsås Kommun, 2013) and the effect of the treatment is reduced due to large amounts of water. During heavy rainfalls an excessive amount of water in the system can cause sewer overflows. When sewer overflows occur, a part of the water is often discharged straight to the recipient instead of passing through the treatment plant (Svenskt Vatten AB, 2004). Sewage water can contain bacteria, nutrients, hormones and heavy metals. When sewage water is diverted straight to recipients these substances are released to the environment where they can have a negative impact on humans or natural ecosystems (Länsstyrelsen Gävleborg, 2009).

If stormwater is discharged separately there is a need for a stormwater treatment method. Some examples of the most common treatment methods for stormwater are: sedimentation facilities, filters, wetlands, local disposal of stormwater solutions (see section 2.1.12) (Stockholm Vatten, 2001b).

2.1.6 Design of stormwater systems

Stormwater flows are usually presented in hydrographs showing how flows or water levels change over time. Hydrographs are often used to study the flow response to a rain in a stream or a conduit, see figure 3. The hydrograph shows the base flow, maximum flow, the time when the maximum flow occurs and the runoff volume. (Arnell, 1980; Ven Te Chow, 1988)

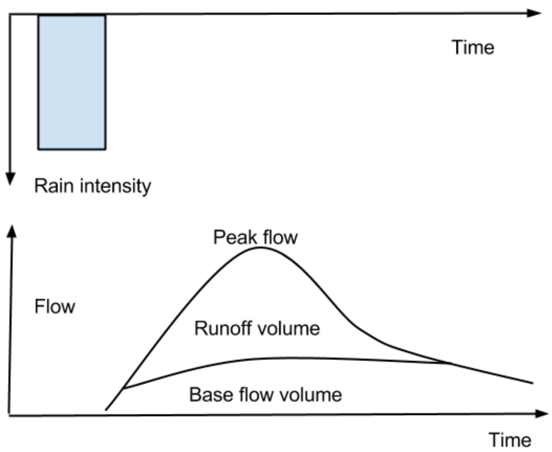

Figure 3; The runoff hydrograph from a rain including the base flow, peak flow and the runoff volume. Modified from (Arnell, 1980) and (Hendriks, 2010).

Base flow is the flow that does not occur as a result of a specific rain but is the underlying flow that mainly comes from subsurface flow (Beven, 2003). Some streams and pipes have a base flow all year around, while others only have a flow as a response to a given rainfall. (Hendriks, 2010).

The design flow is the flow that is used to design pipes and sewers and can be designed after a rain with a certain return period, see section 2.1.7 of rain (Svenskt Vatten AB, 2004).

2.1.7 Precipitation

When designing stormwater systems the return period, the duration and the rain intensity are of importance. The return period is how often a given rainfall, with a certain intensity and duration, recur. The return period of a rainfall is usually referred to as 1, 2, 10, 50 or 100-year rainfall. A

10-year rainfall returns on average 1 time in 10 years and a 100 - year rainfall returns 1 time/100 year. (SMHI, 2010). To select a suitable return period when designing a conduit, consideration need to be taken regarding to if the area in question is enclosed or not and if it is located inside city settlements. An enclosed area is an area where the water can not be diverted by gravity. The duration of the rain is how long the rain lasts, and is usually expressed in number of minutes. Rainfall intensity shows how much it rains per unit time and area, and is expressed in l / s · ha (Svenskt Vatten AB, 2004).

The following types of rainfall data can be used for design and modelling of stormwater systems:

• *Historical rainfalls and rainfall series* from precipitation measurements. Rainfall measurements can be made with a weighty rain gauge or a tipping bucket rain gauge. Historical rainfalls can be data for a single-event rainfall or it can be long-term continuous rainfall series.

• *Uniform time distribution rainfall*. Such rainfalls are the maximum average intensity for a single rainfall during a given duration.

• *Design Storms*. Design storms are special rainfalls used in the analysis and design of sewer systems. The flow that are linked to a certain Design Storm is assumed to have the same return period as the storm. A Design storm used in Sweden when sizing pipelines is the Chicago Design Storm, CDS (Svenskt Vatten, 2011b)

2.1.8 Runoff coefficient and Time of concentration

To calculate how a water catchment area will contribute to a storm water flow, a runoff coefficient φ is used. The runoff coefficient shows how permeable a surface is and is determined by how exploited the area is, the area's slope, the rainfall intensity and the hardness of the ground (Svenskt Vatten AB, 2004). The runoff coefficient varies between 0 and 1 for different types of areas, see Table 3. The areas that contribute to the greatest runoff has a runoff coefficient close to 1, while areas with little runoff has a runoff coefficient near 0 (Hendriks, 2010). If a catchment area is composed of several sub-catchments with different runoff coefficients a joint weighted runoff coefficient can be calculated (Svenskt Vatten AB, 2004).

Table 3; Runoff coefficient for various areas according to Svenskt Vatten. (Svenskt Vatten AB, 2004)

Surface	Φ
Roof	0,9
Concrete, asphalt	0,8
Gravel road strongly sloping hilly park area without any significant vegetation	0,4
Cultivated land, lawn, meadow	0-0,1
Flat, covered forest land	0-0,1

Another important parameter in runoff calculations is the time of concentration, t_c. It is the maximum time taken for a raindrop that falls farthest away in a catchment area to drain to the outlet point. The time of concentration depends on the distance and the water velocity (Ven Te Chow, 1988).

2.1.9 Computational models

Computational models to calculate stormwater flows have existed for two centuries (Beven, 2003). In appendix 1, two calculation methods that can be calculated by hand to make rough estimates of the design flow are presented; *The rational method* and *Time-Area method*. These two calculation models are sometimes also the computational engine in advanced computer based modelling tools.

2.1.10 Climate change

Forecasts predict that climate change over the next 100 years will yield an increased amount of precipitation, increase the rainfall intensities for short-term rainfalls and cause elevated water levels in recipients (Svenskt Vatten AB, 2007). In Sweden, the annual average precipitation will increase by around 10-20% during the next century (Persson, et al., 2007). Along with the rising water levels in the recipients this can for example lead to an increased risk of flooding, increased quantities of water to divert and overflows. As climate change will affect the amount of stormwater in the future, it is important to account for these changes when designing and planning stormwater system. When designing new systems a climate factor, usually called S which varies between 1.05 and 1.30, is used. The climate factor will affect the design flow, see equation 1, where q is the design flow [m^3/s] and $q_{adjusted}$ is the adjusted design flow [$m^{3/}s$].

$$\boldsymbol{q_{adjusted}} = \boldsymbol{S} \cdot q \qquad (1)$$

2.1.11 Disposal

The disposal of stormwater has varied during the last century, and the diversion has been both through open systems like ditches and streams as well as through closed pipes. The sewerage system in Sweden consists of public sewerage as well as private sewerage. The private sewerage are the pipes and conduits that are situated on private property all the way up to the connection point. There are three main systems for sewerage in Sweden; combined system, duplicate system and separate system. The three system types diverts stormwater in different ways, see table 4 (Svenskt Vatten AB, 2007).

Table 4; The three main sewerage systems used in Sweden (Svenskt Vatten AB, 2007)

Systems	Separation
Combined system	Storm- , drainage- and sewage water are diverted in the same conduit
Duplicate system	Stormwater and sewage water in separate pipes. The drainage water can be diverted to either the stormwater pipe or the sewage water pipe, but preferably in the stormwater pipe.
Separate system	Stormwater is diverted in ditches. Drainage and sewage water in the same conduit

Since the 1950's mainly duplicate systems are used in Sweden. Before that it was mainly the combined systems that were used. The last 20 years there has been a system change in Sweden to reduce the volume of stormwater to the sewage system. This is done by local disposal of stormwater, see Section 2.1.12.

2.1.12 Local disposal of stormwater

Local disposal of stormwater means that the water is disposed on private property. By disposing the stormwater locally and imitate the natural system, the response of the sewage system can be delayed which will reduce the peak flows from a rainfall and the flow will be more uniform. This will reduce the amount of stormwater to the public sewerage system and prevent flooding from occurring. Local disposal of stormwater can be done by for example using infiltration devices, green roofs or gutters (Persson, et al., 2009).

2.1.13 Sustainable Drainage Systems, SuDS

Sustainable Drainage Systems, SuDS, is a term mainly used in the United Kingdom. SuDS refers to surface water drainage systems that aims at reducing the impact of a site development by replicating the natural drainage system as much as possible and often also manage the stormwater close to the place where the rain falls. Typical SuDS structures are for example filter strips, swales, infiltration basins, wet ponds, constructed wetlands, infiltration devices, pervious surfaces and green roofs, see figure 4 (Woods-Ballard, et al., 2007).

Figure 4; A green roof is an example of a SuDS Solutions. Photo: Johanna Lind

2.2 Stormwater models

In order to study and answer questions about a system, it is sometimes not possible to make an experimental study. This may be because it is too expensive, too dangerous, or the system does not exist yet. Instead of making an experimental study a model can be used, which is always a simplification of reality (Ljung & Glad, 2011, pp. 11-14; Beven, 2005). Hydrological models are often classified from their properties.

2.2.1 Model classification

Mathematical models and systems can be dynamic or static. In a static model there is a direct relation for how a variable changes over time. For a dynamic model, however, the variables can change over time without direct external influence. In a dynamic system the output often depends on all previous inputs (Ljung & Glad, 2011, pp. 31, 52).

Models are either stochastic or deterministic depending on whether the model output includes some type of uncertainty estimation or not. A stochastic model always contains a certain type of probability or uncertainty and output will therefore always have some uncertainty in itself. While a deterministic model, however, always produces the same output with a given input data (Beven, 2005, p. 18; Ljung & Glad, 2011, p. 31).

Hydrological deterministic models can be divided into lumped or distributed models depending on how the model handles spatial patterns. In a lumped model the catchment is one unit where for example the rain falls equally over the entire area. In a distributed model consideration is taken of the distribution in the catchment (Solomatine, 2011; Beven, 2003). Runoff models for urban areas are usually deterministic and distributed (Zoppou, 2000).

Stormwater modelling tools can be continuous and/or event-based models. A continuous stormwater model uses long rainfall time series, including dry periods that can occur between rainfalls, to simulate stormwater runoff and is well suited for long term studies. An event model look either at a single rain event and is called single event model, but can also look at several short-term rainfall (Ahlman, 2006; Zoppou, 2000).

Stormwater models usually consist of a hydrologic and a hydraulic component. Hydrological models are used to study systems that control the movement and storage of water and to understand how the hydrological cycle interacts (Solomatine, 2011). The hydrological part of the Stormwater models usually consists of rainfall-runoff processes and calculations (Autodesk, 2013; CHI, 2014a; EPA, 2010).

Hydraulic models are used to calculate hydraulic processes in the network and describe water flow and pressures in pipes and channels in the network. This is also called the routing. Computer-based hydraulic models are used for accurate design, sizing and analysis of sewer. This is done by dividing the catchment into subcatchments and connecting the sub-catchments to the nodes in the network. It is common for hydraulic models to use dynamic wave theory for the calculations. The input to hydraulic models often consists of coordinates, levels, dimensions, pipe materials and computational results from hydrological models (Svenskt Vatten AB, 2004, pp. 40-41).

2.2.2 Flow dimensions for stormwater models

In stormwater modelling tools, the flow can be presented in different dimensions such as 1-dimensional (1D) and 2-dimensional (2D) flows. The velocity for 1-dimensional flow only depends on one dimension. An example is flow in a pipe where the flow only depends on the radius of the pipe, dimension x, see figure 5. A 2-dimensional flow depends on two dimensions, x and y (Crowe, et al., 2010).

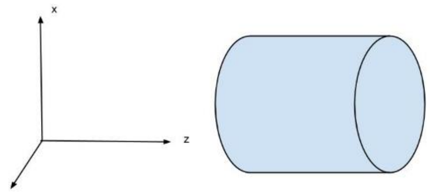

Figure 5; Dimensions in a 1-dimensional and 2-dimensional flow in a pipe.

2.2.3 Model selection

When choosing a suitable model, it should first be considered if it is possible to use the model in respect of investments in time and money. It should then be considered whether the model gives the desired output data required for the project and if the input data required is possible to obtain within a reasonable amount of time and price (Beven, 2003, p. 19). A complex model often requires more input data than a simple model, while a simple model with fewer input data instead may not be specific enough for the current study. It is therefore important to select a good combination of model complexity and available input data (Shamsi, 2005). Finally it should be considered whether there are limitations in the model that will affect the results (Beven, 2003, p. 19). The main steps in choosing a model are presented in figure 6.

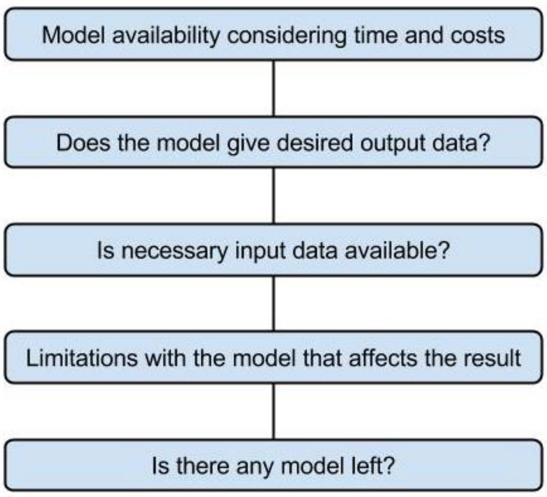

Figure 6; Step by step to choose a proper model

2.2.4 Calibration and validation

When a model is selected the parameters usually require calibration, evaluation and validation. During calibration the parameters are adjusted so that the model should reproduce observed data and the acceptable difference between the model and observations should be as small as possible. The extent of the difference may depend on the model application and the scope of the study (Solomatine, 2011; Ljung & Glad, 2011). Calibration is often done by taking a measured rainfall and measured flows from the area in question and compare them to the flows calculated by the model (Beven, 2005). In computer-based modelling tools, calibration can be done both manually and automatically. Manual calibration is very likely to reflect the knowledge of user performing the manual calibration. An experienced user is likely to implement the manual calibration faster and more accurate than an inexperienced modeler. Unlike the manual calibration, automatic calibration can provide an unbiased and faster calibration. Today's state of the art automatic calibration is preferred before manual calibration (Rosbjerg & Madsen, 2005; Beven, 2005).

After the model has been calibrated evaluation occurs. Hydrological models can be evaluated in many different ways, but it usually involves validation of the prediction performance under changed conditions and sensitivity and uncertainty analysis (Solomatine, 2011).

Validation of performance is often done by using an independent data set to see how well the model performs for predictions. Often the so called split-sample technique is used, which means that the data series are divided into two sets, one of which is used for calibration and the other for validation. Finally, after the split-sample validation, a calibration of the model with the entire data series is done (Rosbjerg & Madsen, 2005). Sensitivity analysis is performed to study how different parameters and variables affect the uncertainty of the model output (Solomatine, 2011).

Uncertainty analysis is done due to that runoff models are always a simplification of reality and contain uncertainties. It is important to know the degree of uncertainty between the estimated value provided by the model and its true value. The most common causes of uncertainty in the models is poor understanding of the watershed systems, data uncertainty, parameter uncertainty and model structure uncertainty (Solomatine, 2011; Rosbjerg & Madsen, 2005; Beven, 2003).

The more complex models do not always give a more accurate result, as more complex systems contain more parameters contributing to the uncertainty in the model. Sometimes it may therefore be better to choose a simpler model (Beven, 2005).

2.2.5 Integration and interoperability for computer-based modelling tools

Stormwater Modelling tools can be both stand-alone programs with their own graphical user interface or they can be integrated into other software, such as ArcGIS from ESRI, Autodesk's AutoCAD or QGIS.

For engineers, city planners and other users of computer-based stormwater modelling tools the possible integrations with other software are often of importance since multiple software tools are sometimes used to solve a problem and data might need to be transferred between different software. Integration between the programs might ease this task. For the same reason it is important which formats can be imported and exported to the modelling tool.

2.3 Modelling tools

There are various computer-based modelling tools for modelling stormwater quantity and quality. In Sweden the tools StormTac and Mike Urban are widely used, but in other countries other tools are used. In section 2.3.1-2.3.14, fourteen modelling tools used worldwide are presented. There exists several other similar stormwater modelling tools that are not included in this brief market research.

From this market research three stormwater modelling tools were chosen for the continued evaluation and comparison. The three tools chosen were StormTac, Infoworks CS and MUSIC. In the following section they are marked with a star (*) and are also more comprehensively described than the tools that were not chosen for further studies.

The reason for selecting StormTac for continued studies was that it is one of the tools often used in Sweden. Infoworks CS is a common tool used in UK and MUSIC is a common tool used in Australia. The reason these three were chosen for the continued study was mainly because of their different model layout. It was found very interesting that the models had similar focus but their structure, layout, input data and level of detail seemed to be very different. At the same time they all three are currently used in different parts of the world. It would probably have been easier to give a like for like comparison if modelling tools with more similar layout would have been chosen for example by comparing Infoworks with Mike Urban and PCSWMM that all include a complete buildup of a sewer network. A fourth tool, not presented in this market research of commercial modelling tools - SuDS Studio, was also chosen for the continued evaluation and comparison part. This selection is also marked with a star. SuDS Solutions and local disposal of stormwater solutions are becoming more and more state of the art to use. Therefore this modelling tool was also selected for further studies.

2.3.1 SWMM

SWMM is a hydraulic and hydrologic model, developed by the United States Environment Protection Agency, EPA. The model was developed in the early 1970's and has continuously been updated since then. The latest version is SWMM 5.0 and unlike previous versions, it has a Graphical User Interface (GUI) (Shamsi, 2005).

SWMM is used worldwide for design, planning and analysis. It is primarily used for urban catchments but can also be applied on non-urban areas. The model includes stormwater and wastewater systems, combined systems and natural drainage systems. SWMM can be used to calculate both water quality and quantity and also include estimates of Low Impact Development controls, LID, such as green roofs, infiltration trenches and permeable pavements. SWMM simulates dry and wet-weather flows and is suitable for both continuous long-term predictions as well as calculations of single events. The modelling tool is divided into three modules: TRANSPORT - for dry-weather flows, RUNOFF-for wet weather flows and EXTRAN - for flow routing in the collection system (Shamsi, 2005; EPA, 2010).

The results from a simulation can be presented as a status report, time series graphs, time series tables, drainage maps, profile and scatter plots and statistical frequency analyzes (EPA, 2010).

SWMM 5.0 is a standalone modelling tool, but is also used as a calculation engine in other third-party stormwater modelling tools, se figure 7. In these tools SWMM is used either as the standard calculation engine or as an optional calculation engine. (Shamsi, 2005)

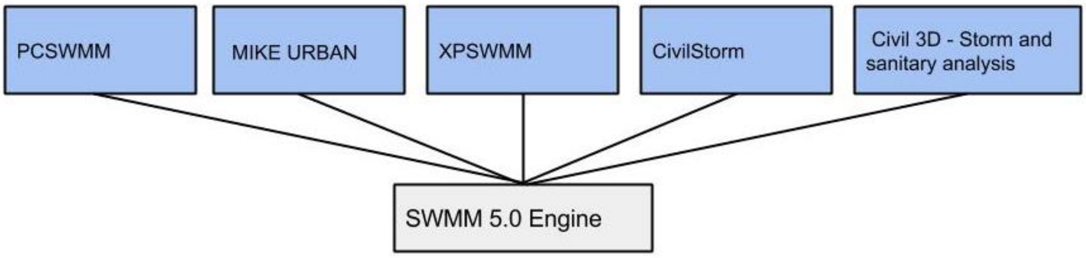

Figure 7; SWMM 5.0 is used as a calculation engine in other modelling softwares like PCSWMM, MIKE URBAN, XPSWM, CivilStorm and Civil 3D- Storm and Sanitary analysis

2.3.2 PCSWMM

PCSWMM is a third-party interface for SWMM and is developed by Computational Hydraulics Inc. (CHI). It is a GIS integrated model that uses SWMM 5.0 as the model computational engine for hydrologic and hydraulic calculations. It is a stand-alone modelling tool with all necessary GIS-tools included and it has support for various CAD and GIS formats (Shamsi, 2005; CHI, 2014b). PCSWMM models can be used for both continuous long-term predictions and single-event modelling. It is an integrated catchment model that includes storm sewers, combined sewers, river systems, LID controls, treatment plants and receiving waters. The models can be lumped or distributed, empirical and/or deterministic. The catchment area can be divided into subcatchments and the model can be used for both 1D and 2D computations (CHI Water, 2011).

PCSWMM is a tool used in more than 70 countries worldwide by cities, governments, consulting firms and universities (CHI, 2014b). It is possible to get parameter uncertainty estimations of the input data (CHI, 2014a).

2.3.3 MIKE URBAN

MIKE URBAN is a complete GIS-integrated modelling tool developed by the independent research and consulting organization DHI group. The MIKE URBAN software can be used for stormwater and wastewater systems, both combined and separate sewers, as well as water distribution systems.

MIKE URBAN is a module software. The main modules are: Model Manager, Water Distribution, Collection Systems (CS) and 2D Overland flow. The Model Manager is the base module of the interface and uses the computational engine SWMM for stormwater and sewer systems. The Collection System consists of several add-on modules like CS-Pipeflow, CS-Rainfall Runoff, CS- Pollutant Transport, CS- Control and CS- biological processes. For the add-on module CS-Pipeflow the computational engine MOUSE (Modelling of Urban Sewers) is used.

With the complete MIKE URBAN software package the model can for example be used for water quantity and water quality calculations, LID controls, simulation of 1D pipeflow and 2D overland flow. The results can be presented as 1D, 2D and 3D visualizations, time series, profiles, maps and animations (Esri, 2012; DHI Group, 2011).

2.3.4 Infoworks

Infoworks is a product group from Innovyze. It consists of Infoworks ICM, (Integrated Catchment Model), Infoworks CS (Collection System), Infoworks SD (Stormwater Drainage) and Infoworks RS (River Systems). The tools in this product group can act as standalone tools or together.

Infoworks SD is a comprehensive tool specialized for stormwater modelling and can be used for both single event and long-term continuous simulations. Infoworks RS is a river and channel modelling solution (Innovyze, 2014a). Infoworks ICM is a hydraulic and hydrologic model that integrates urban and river catchments in one model. The model includes 1D flows in rivers and channels, 2D surface flows as well as water quality simulations in both 1D and 2D areas. In Infoworks ICM the Infoworks 2D engine is included. Examples of applications for the model are Surface Water Management Plans, Master planning studies of river, drainage and sewerage and SuDS implementation. Infoworks ICM can interchange data with GIS and other third party software like Excel. The results can be presented in the same ways as Infoworks CS (Innovyze, 2014b).

Infoworks CS was chosen for further studies and is more comprehensively described in section 2.3.12.

2.3.5 XP Storm

XP Storm is a product from XP Solutions in Australia. It is an integrated hydraulic and hydrologic model used for stormwater and river Systems/floodplain management. Areas of use regarding stormwater analysis, design and planning includes among others Stormwater master plan design, LID structures, Detention pond optimization, 1D and 2D urban flooding. The program has GIS and CAD integrations and can import and export several GIS and CAD formats. SWMM 5.0 formats can also be imported and exported. The simulation results can be presented as result documents, tables, profile plots, flood mapping and animations (XP Solutions, 2014.; XP Solutions, 2011).

2.3.6 XPSWMM

XPSWMM is another hydraulic and hydrologic modelling tool from XP-solutions and has been used for analysis, design and simulations for over 25 years. Like XP Storm, XPSWMM includes stormwater and river systems/floodplains. Additionally it also includes wastewater management. The model simulates 1D network flows in combination with 2D overland flows, LID structures and stormwater quality. The tool can be used for natural systems like for example ponds, rivers and lakes and manmade environments like pipes, conduits and streets.

XPSWMM is a standalone tool but has connections to both CAD and GIS, which makes it possible to use a variety of CAD and GIS formats. XPSWMM can also import and export SWMM 5.0 data formats and models and use the SWMM 5.0 as computational engine. The result can be presented in similar ways to results from XP Storm (XP Solutions, 2014; XP Solutions, 2014).

2.3.7 StormCAD

StormCAD is a product from Bentley and is a tool used for designing and analyzing stormwater sewer systems. The modelling software program is suitable for land developers, stormwater master planners, transportation designers as well as plan reviewers. It can be used as a standalone product or within other software tools like AutoCAD. StormCAD uses the rational method to calculate peak flows and does not account for detention structures and flow changes over time (Bentley, 2014b).

2.3.8 CivilStorm

Another product from Bentley is CivilStorm. It is a stormwater modelling software that models more aspects of the system than StormCAD. CivilStorm is a dynamic model that accounts for storage, detention and flows over time and is therefore a more advanced modelling tool than StormCAD. It is used for master planning, modelling the effect of LID Structures as well as studying the water quality. It can, like StormCAD, be used as a stand-alone product but also within AutoCAD and other software tools. The user can chose to use the SWMM engine or CivilStorms imbedded solution. The results can be presented as for example thematic mapping, dynamic graphs, profiles and tables (Bentley, 2014a).

2.3.9 SEWSYS

SEWSYS is a computer model developed in the mathematical computing program MATLAB/Simulink within a doctoral project for the research program Urban Water. SEWSYS is a substance flow model that can be used to evaluate and simulate the flow of 20 different stormwater pollutants. Another application of the model is to evaluate various actions to reduce the pollution. The model accounts for both stormwater and wastewater pollution. It is also possible to define the sources of the pollutants within the catchment area. MATLAB / Simulink are required to run the model and the results can be used in MATLAB or exported to Microsoft Excel or other similar programs. The results can be presented as hydrographs, total pollutant amounts and amounts of pollution per year. (Ahlman, 2006a)

2.3.10 Civil 3D – Storm and Sanitary analysis

Storm and Sanitary analysis is a modelling package from Autodesk that is included in Map 3D and AutoCAD Civil 3D. The modelling package also has interoperability with GIS and can import and export various GIS database structures.

Storm and sanitary analysis is used for analyzing and designing storm and sanitary sewers and highway and urban drainage systems. It is a hydraulic, hydrologic and water quality model that includes analysis and design of detention ponds.

The modelling package uses various hydrology analysis methods including SWMM 5.0 and the Rational method. The results can be presented through time series, color-coded plan view plots and profile plots. Animations, that can be recorded, can be made for the plan view and profile plots. (Autodesk, 2013)

2.3.11 StormTac (*)

StormTac is developed by Thomas Larm and is based on the work presented in his dissertation *Watershed-based design of stormwater treatment facilities: model development and* *applications*. The tool has been used for over 10 years to calculate and study stormwater and recipients. StormTac can be used for both stormwater quantity and stormwater quality to calculate for example system capacities, detentions volumes and to make water quality forecasts.

2.3.11.1 Model layout and input data

StormTac is a static stormwater model built as a flowchart consisting of five sub models that together give a comprehensive picture of the stormwater runoff processes. The five sub models are runoff model, pollutant transport model, recipient model & water quality criteria, stormwater treatment model and detention model (figure 8) (Larm, 2011) (StormTac Corporation, 2014). StormTac is Microsoft excel based and there are various excel tables that operate the flowchart containing for example default values, equations and standard values that can be changed or studied (Larm, 2000a). StormTac is at the moment a desktop application but a web application is under development (StormTac Corporation, 2014).

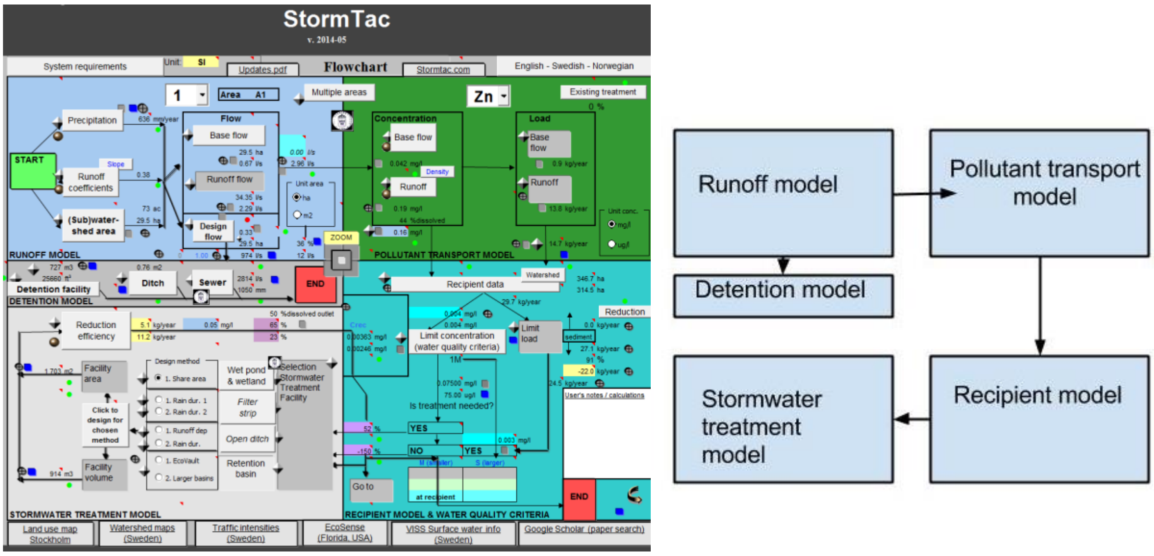

Figure 8; StormTac is an excel-based flow-chart, to the left is a screen shot of the model and to the right is a schematic picture of how the five sub-models cooperate.

StormTac can be used for calculations of:

- Long-term runoff flows (yearly and monthly)
- Pollutant loads
- Design and dimensions of Stormwater treatment facilities (STF's)
- Costs for STF's

StormTac is best suited for long term predictions and is not suitable for dynamic/short-term predictions (Larm, 2005) .

The only mandatory input data needed to run the model is the catchment area, the land use for each subcatchment and if design flows are to be simulated the time of concentration is also a necessary input data. Most of the default values in StormTac can be changed (StormTac Corporation, 2014). It is possible to calibrate the model against measured data like e.g. flows, pollutant concentrations and rain intensity.

2.3.11.2 Rainfall-runoff calculations

The first sub model is the Runoff model and here the parameters for the rainfall-runoff calculations are defined. The rainfall input is as yearly corrected precipitation in mm/year including both rain and snow. Corrected means that account is taken for systematical measurement errors like wind and evaporation. In Sweden the correction factor is normally 1.1-1.2 for liquid precipitation (Gustafsson, et al., 1999).

The catchment of interest is divided into different land use classes. For example a catchment with a total area of 10 ha might consist of 1 ha road and 9 ha green area. The catchment can also be divided into subcatchments and then the land use for each subcatchment can be added. In StormTac there are various land use areas to choose from, with corresponding runoff coefficients. The runoff coefficients have default values but these values can be changed by the user.

StormTac can calculate both runoff and base flow, although the base flow can be excluded from the model. The runoff flow is calculated on a yearly or monthly basis according to equation (2) and table 5, (Larm, 2005).

$$Q = 10p \sum_{i=1}^{N} \varphi_i A_i \qquad (2)$$

Table 5; Variables used in equation 2.

Variable	Description
Q	Flow [m^3/year]
A	land use area [ha]
φ	runoff coefficient
p	corrected precipitation
i	1,2,…,N

2.3.11.3 Pollutants

In sub-model 2, the pollutant transport model, the pollutants can be studied both as concentrations and loads. StormTac uses standard values for pollutant concentrations for surfaces for different land use classes. StormTac contains data for around 70 different substances. The concentrations of the substances are empirical standard values collected and calibrated for different case areas. Some standard values have more uncertainty than others and the uncertainty for each pollutant and land use is categorized as most certain data, average certain data and most uncertain data. StormTac calculates the pollutant load according to equation 3 where L is mass load rate [kg/year], C is standard concentration [mg/l] and j is substance (Larm, 2005).

$$L_j = \frac{\sum_{i=1}^{N} Q_i C_{ij}}{1000} \qquad (3)$$

2.3.11.4 Recipient, treatment and detention

The third submodel – Recipient model & water quality criteria, includes data regarding the recipient as well as guideline values for how much of the pollutants that can be released to the recipient in question. If the pollutant concentrations exceed the guidelines StormTac will notify the user that treatment should be added to the system.

In the fourth submodel – Stormwater treatment Model, different Stormwater Treatment Facilities can be added such as wetlands, filter strips, open ditches, sales and wet ponds. The STF's have several parameters that can be added or adjusted to be suitable for the study. StormTac will calculate the necessary area for the STF, the volume and the treatment effect.

In the fifth and last sub model – Detention model, it is possible to design detention facilities, ditches and the sewer system. However, there is no complete buildup of a sewer system network as for example in Infoworks, see section 2.3.12

2.3.11.5 Result presentation

Some results are shown directly in the flowchart, but more results can be obtained as excel files.

2.3.12 Infoworks CS (*)

Infoworks Collection Systems (CS) is a modelling tool, from Innovyze that is one of the tools in the Infoworks series of modelling tools with various objectives.

2.3.12.1 Model layout and input data

Infoworks CS can be applied for both stormwater and wastewater studies for both long term and short term studies. The tool can be used for hydrological and hydraulic modelling, to predict flooding, to study potential overflows and for studying water quality and sedimentation in the pipe system. A water pipe network system can be built containing conduits and pipes as well as nodes, manholes and outlets. The pipelines can be stormwater systems, wastewater systems as well as combined systems depending on the objective of the study.

The catchment area can be divided into subcatchments that are connected to the pipe network by linking each subcatchments to a node in the system, see figure 9. Each subcatchment will contain information on the different land uses in the area. Each land use will be classified as either impervious or pervious (Infoworks version 13.5.3, 2014).

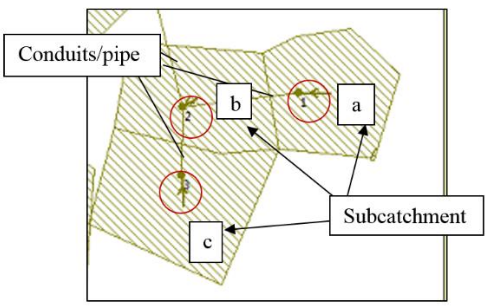

Figure 9; Screen shot of a basic structure with 3 subcatchments (a, b and c), pipes and the nodes named 1,2 and 3 marked with a red circle. The 3 subcatchments in are linked to one node each e.g subcatchments a is linked to node 1, b to node 2 and c to node 3.

Infoworks CS uses so called Workgroups and a model is built up of for example a network workgroup containing the network, a rainfall workgroup with the rainfall events that are to be used as input data and a run workgroup with the different runs of the model (figure 10). The models are saved in a central Master Database. Two of the many advantages with this structure are that model replication is avoided and the models are continuously being backed up so that information will not be lost in case of for example technical computer problems (Innovyze, 2011).

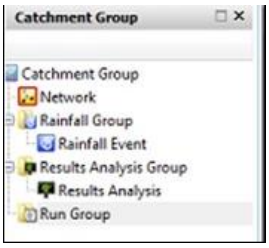

Figure 10; A screen shot from Infoworks of the workgroup structure when building a model with a network in the Catchment group, a rainfall event added in the Rainfall group and a Run group which is needed for making simulations.

For building a model in Infoworks there are various input data needed. Necessary input data for the network are properties of the conduits, pipes and manholes such as for example length, width, invert levels and roughness. For the catchment, the entire area and contributing area have to be added as well as for example various land use classes in the subcatchment and connectivity with foul networks. The necessary input for running the model depends on what elements the user want to include and therefore not all necessary input data are listed here.

2.3.12.2 Rainfall- runoff calculations and hydraulic equations

There are several rainfall-runoff calculation models included in Infoworks CS; Fixed Percentage, New UK, Wallingford, SCS Method, Green-Ampt, Horton and Constant Infiltration.

The rainfall-runoff calculation model handles the rainfall-runoff process in various ways and which model that is suitable for a calculation depends on the objective of the study as well as the surface types. For example, the fixed percentage model can be applied to all surface types in an area and calculates the runoff from the different surface types with a certain percentage of how much of the water will create runoff for every surface. The percentage varies from surface to surface in a similar way as the runoff coefficient discussed in section 2.1.8. The percentage for each area is manually set by the user. This calculation model does however not account for the ground getting wetter during a rainfall event. As the ground gets wetter it may not allow the same amount of water to infiltrate as it did in the beginning of the storm i.e. the infiltration capacity can decrease as the storm goes on.

A rainfall-runoff calculation model included in Infoworks that does account for the ground getting wetter is the New UK model. This rainfall-runoff model can only be applied to permeable surfaces and if it is applied in a system, all permeable surfaces most use this runoff model. It calculates the runoff by taking into account the precipitation amount the previous 30 days (Allitt, 2013).

The routing methods can also be specified and the following are a selection of the routing methods available in Infoworks CS; Large Catchment, SWMM, Unit, and Wallingford.

Infoworks can be used to simulate steady state conditions or solve the dynamic Saint Venant's equations. It is an equation used to describe one-dimensional overland and channel flow. The equations assume that average cross-sectional velocities and depths can be used to describe the actual 3D-flows and it is considered to be a good approximation, se equations 4 and 5 and table 6.

Mass balance equation:

$$\frac{\partial A}{\partial t} = -A\frac{\partial v}{\partial x} - v\frac{\partial A}{\partial x} - i \qquad (4)$$

Momentum balance equation:

$$\frac{\partial Av}{\partial t} + \frac{\partial Av^2}{\partial x} + \frac{\partial Agh}{\partial x} = gAS_0 - gP\frac{f}{2g}v^2 \qquad (5)$$

Table 6; Variables used in equation 4 and 5 (Beven, 2003)

Variable	Description
A	cross-sectional area [m]
V	flow velocity [m/s]
t	time [s]
Q	discharge [m^3/s]
x	distance downslope/downstream [m]
i	net lateral inflow rate/unit length of channel [m^2/s]
g	gravitational acceleration [m/s^2]
h	average depth of flow [m]
S_0	channel bed slope [-]
P	wetted perimeter [m]
f	Darcy-Weisbach uniform roughness coefficient

The Colebrook Whites equation describes turbulent flow in pipes with various roughness. A smooth pipe have a lower roughness coefficient than a rough pipe (Svenskt Vatten AB, 2004). This equation is sometimes also called Prandtl-Colebrooks equation, see equation 6. In equation 6 q is the flow [m^3/s], D the diameter[m], k the roughness coefficient [mm], v the kinematic viscosity [m^2/s] and S_o the slope of the conduit [m/m] (Svenskt Vatten AB, 2004).

$$q = -\frac{\pi D^2}{2}\sqrt{2gDS_0}log\left[\frac{2.51v}{D\sqrt{2gDS_0}} + \frac{k10^{-3}}{3.71D}\right] \qquad (6)$$

2.3.12.3 Pollutants

There is a water quality component in Infoworks that includes pollutants for stormwater and for wastewater. It is possible to study wash off for pollutants, sedimentation in the pipes and pollutant transport. There are four default pollutants in Infoworks that can be used for simulations; Total Kjeldahl Nitrogen, Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD) and Ammonia. Total Kjeldahl Nitrogen is the sum of ammonia, organic and reduced nitrogen but does not include nitrate and nitrite (United States Environmental Protection Agency, 2013). Besides these pollutants it is possible to add four user defined pollutants.

It is also possible to simulate pollutants varying over time using pollutographs. A pollutograph is a time series of a concentration of a pollutant. The emission described of the pollutograph can be added somewhere or at multiple places in the network (Innovyze, 2014c).

2.3.12.4 Result presentation

The results from Infoworks can for example be presented as plan views, time varying sections and graphical data, database grid reports and 3D terrain views (figure 11).There is also the possibility to record and show an animation of a simulation of a rainfall event.

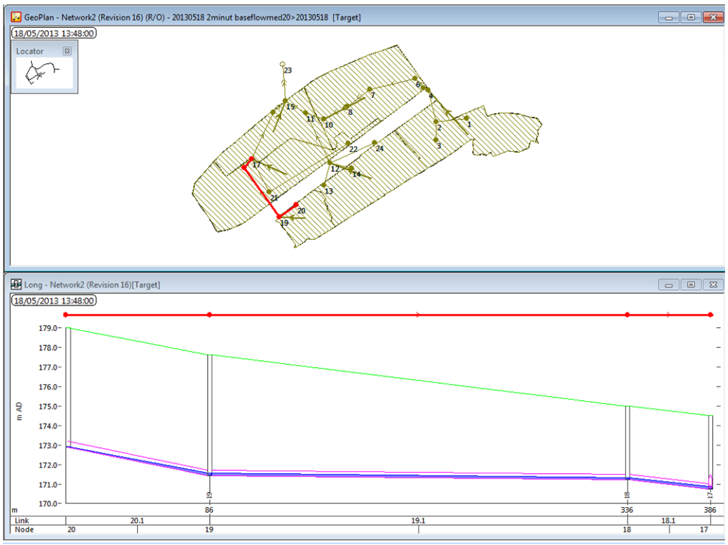

Figure 11; A screen shot of two options for displaying the results graphically through a geoplan view or a long section view of chosen conduits.

2.3.13 MUSIC (*)

MUSIC is a stormwater modelling tool developed by eWater and is mainly used in Australia.

2.3.13.1 Model layout and input data

MUSIC is used to study and evaluate the water quality and water quantity for both small and large catchments and to study the effect of different stormwater treatments. It is a support tool for decision and evaluation of stormwater systems. According to the publishers and developers, MUSIC is not a detailed design tool and should not be the only tool used for making decisions (eWater, 2014).

A MUSIC model consists of a catchment with a chosen rainfall profile. Rainfall profiles can be chosen from templates available in the program or the rainfall can be imported as time series. The catchment is divided into nodes that are connected through drainage links, see figure 12. The nodes can be subcatchments (source nodes), recipient (receiving node), treatment structures (treatment nodes) and other nodes. The endnote has to be recipient, and there can only be one recipient for each catchment.

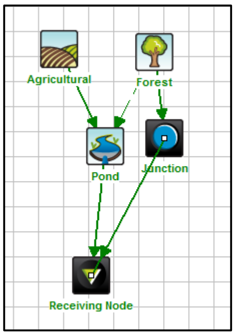

Figure 12; Screenshot from a trial version of MUSIC (6.0.1) of a very simple model with two subcatchments that both drains to a pond before the water is released to the recipient. Some water from the forest is diverted straight to the recipient and not through the pond.

There are three default subcatchments to choose from; Urban, Agricultural and Forest. There is also a User defined source node where all information can be added manually by the user (eWater, 2013a).

The subcatchments differ by their default pollutant concentrations but these values can be modified both for base flow and for runoff flow. For every sub-catchment it is possible to modify the following parameters: area, percentage impervious area, rainfall-runoff parameters such as impervious area properties, pervious area properties and groundwater properties.

There is no complete building of the sewer systems, as for Infoworks for example, where manholes and conduits are identified with for example elevation and dimensions. Instead the nodes are connected with drainage links that can be both primary and secondary links from one node. With the ability to have two drainage nodes from one link, the user can choose to split the flow and divert it in two directions. The routing method for the links can be either translation only, Muskingum-Cunge routing or it can also be an option to choose no routing for the links (eWater, 2013a).

2.3.13.2 Pollutants

There are three default pollutants included in MUSIC; Total Phosphorus, Total Nitrogen and Total Suspended Solids. However, in the same way as it is possible to add user defined nodes, it is possible to add and define other pollutants (eWater, 2013a).

2.3.13.3 Result Presentation

Results of the model can be presented as time series graphs for each node. Both flows and pollutants can be presented as time series with various time steps. Other ways of presenting the results are as statistics, cumulative frequency graphs and life cycle costing (eWater, 2014).

2.3.14 SuDS Studio (*)

SuDS Studio is a tool to screen for opportunities and define locations to retrofit Sustainable urban drainage systems, SuDS. The tools is also used to identify the impact that SuDS solutions could have on water quantity and water quality. SuDS Studio was in 2013 the only tool available that define locations to retrofit Sustainable urban drainage systems, SuDS, with the aim of reducing water flows (Breton, et al., 2013). SuDS studio is developed by Atkins UK and is a plugin tool for the open source Geographic Information System QGIS. QGIS can be downloaded for free and is required for using SuDS Studio.

2.3.14.1 Model layout and input data

SuDS Studio is used for looking at contaminant loads and defining suitable SuDS options. The tool includes different SuDS solutions such as permeable paving on minor roads, green roofs on large buildings, temporary underground storage for large buildings or man-made surfaces, pocket street infiltration and opportunity to install a pond. In the version used for the case study 13 SuDS solutions are included. When using SuDS Studio the input data needed for making the simulation is the rainfall depth in mm as well as a vector-file with the catchment of interest containing information of the different land use attributes. Figure 13 shows how an area can be divided into different land use classes.

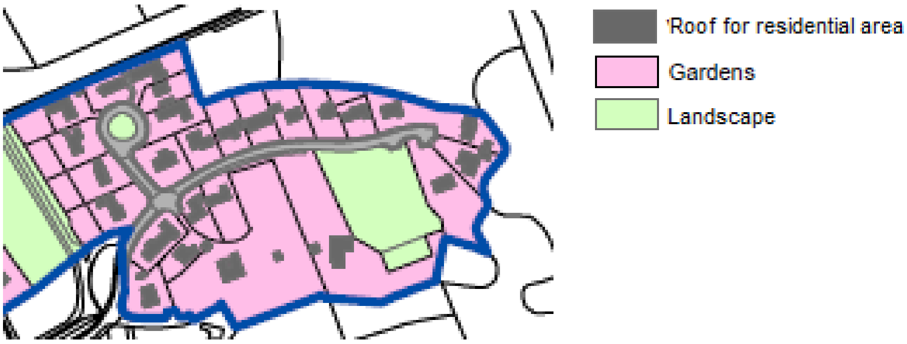

Figure 13; Different land use classes in a residential area.

The output from the tool will be maximum and minimum contaminant loads for the different land uses in the area. The tool will also identify suitable SuDS options as well as calculate the allowable flow to each SuDS option. Some SuDS solutions are only suggested for certain land uses. For example a green roof will only be suggested for buildings and not for roads (Breton, et al., 2013). SuDS Studio is continuously being developed and more features are being added.

2.3.14.2 Rainfall-runoff calculations

SuDS Studio assumes 100% runoff from impermeable surfaces such as buildings, roads and other man-made surfaces. For green areas the surfaces are considered to be completely permeable and not generate any runoff.

2.3.14.3 Pollutants

There are 13 different pollutants included in SuDS Studio and the pollutant loads are calculated from maximum and minimum standard concentrations for each land use surface.

2.3.14.4 Result Presentation

The output format is as GIS vector- files and .csv files. The.csv files can be used for making plots and calculations in excel or other such programs.

2.3.15 Comparison – summary

In appendix 2, there is a comparison table with the tools presented in parts 2.3.1-2.3.13.

3 Material and Methods

3.1 Evaluation criteria

To make an objective and measurable comparison of the modelling tools and their performance five main evaluation criteria were developed, see table 7. To reduce the subjectivity in the analysis and comparison the main criteria were divided into sub-criteria.

When the evaluation criteria were developed, it was important that the criteria all together could provide a comprehensive picture of the modelling tools and reflect on the user friendliness, but to place the emphasis of the evaluation on the performance of the tools and their fields of applications. It was also important that the evaluation criteria were designed so that the assessment and comparison would be as objective as possible. The evaluation criteria was also designed in a way that would help when selecting a model according to the five steps in figure 6.

The goal with the first evaluation criteria *Model characteristics* was to give a good overview of the modelling tool by describing what features are included in the modelling tool, how detailed it is what computational methods that are used for example when calculating runoff in a catchment. The features included in the model that were evaluated were if the model contained only stormwater systems or also wastewater and combined systems, if the model contained pipe networks, pollutants or treatment. This first evaluation criteria should also help in answering the first step in figure 6.

The second evaluation criteria *Input requirements* was developed to establish the type and amount of input data required to run the model. It should also establish how easy the required input data is to obtain. The result of this evaluation criteria should be the background material for answering the first and third step in figure 6.

The third evaluation criteria is *User friendliness.* It was developed to evaluate the usability and facilitate the choice of model for the modeller. Some modelling tools require more experience and knowledge of the modeller and the output might be affected by who the user is, the users choice of input data and previous experience of calibration and validation of the model. User friendliness is therefore an important evaluation criteria. This criteria will also help answer step one and four in figure 6.

The evaluation criteria *Obtained Results* is the most important one out of the five criteria. The results from this criteria will help answering both step two and four in figure 6. The evaluation criteria was developed to assess the model's performance. The goal was to evaluate whether the model provides the desired type of output and also to evaluate the performance. For the evaluation of the performance it was important to see how well the model performance is compared to observed data and also in comparison with other models. Finally it was significant to compare and evaluate the calibration and validation possibilities with the models.

The fifth and final evaluation criteria aims to answer which *field of application* each model should be used for.

Table 7; The evaluation criteria.

Model characteristics	Input requirements	User friendliness
- Included in the model - Model objectives - Level of detail -Desktop application or Web-based application - Mathematical basis - Spatial and temporal scale	-Input data required to run the model - Input format -Type of input data -Availability of input data	-Learning period -Manual -User experience -Flexibility -Support -Forum
Obtained results	**Model application**	
-Output -Calibration (Manual or Automatic) -Compared to observed data (for default values) -Compared to each other -Presentation of results -Uncertainty in predictions -Parameter sensitivity	-Fields of application -Case studies	

The evaluation will focus more on some of the criteria, for example the output, the obtained results compared to each other and fields of application.

3.2 Case study

The same case study was modelled with each of the four modelling tools.

3.2.1 Study area

This case study consists of Deans Industrial Estate, which is located 20 kilometers west of Edinburgh between a trunk road and a highway, as well as a Residential area south of the highway (figure 14). It has a total catchment area of 49.9 ha and drains to the watercourse Dechmont Burn north of the area.

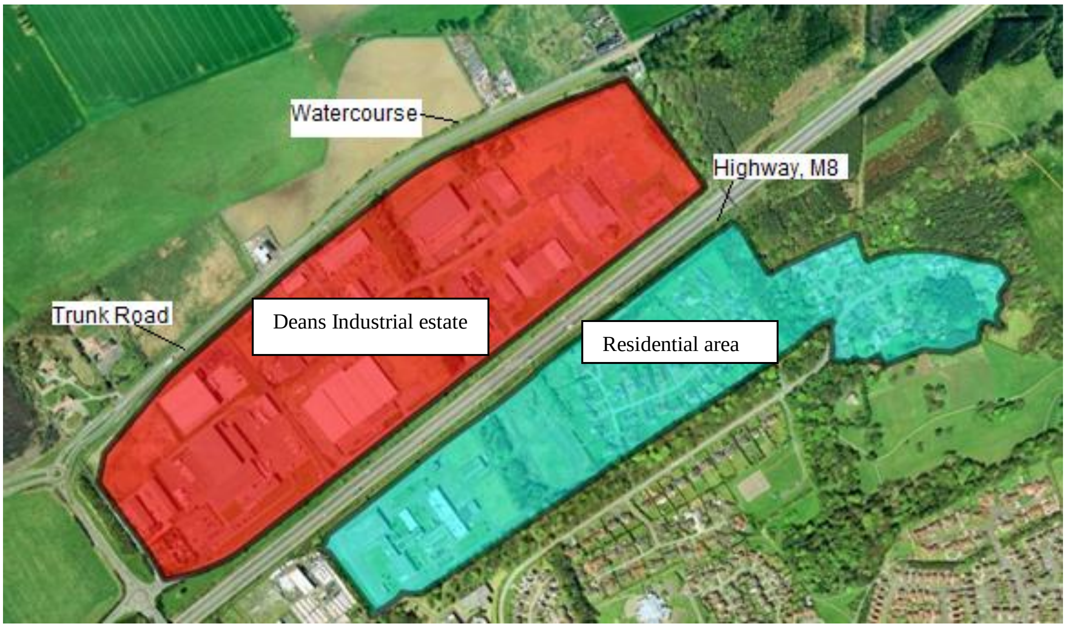

Figure 14; Map of the area used in the case study with Deans industrial estate and the residential area (Mapdata 2014 Google).

Deans Industrial estate has a catchment area of 29.4 ha. The residential area has a total area of 20.5 ha. The land use for the entire area is shown in table 8. The entire area of Deans Industrial Estate including the Residential area south of the highway has a slight slope down towards the watercourse. Deans Industrial area consists of several types of light industries and offices. The entire catchment with Deans Industrial Estate and the Residential Area will from now on be called Deans.

Table 8; The land use classes for the catchment.

Landuse		**Area (ha)**
Deans Industrial estate (29.4 ha)	Roof	5.6
	Roads	2.4
	Carparks	1.6
	Storage yards	0.5
	Service yards	5.3
	Landscape	14.0
Residential area (20.5 ha)	Residential area	17.1
	Forest	1.2
	Landscape	2.2
Total		49.9

Impermeable land use classes cover almost 50% of Deans Industrial Estate (figure 15). The impermeable land use classes are roofs, storage yards, parking lots, service yards and roads for Deans Industrial Estate.

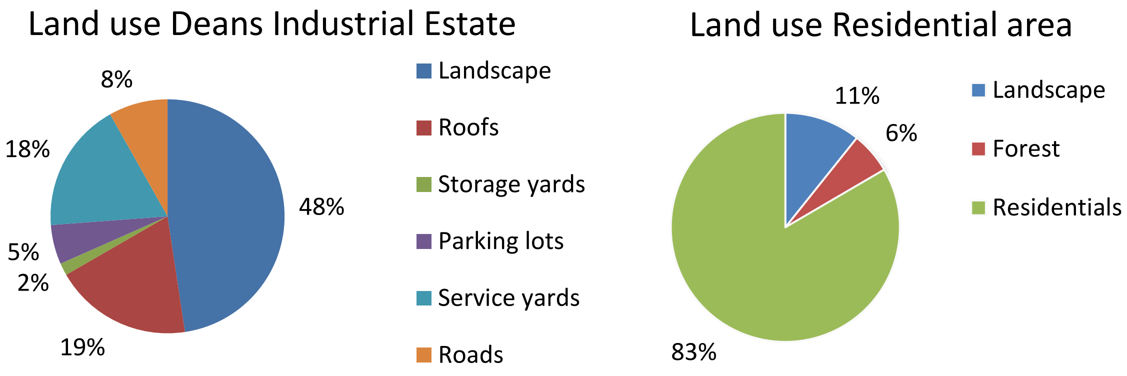

Figure 15; Percentage of each land use class in Deans Industrial Estate and in the Residential area.

The landscape land uses are in many cases small green areas in between the parking lots, service yards and roads. (figure 16). In the residential area there are no storage yards, service yards or parking lots.

Figure 16; The different land uses for the area of the Case Study.

The yearly average temperature, measured at the weather station Livingston, 1 mile away from Deans Industrial estate is 11.9 °C and the yearly average precipitation 1981-2010 was 974 mm. October – January were the months with the largest average amount of rainfall (MetOffice, 2014).

Deans Industrial Estate and the Residential area drain through a stormwater system to the watercourse Dechmont Burn north of the area. The location of the Surface Water Outfall (SWO) from the area is shown in figure 17 and for this outfall monitoring pollutant and flow data are available. The outfall has been marked in figure 17. The highway and the trunk road are not included in the catchment and are not drained by this stormwater system.

Figure 17; Map of the stormwater system with the outfall (SWO) marked (Map by OpenStreetMap 2014)

3.3 Data

Available data for building the model was a vector-file containing the different land use of the area, a vector-file with the pipe network as well as precipitation, flow and monitoring data. There were also available data of the stormwater sewer network with conduit lengths, positions, widths, as well as a few invert depths and invert levels. No topographical data of the area or information about the manholes were available. According to Wastewater planning users group (2002) the minimum amount of data needed for building a pipe system is site plans, system layout and pipe sizes. Although it is preferred to have more information for building a model such as details of the sewer network, connectivity, ground levels, pipe levels and pipe roughness (Wastewater Planning Users Group, 2002).The available amount of data was therefore considered to be enough to build a simplified model of Deans' Catchment.

3.3.1 Monitoring data

There exist flow and precipitation data as well as pollutant monitoring data from Deans Industrial Estate.

3.3.1.1 Flow and precipitation data

Flow data collected at the SWO with 2-minute interval is available. In this thesis data from May to June 2013 is used. There is also precipitation data from several rainfalls collected with a rain gauge a few kilometers away from the outfall collected with a fifteen minute interval. The yearly amount of precipitation for 2013 was 932 mm which was considered a representative year compared to the average rainfall from 1981-2010. A rainfall event from May 2013 was chosen for further studies and used in the modelling, (figure 18). The event was chosen as the amount of data was comprehensive and included rainfall data, flow data as well as monitoring pollutant data. The total rain depth during this event was 14 mm. The start of the rainfall event was at 10:00 and in the end of the rainfall was at 19:00

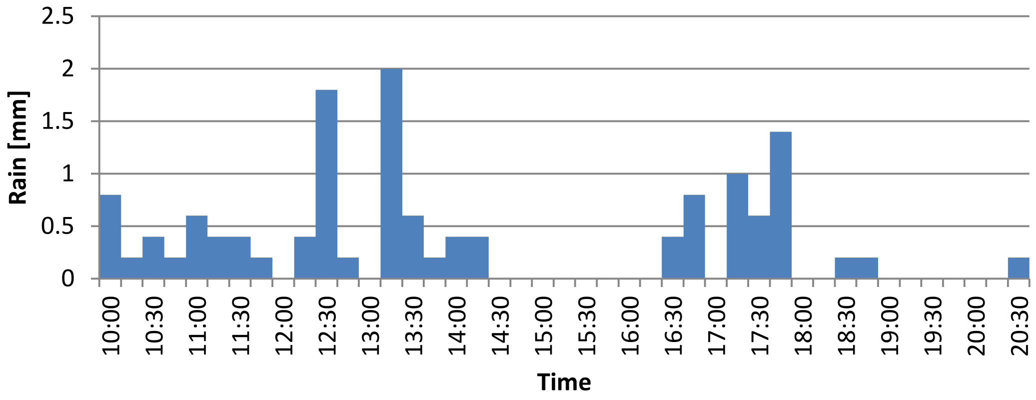

Figure 18; The rainfall event from May 2013.

The corresponding discharge flow is shown in figure 19.

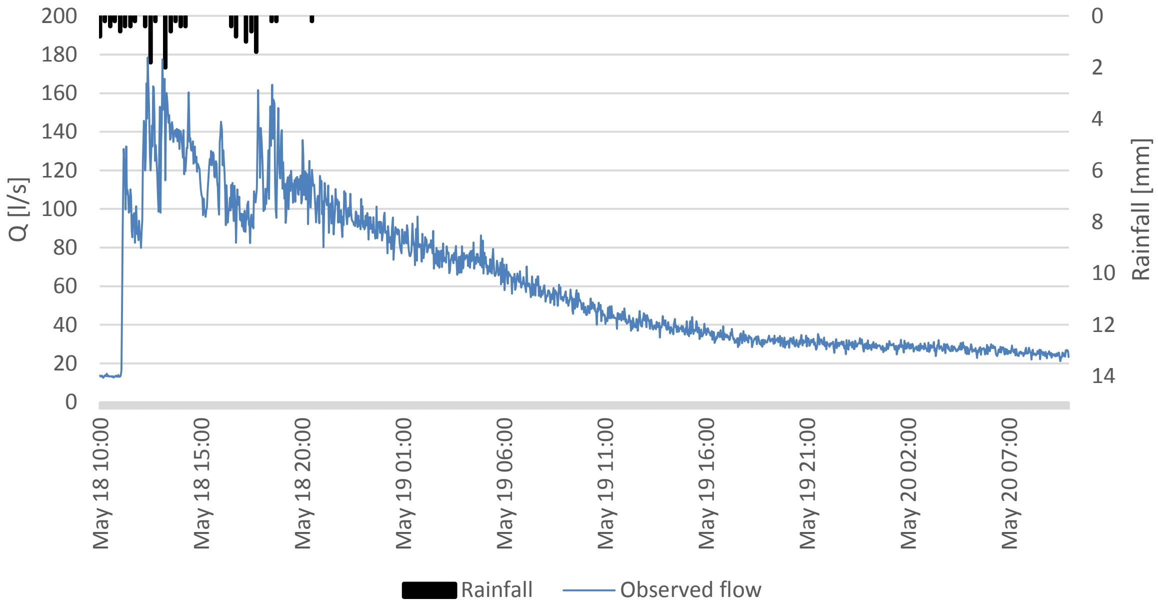

Figure 19; Flow data collected at the SWO 2013-05-18 – 2013-05-20.

Flow for Deans Industrial for two months is shown in figure 20.

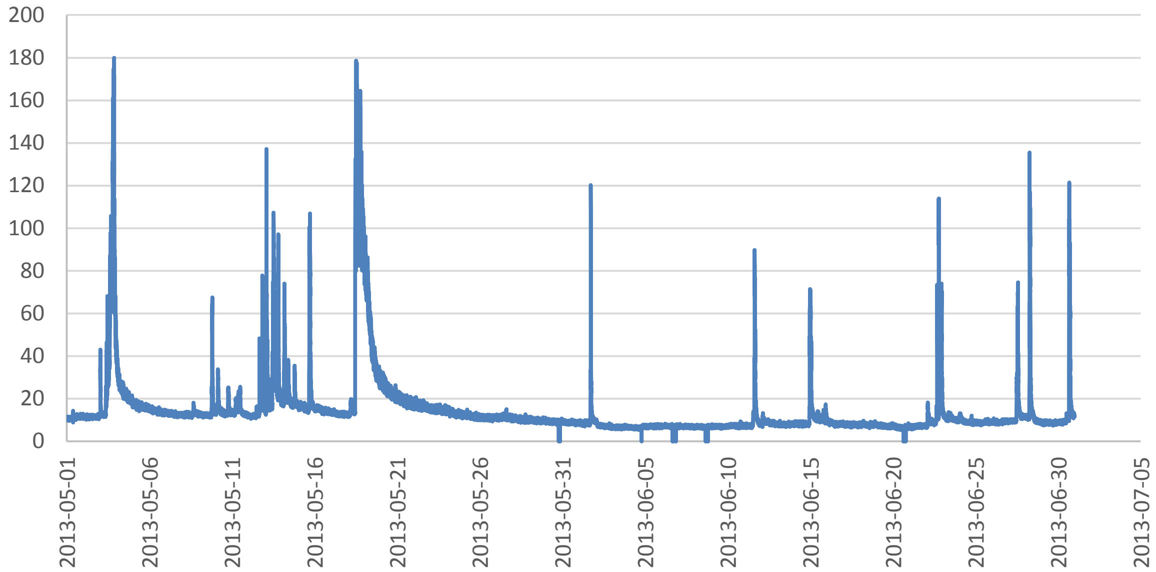

Figure 20; Flow at Deans Industrial estate measured at the SWO during two months during May-June 2013.

3.3.1.2 Pollutant data

Monitoring pollutant data are available for Deans Industrial SWO. Spot samples collected on a monthly basis at the outfall during dry periods are available in this case study as well as storm samples from a number of rainfall events including the rainfall shown in figure 18.The storm samples were collected with a kind of time controlled sampling. The substances for which monitoring data is available are shown in table 9.

Table 9; Substances that will be compared in this case study with the observed data from monthly spot samples.

Substance		Average
P	-	Not available
N	-	Not available
Pb	(µg/l)	2.33
Cu	(mg/l)	0.01
Dissolved Cu	(mg/l)	0.01
Zn	(µg/l)	34.5
Dissolved Zn	(µg/l)	37.1
Cd	(µg/l)	0.09
Dissolved Cd	(µg/l)	0.06
Cr	(µg/l)	1.59
Dissolved Cr	(µg/l)	4.1
Ni	(µg/l)	1.67
Dissolved Ni	(µg/l)	1.45
Hg	(µg/l)	0.02
Dissolved Hg	(µg/l)	0.02
BaP	(µg/l)	0.02

The substances from the rainfall event in May 2013 are presented in table 10.

Table 10; Substances and the average concentrations during the rainfall in May 2013 measured at the SWO.

		Average
Pb	(ug/l)	1.21
Cu	(mg/l)	0.008
Cd	(ug/l)	0.15
Cr	(ug/l)	1.94
Hg	(ug/l)	0.05
Ni	(ug/l)	4.38
Zn	(ug/l)	77.1
SS	(mg/l)	7.25
BaP	(ug/l)	0.005

3.4 Methods

A model of Deans' catchment was built with each one of the four selected modelling tools; StormTac, Infoworks CS, MUSIC and SuDS Studio. The goal was to apply all models under as similar conditions as possible to make the result comparable. If the main assumptions about the area of the case study would have differed too much between the models, the comparison would have been irrelevant.

A trial version of MUSIC was used in this evaluation and case study. Some of the features in MUSIC are only available in the full version and therefore some simplifications had to be done that most likely would not have been necessary if the full version had been used. The most problematic missing feature in the trial version was the inability to add a rainfall time series, and the only rainfalls available were three design rains from Australia. This problem is more thorough explained in section 3.4.2.

All four models were run with a *Default run.* The default run is here defined as a run with the models with all site specific data added into the model such as land use, runoff coefficients, rainfall, pipes and nodes. The default runs were made with two scenarios; a yearly rain from 2013 and with the single event rainfall from May 2013 in figure 19. In the default runs the models are not calibrated and validated against observed data, but the results are compared against observed data and an intercomparison between the models are done.

The goal was also to calibrate each model with another rainfall event from June 2013 and do a *Calibration run*. After doing one or more calibration runs the goal was to do a final *Validation run* with the rainfall event from May 2013 and the yearly rainfall from 2013 again.

Due to differences between the models and to properties in the modelling tools not all of these could be accomplished for all four models. The simulations performed was different for all four models, table 11.

Table 11; Simulations made with the four modelling tools.

Tool	Simulations
StormTac	Default runs (yearly 2013 and single event from May 2013) Calibration of base flow Validation run (yearly 2013 and single event from May 2013)
Infoworks CS	Default runs (yearly 2013 and single event from May 2013) Calibration runs (according to the split sample technique with rainfall June 2013) Validation run (yearly 2013 and single event from May 2013)
SuDS Studio	Default runs (yearly 2013 and single event from May 2013)
MUSIC	Default run (single event from May 2013)

For the calibration in Infoworks, a rainfall event from June 2013 was used. After the calibration, the model was once again run with the rainfall from May 2013, which is also called the validation rainfall. The calibration of the model was only made regarding the volume of water and the calibration was done manually. Due to time constraints of this project and also model structural problems calibration was not always possible or successful.

3.4.1 Catchment, subcatchments and land use

Deans' catchment is a flat catchment and has a slight slope down towards the recipient Dechmont Burn north of the area. A topographical map was not available nor was any more heights than the few invert levels and invert depths available for the pipe network. The few invert levels and invert depths indicate that the catchment is rather flat and this was therefore assumed for the entire catchment. Although to verify this assumption, a topographical map would have been required.

To make the conditions as similar as possible the same categorizing of the land use was made for all four models. The entire catchment was divided into four main land use classes (table 12). This was done to be able to implement the same land use classes in all four models.

Table 12; the four land use types implemented in the four models

Land use	Included
Roads	All roads
Manmade surfaces	Parking lots, storage yards, service yards, all areas on the industrial area except roads or buildings
Buildings	All buildings, both in the industrial area and in the residential area.
Landscape	All green areas

The area was divided into six subcatchments (figure 22) based on land use, stormwater network, property boundaries and the slight inclination in the catchment down towards the watercourse.

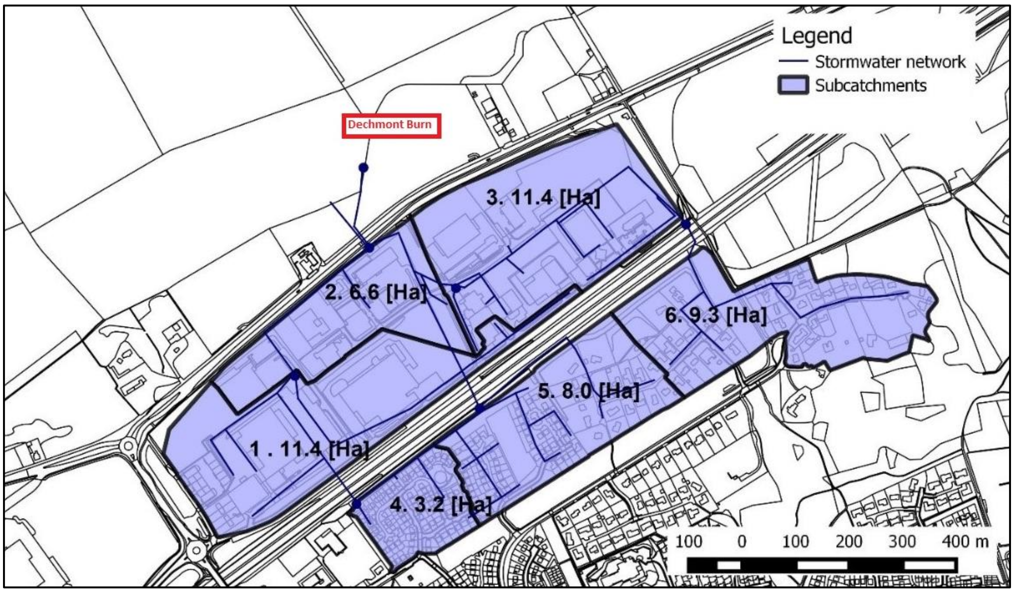

Figure 21; Division into subcatchments according to land use, property boundaries, stormwater network and the slight slope down to Dechmont Burn.

The area and land use statistics for each subcatchment were calculated in ArcGIS (table 13). The roads, man-made surfaces and buildings were defined as impermeable areas and green areas as permeable. Subcatchment 1 has the largest percentage of impermeable area with 62%.

Table 13; Total areas for the subcatchments, the percentage of different land uses and the percentage impermeable area.

			Impermeable areas		**Permeable area**
Subcatchment	**Total area [ha]**	**Roads [%]**	**Man-made surfaces [%]**	**Buildings [%]**	**Green Area [%]**
1	11.4	10	27	24	38
2	6.6	13	26	18	43
3	11.4	6	24	15	55
4	3.2	19	0	17	64
5	8.0	8	0	11	81
6	9.3	8	0	9	84
Total	49.9	9	15	16	60

3.4.2 Precipitation

The rainfall event from May 2013 was used as the rainfall event in the default run and in the validation run. For the yearly rain the yearly precipitation from 2013 at Deans' was used. The yearly rainfall was used to run all models except MUSIC. For the yearly rainfall event a correction of 1.1 was used to correct for measurement errors. For the rainfall event no correction factor was used. Even though the same precipitation was applied in all four models, the way of implementing these rainfalls into the four modelling tools differed.

The site specific yearly rainfall from Deans' during 2013 was 932 mm/year. This was considered to represent an average year as the average yearly rainfall at Deans' during 1981-2010 was 974 mm/year. With the correction factor the yearly rain from 2013 was 1026 mm/year.

StormTac
In StormTac the yearly rainfall is implemented as a single value in mm/year. The yearly corrected rainfall event for Deans for 2013 of 1026 mm/year was used. For the single event rainfall from May 2013 the rainfall depth was 14 mm and the duration was 9 hours.

Infoworks CS
When running Infoworks a design rain or an imported rainfall time series can be used. The rainfall event, expressed as the rain intensity in mm/hour, from May 2013 was imported as a time series with a 15-minute time step (figure 18 section 3.3.1.1). The yearly rainfall event was imported in the same way.

For Infoworks a calibration rainfall event from June 2013 was used for calibrating the model.

SuDS Studio
In SuDS Studio the rainfall is implemented as a single value as for StormTac. The rainfall is added in mm. The precipitation amount used as input data is the same as in StormTac with the yearly corrected rain as 1026 mm and the rainfall event as 14 mm.

MUSIC
In the full version of MUSIC it is possible for the user to load a rainfall time series, but in the trial version the only rainfalls available are three yearly design rains from Australia. As Deans Industrial is in Scotland this was problematic as the amount of rainfall/year, evaporation, temperatures and rainfall patterns for example differ between the sites. As this is one of the most important input data, any choice of design rainfall would have made the comparison irrelevant. To still be able to do a comparison the rainfall data for the chosen rainfall event in May 2013 was added manually into the design rainfall. As the data could only be changed one value at the time, and the data was for every 6th minute, this would have been to time demanding to do for the entire year. Therefore only results for the single event were compared for MUSIC.

3.4.3 Stormwater network

The four modelling tools handle stormwater sewer systems in very different ways. Infoworks distinguishes itself from the other tools by having a complete buildup of the network system.

StormTac
In StormTac there is no complete buildup of the stormwater network system as in Infoworks.

Infoworks
In Infoworks a simplified stormwater network was built with pipes, manholes and outlet (figure 22). The network was manually added into Infoworks CS with the coordinate reference system British National Grid. The XY -coordinates were obtained from the vector-file with the pipe system. The main simplifications consisted in excluding the service lines as well as most of the manholes. These simplifications were mainly expected to affect the time of concentration and

not the volume in the system as the same amount of water from each subcatchments was still directed to the pipe system. It was therefore considered to be a reasonable simplification.

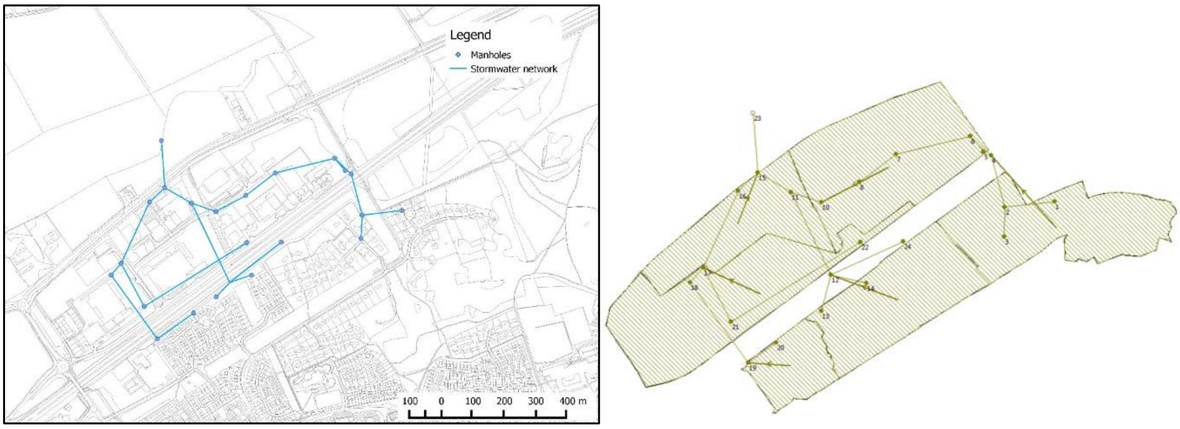

Figure 22; Simplified pipe network to the left and a screen shot of the implementation into Infoworks CS to the right.

Where data of the invert levels or invert depths for the pipes were available they were directly implemented into the model. For the rest of the conduits a mean gradient was calculated from the existing pipes and then the levels were interpolated backwards and forwards in the system. The calculated mean gradient was 10.3 ‰. This way of accounting for the missing data will not give a perfect accuracy, but according to Wastewater planning users group (2002) when missing data "*Invert levels may be estimated from known levels or depths, or if no other information is available the depths can be assumed*" (Wastewater Planning Users Group, 2002). Although this assumption will give a lower accuracy than if the levels and depths are available. The calculated mean gradient, 10.3 ‰ for the system was assumed reasonable according to the guidelines and requirements that Svenskt Vatten has regarding minimum gradients of pipelines that should be self-draining (Appendix 3). The gradient in the pipes should not yield maximum velocities of the water of more than 8 m/s to avoid erosion (Svenskt Vatten AB, 2004). A few pipe sizes were missing, and those were, in accordance with recommendations from Wastewater planning users group (2002), estimated from upstream and downstream pipe sizes.

As topographic data was not available, the ground surface gradient was assumed to have the same slope as the pipes. This was a rough estimate based on the Svenskt Vattens' publication P90 saying that "*Generally, pipes should be in the same slope as the ground for minimal excavation depth."* (Svenskt Vatten AB, 2004).

For the roughness of the conduits a Colebrook White roughness coefficient, *k*, of 3.0 was used. The values of *k* for a new concrete pipe can be around 0.5 but even small defects can give a roughness of 3-6 mm (Svenskt Vatten AB, 2004). The pipe network in Deans was not new and therefore expected to have at least some small defects and therefore the value of 3.0 mm was chosen.

The SWO was defined as an outfall and the rest of the nodes were all defined as manholes. As information regarding the manholes were not available, all manholes were given the same dimensions of 1 m^2 shaft plan area and 1 m^2 chamber plan area and their levels were defined in accordance with the ground levels. The six subcatchments were connected to the network by linking each subcatchment to nodes in the network where all the water from that basin would drain. The routing calculation model chosen for Infoworks was the Large Catchment model.

MUSIC
In MUSIC there is no buildup of a complete network. Instead the source nodes are linked together by drainage links. The routing method chosen for these drainage links were translation only and the K constant which equals the time it takes for the water to run through the system was chosen as the smallest constant available, which is 6 minutes, (figure 23).

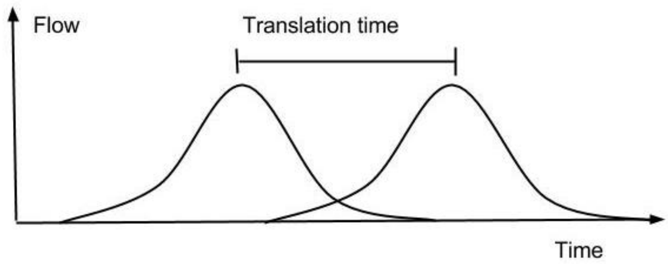

Figure 23; The routing method translation only was chosen in the MUSIC model of Deans Industrial Estate. The translation time was chosen as 6 minutes.

3.4.4 Runoff and implementation of the land use categories

The modelling tools handle runoff in various ways. For Infoworks CS one or more rainfall-runoff models have to be selected which is not the case for the other three tools where the choice of runoff model is handled automatically.

StormTac
In StormTac land use classes are defined by selecting from a list of 80 different predefined land use classes (StormTac Corporation, 2014). The four land use classes; road, manmade surfaces, buildings and landscape were inserted into StormTac as four of the available land use classes in StormTac; Road [1000 vehicles/day), Industrial area, Roofs and Mixed green area.. For each land use there is a corresponding runoff coefficient which is included in the model, (table 14).

Table 14; The land uses in StormTac that correspond to the four main land uses used in this case study.

Land use	Runoff coefficients StormTac
Road	0.85
Manmade surfaces	0.6
Buildings	0.9
Green area	0.1

Infoworks
In Infoworks there are several rainfall-runoff models to choose from. The rainfall-runoff models chosen for this case study was "Fixed" and "New UK". This function is explained in section 2.3.12.2. There are no default runoff coefficients included in Infoworks CS, instead they have to be set by the user. The runoff coefficients for the Fixed model was chosen according to Svenskt Vatten (table 3) and for Man-made surfaces the same runoff coefficient as in StormTac was chosen (table 15)

Table 15; The rainfall-runoff models used in the simulations and the chosen runoff coefficients.

Land use	Rainfall-runoff model	Runoff coefficient
Roads	Fixed	0.8
Man-made surfaces	Fixed	0.6
Buildings	Fixed	0.9
Green area	New UK	-

SuDS Studio

The land uses in SuDS Studio are identified from the input data vector-file. To identify the land uses, a Visual Basic-script was written to define the areas as *buildings*, *roads* and *manmade surfaces*. These land use classes are all assumed to be impermeable in the model and to generate 100% runoff. The remaining land use class called *Green areas* are assumed to be permeable areas by SuDS Studio and permeable areas are assumed to not generate any runoff. The flows from SuDS Studio was calculated manually by taking the rainfall depth and apply it on all impermeable surfaces.

MUSIC

In MUSIC the entire catchment is divided into subcatchments and the subcatchments are called source nodes. As explained in section 2.3.13, there are three default source nodes; Agriculture, Urban and Forest. Besides these default nodes there is a user defined source node, but here the user has to manually add all parameters. For each source node the area is defined as well as the percentage impervious and pervious area and also the pollutant loads for TSS, N and P.

For all areas except the industrial man-made surfaces the *Urban* source node was used and modified with different pollutant concentrations and amount of pervious/impervious area. The percentage pervious/impervious area used for the land use classes (roads, roofs and green area) were chosen according to guidelines from Blacktown city council which is a city council in Australia. For Man-made surfaces the percentage was chosen in the same way as in StormTac (table 16) (Blacktown City Council, 2013).

Table 16; The runoff coefficients for the various land uses (Blacktown City Council, 2013).

Subcatchment	Roads	Man-made	Roofs (buildings)	Landscape
1-6	0.95	0.6	1	0

3.4.5 Base flow

The models handle base flow in various ways.

StormTac

StormTac calculates the base flow automatically according to equation 7, where $Q_{base\ flow}$ is the base flow[m^3/s], K_x [-] is the part of infiltrated water that reaches the base flow, K_{inf} [-] is the part of precipitation that infiltrates into the ground, p is precipitation [mm/year] and A is area [m^2] (Larm, 2000b).

$$Q_{base\ flow} = 10K_xK_{inf}pA \qquad (7)$$

The volume of base flow can be calibrated against measured values. The default value for K_x is 0.7 and was used in the default run for StormTac. The value for K_x was changed later as the base flow turned out to be too low for Deans catchment.

InfoWorks

InfoWorks requires the user to manually enter the base flow. In other words, there is no automatic calculation of base flow as default in Infoworks. For the model of Deans catchments, the first assumption was that the there was no leakage into the pipes, and therefore no base flow as it is a storm water system. This assumption was used in the default simulation, but was changed later during the calibration as it was clear that Deans' catchment has a constant base flow.

The average base flow was calculated using the monitoring data from May and June by removing all peak flows at rainfall events and then take the mean average value of the flow. The average base flow was estimated to 11.1 l/s.

SuDS Studio

In this version of SuDS studio there is no calculation of the base flow. Instead the base flow was calculated from the measured values in the same way as for Infoworks.

MUSIC

In MUSIC it should be possible to add base flow as a time series. During the buildup of the Deans' model it was not possible to add the base flow as the program crashed several times. This could be due to the fact that a trial version was used, and therefore no emphasis was given to this during the evaluation. Instead when comparing volumes of water the base flow was calculated separately in the same was as for Infoworks.

3.4.6 Pollutants

In this case study only the predefined pollutants in the different modelling tools have been evaluated (table 17). For Infoworks and for MUSIC it is possible to add user defined pollutants, but this was not done in this study. For StormTac there are 70 substances that can be evaluated, but only the pollutants included in the Swedish guidelines were evaluated in this case study.

Table 17; The contaminants tested in this case study. For Infoworks and MUSIC, only the three default pollutants were included.

Contaminants	StormTac	Infoworks CS	SuDS Studio	MUSIC
P [µg/l]	X	-	X	X
N [mg/l]	X	X	X	X
Pb [µg/l]	X	-	X	-
Cu [µg/l]	X	-	X	-
Zn [µg/l]	X	-	X	-
Cd [µg/l]	X	-	X	-
Cr [µg/l]	X	-	X	-
Ni [µg/l]	X	-	X	-
Hg [µg/l]	X	-	X	-
Oil [mg/l]	X	-	X	-
BaP [µg/l]	X	-	X	-
SS [mg/l]	X	-	-	X

StormTac

In StormTac there are as explained in section 2.3.11, standard concentrations for the pollutants for each land use (Appendix 4). The concentrations are based on three levels of certainty in the data; most certain data, average certain data and most uncertain data (StormTac Corporation, 2014). There are maximum, minimum and standard values for the concentrations and shown in the appendix are the standard values.

The pollutant output from a run with StormTac is as yearly concentrations and loads per substance for base flow, runoff flow and total flow. It is also possible to obtain the average runoff flow from the particular rainfall event with concentrations, even though the model is not made for use during a single rainfall event. From these concentrations the volume water for the rainfall event can be calculated as well as the loads of the pollutants. The loads for a particular rainfall was calculated according to equation 8 where L is load [kg/rainfall event], c is concentration [mg/l] and Q is flow [m^3/rainfall event].

$$L = \frac{Q \cdot c}{1000} \qquad (8)$$

Infoworks

Infoworks CS have four default pollutants included; Total Kjeldahl Nitrogen, Ammoniacal Nitrogen, COD (Chemical Oxygen Demand) and BOD (Biological Oxygen Demand) (Innovyze Ltd, 2012). The pollutants are by default included in Infoworks *Surface Pollutant Editor* that simulates wash off from the surfaces. The output from a simulation is pollutant concentrations as time series and pollutant mass flow. The model also distinguishes between dissolved and sediment attached pollutant.

SuDS Studio

SuDS Studio also uses standard concentrations for the different pollutants and land use classes in a similar was as StormTac does. Although they are not the same standard concentrations as in StormTac. When running SuDS Studio no values have to be added by the user for calculating the pollutants. The substances included in SuDS Studio are phosphorous, nitrogen, lead, cupper, zink, cadmium, chromium, nickel, mercury, total suspended solids and benzo(a)pyrene. The output from SuDS Studio was pollutants for each surface, with the minimum and maximum loads.

MUSIC

In MUSIC, there are three default pollutants. These pollutants are total suspended solids, total nitrogen (TN) and total phosphorous (TP). The pollutants have default values for each land use class, but these values can be changed if the land use class is changed. Blacktown city councils recommendations for land use classes was used in this thesis (Blacktown City Council, 2013), Appendix 4.

4 Results

The results are divided into two parts. The first part includes results from the literature study and experience when using the tools in the case study. The second part consists of the results from the case study. Together they include results that meet the evaluation criteria.

4.1 Results from comparison according to Evaluation criteria

The results from the literature study and the user experience from the case study are presented and also compared between the modelling tools. The results from this part are summarized in table 18.

4.1.1 Model characteristics

All four tools; StormTac, Infoworks CS, SuDS Studio and MUSIC are appropriate and applicable for use of stormwater studies. However, the main focus of the tools differs between the stormwater issues. When handling stormwater there are two main issues; pollutants and flooding. StormTac, SuDS Studio and MUSIC are similar in the way that their main focuses are pollutants and actions to reduce pollutants. Infoworks CS on the other hand has its main focus on the collection system and mainly on the network. However, Infoworks CS is also capable of handling stormwater pollutants. A feature in Infoworks CS is that it is also a solution for studies and design of combined sewers or wastewater sewers. This gives Infoworks CS a wider area of use than the other three tools which are developed for stormwater studies.

Sewer network system

Infoworks CS distinguishes itself from the other three tools by being the only tool where the stormwater sewerage system has to be completely built up. In Infoworks CS the central part of the model is the sewerage network. The complete buildup of a network in Infoworks CS enables studies of potential flooding as well as identification of where in the system flooding is likely to occur. Although the main focus of Infoworks CS is the network, the modelling tool also includes subcatchments and buildup and wash off of contaminants from various surfaces. However, to be able to study these pollutants in the system a complete network is needed.

MUSIC is the only tool that can be compared to Infoworks in the sense that a network is built. In MUSIC, the drainage links explained in section 2.3.13 represent the pipes. The drainage links in MUSIC are however less detailed than the network in Infoworks. MUSIC is not made for detailed design of stormwater networks, only for design on a conceptual level. In StormTac there is no buildup of a network.

Pollutants

The amount of predefined pollutants available for simulation differs between the tools. StormTac contains the highest number of available substances to simulate with around 70 substances in total. SuDS studio has the next highest number with 13 different contaminants. In Infoworks there are only four predefined pollutants and in MUSIC only three. In both Infoworks and MUSIC it is possible to add user defined pollutants but this requires an effort and research for the user to define parameters. Only four user defined pollutants can be added in Infoworks CS. In MUSIC, adding a user defined pollutant replaces one of the three existing default pollutants. A large number of predefined pollutants is not necessary better than the possibility for the modeler to define its own pollutants as predefined pollutants might not always give good predictions. This matter is further discussed in Discussion, section 5.

For pollutant studies, Infoworks has the option to simulate emissions from point sources through pollutographs. Similar possibilities were not found in the other three tools

Treatment
StormTac and MUSIC include treatments such as wet ponds, filter strips and ditches as well as detention facilities. SuDS Studio distinguishes itself as it is a screening tool for potential SuDS options and the version compared in the case study includes 13 different SuDS options. It was in 2013 the only tool available that define locations to retrofit SuDS solutions, with the aim of reducing water flows. SuDS solutions can be ponds, detention basins or permeable pavings. For StormTac, MUSIC and SuDS Studio it is possible to study the effect on water quality of a certain treatment or SuDS solution. As the reduction effects have not been included in this study, no further evaluation of these properties is made.

In Infoworks CS it is possible to model SuDS solutions as well. This is done by for example portraying a swale as a leaking link or a soakaway as a leaking node (Innovyze, 2013).

StormTac includes the sub-model Recipient model and water quality criteria that inform the user of whether or not treatment is needed according to current guidelines and restrictions. This is a unique feature of StormTac in comparison with the other three tools.

Level of detail
The level of detail varies between the four tools. MUSIC is a not a detailed tool and should only be used as a decision support and not for detailed design according to the publishers. Infoworks is more detailed since it takes into account for example the pipe gradients, roughness of the pipes and initial losses. and can be used for design of systems according to Innovyze. StormTac is best suited for long-term predictions and not for single event rainfalls. It is possible to calculate the results from a single event, as done in the case study. It is however not the purpose of the modelling tool.

Mathematical basis and implementation
The four tools calculate runoff in similar ways by applying a fixed runoff coefficient to impermeable surfaces. The runoff coefficients used differ between the tools. There are more differences for how the models handle runoff from permeable surfaces than for impermeable surfaces. SuDS Studio and MUSIC both assume for 0% runoff from permeable surfaces. For StormTac, there are different runoff coefficients for different permeable surfaces. The land use classification made in the case study for permeable surface was Mixed green area that has a runoff coefficient of 0.1. InfoWorks CS is the only of the four tools where a fixed runoff coefficient is not used for permeable areas. When using the New UK rainfall-runoff model, Infoworks takes into account the fact that the ground gets wetter during a rainfall event. This is a difference between the tools as the other three tools do not account for any previous rainfall or change in ground wetness during the rainfall event, instead they assume a fixed runoff coefficient for the entire rainfall.

The implementation of land use classes differs between the models. StormTac has the largest number of land use classes to choose from.

Underlying equations and computational models are very different between the four modeling tools. This is mainly because the tools are structured in such different ways with for example different objective and include different parameters, runoff models, treatment methods and sub-models. Some of the underlying equations are described in Section 2.3 –Modelling tools.

Spatial and temporal scale
Infoworks is a fully distributed model. The other three modelling tools are semi-distributed models.

InfoWorks CS is a dynamic modelling tool where both changes in flows and pollution over time can be studied. Time series for flows, pollutant loads and concentrations can be presented as graphs. The flow can also be presented as plan views, long plan sections with accompanying animations to see where and when during then rainfall flooding might occur. StormTac is a static tool where the runoff flow, base flow and total flow are calculated as mean flow values during the year, or for an average rainfall event. In MUSIC, time series of flows, pollutant concentrations and pollutant loads are outputs. This can be calculated on yearly and rainfall event basis. For SuDS Studio no time series are available, instead the pollutants are given as loads in an upper and lower boundary level.

4.1.2 Input requirements and user friendliness

From the perspective of a user with no previous experience in any of the four studied tools, an evaluation of the user friendliness was made. The goal was to evaluate the user friendliness from the specified evaluation criteria: learning period, user experience, manual, flexibility, support and necessary programs and plugins. The learning period criteria is subjective. A subjective ranking was made regarding the learning curve for the four tools based on the time taking to implement the case study of Deans' catchment (figure 24).

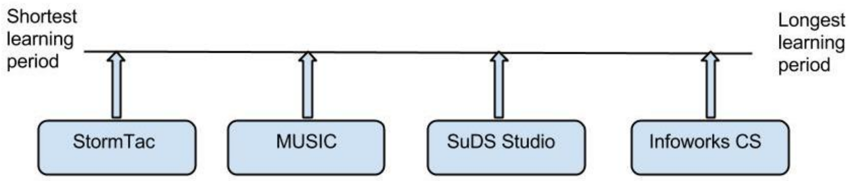

Figure 24; A subjective ranking of the learning periods required for the four modelling tools.

InfoWorks CS had the longest learning period and the amount of time spent to build the model of Deans catchment was by far the longest compared with the other tools. This is because when a model in Infoworks Cs is built from scratch, many parameters have to be entered manually which is time demanding but this also requires more preparatory work than for the other models. In StormTac and SuDS Studio only a few input parameters are needed to be able to run the model. On the other hand, for analyzing the output results, SuDS studio was the most time demanding. Building the model in MUSIC is more time demanding than doing a simulation in SuDS Studio, but the results are easier to interpret for an inexperienced user.

Flexibility of the models is in this evaluation defined as how easy it is to change the conditions of a model during the modelling process, for example to redefine land use classes, change the areas or alter precipitation. In Infoworks multiple rainfalls can be added and simulated simultaneously and the parameters for pipes, nodes and subcatchment can easily be changed. StormTac is also flexible in the sense that it is easy to change areas, land uses and rainfall. For MUSIC it is possible to change parameters for the nodes, but a way to change the rainfall profile once the model was built was not found. The run with SuDS studio has to be remade if any conditions are changed.

4.1.3 Obtained results

The obtained results will be evaluated from the case study, section 4.2. For other purposes of the modelling other output can be obtained from the tools. For example for SuDS Studio, one important output from the program is defining where SuDS options can be retrofitted. As only pollutants and flows were compared in this study, these results were not evaluated.

Presentation of results

Options for presentation of results also differs between the models. Infoworks have a strength in its way of presenting the results graphically as it is possible to view to system as for example geoplan, long section, graphs or making animations. SuDS Studio will display the SuDS options as GIS files giving a visual view of where SuDS options would be a possibility. For MUSIC time varying graphs is a possible way of presenting the results. To present the results from StormTac visually other programs are preferable to use. Output from StormTac is as excel files.

Calibration and Validation

Automatic calibration was not found as a feature in any of the tools. Automatic validation on the other hand were in some way included in all four tools. For Infoworks CS an automatic validation of the built network is performed before every run when parameters have been changed. If not all mandatory input data is added into Infoworks or if a parameter is added in a non-correct way, the model can not be validated and simulations can not be made. This is a strength in Infoworks as it can minimize the risk of erroneous input data from the user. However, a risk with this validation is if the user place blind trust in this validation and are not attentive of other potential errors that were not detected by the automatic validation. No results are obtained if errors are found in the validation. In MUSIC for each run the model displays the drainage links in green if they passes the "validation". The model gives results even though errors are made somewhere in the model. In StormTac there is also a kind of validation as warnings are displayed in the flow chart if some values seem to deviate too much from expected values. These warning signs do not have to be adjusted for the model to run as in InfoWorks, it is up to the user to control whether the warnings are relevant or not.

4.1.4 Model application

StormTac is used for stormwater studies and includes the recipient in the model. The tool can be applied for calculations of long-term runoff flows, pollutant loads and concentrations, design of STF's, pre and post treatment comparisons and costs for STF's. It is not suitable for dynamic/short-term predictions. Infoworks CS can be used for stormwater and wastewater studies for both hydraulic and hydrologic modelling including both complete buildup of a pipe network as well as rainfall-runoff process. It is also applicable for water quality studies of source pollutants as well as wash off of pollutants from surfaces and studies of sedimentation in the pipes. It is a dynamic model that can be used for both single events and long-term predictions. SuDS studio is a screening tool used for finding suitable options for building or rebuilding SuDS solutions. It can also identify the impacts that these solutions have on water quality and quantity. MUSIC is a conceptual model used mainly for pollutant studies and studies of the effect of different treatment methods. It can also be used for looking at flows. It is not a detailed design tool.

Several case studies were in the past performed with each of the four tools (ewater, 2015; Innovyze, 2013). The only tool where case studies from Sweden were found was StormTac (StormTac Corporation, 2014).

4.1.5 Comparison according to evaluation criteria

A comparison table (table 18) was set up scoring the models from the evaluation criteria in section 5.

The evaluation criteria were scored with -, +, ++, +++ or by other symbols, for the different evaluation criteria according to the explanation below.

- *Included systems*: Stormwater = S, Wastewater = W, Combined = C,
- *Level of detail:* A higher score is given for a higher level of detail i.e. low level of detail is + and high level of detail is +++.
- *Network*: A higher score was given for a complex network, and – was given if no buildup of a network existed.
- *Pollutants*: A higher score for more pollutants included by default in the tool.
- *Desktop-/Web-application*: A D was given for desktop-application, W for web-application and P for plugin-tool.
- *Input data required to run the model*: A lower score was given when many input data are needed to run the model and a higher score when few input data are needed.
- *Availability of input data:* A higher score was given for easy obtained input data such as rainfall that can be obtained from meteorological websites. And a lower score when for example measurements are necessary to collect by the user.
- *Necessary programs/add in modules*: A higher score was given if there are necessary programs or add-in modules needed for using the tool. If no necessary tools were given, it was scored with a -.
- *Learning Period:* A lower score was given for a longer learning period, and a higher score for a shorter learning period.
- *Manual*: A higher score was given if a user friendly manual was available and a lower score was given for a less descriptive manual. If no manual was available, a score of – was given.
- *User experience*: The tools were evaluated from the user experience with regards to stability of the software, time for a simulation. Higher scores were given for a good user experience and lower for a less satisfying user experience.

- *Flexibility:* If it was considered easy to change basic conditions in the tool a higher score was given. If it was considered difficult or not possible a lower score was given.
- *Support*: A higher score was given for existing and easy accessible support. No support was scored with a -.
- *Output:* For many relevant outputs and outputs relevant for different kind of use were given a higher score. For few outputs or outputs with a single area of use lower score was given. This was to show the versatility of the tools.
- *Calibration:* M if manual calibration is possible in the tool, and A if automatic calibration is included.
- *Presentation of results:* If the results can be presented in many different ways, a higher score was given.
- *Fields of applications:* For multiple fields of application a higher score was given and for few fields of application a lower score was given.
- *Case studies:* A higher score (+++) was given for multiple case studies performed, including case studies in Sweden and outside of Sweden. For multiple case studies performed but none in Sweden a medium score (++), and for few case studies performed a lower score was given (+).

	StormTac	SuDS Studio	Infoworks CS	MUSIC
Model characteristics				
Systems included	S	S	S,C,W	S
Network	+	-	+++	++
Pollutants	+++	++	+	+
Treatment	++	+++	+	+++
Level of detail	++	+	+++	+
Desktop/Web- application	D	P	D	D
Mathematical basis	Section 2.3.11.2	2.3.14.2	2.3.12.2	2.3.13
Spatial and temporal scale	Semi- distributed	Semi-distributed	Fully distributed	Semi-distributed
Required input				
Input data required to run the model	+++	+++	+	++
Availability of input data	+++	++	+	+
Compatibility and/ or dependence of third-party software				
Necessary programs/add-in modules	+	+	-	-
User friendliness				
Learning period	+++	++	+	+++
Manual	+++	-	++	+++
User experience	+++	+++	+++	(*)
Flexibility	++	++	+++	++
Support	+++	(**)	+++	+++
Forum	-	-	++	++
Obtained results				
Output	++	+	+++	++
Calibration (M/A)	M	-	M	M
Compared to observed data (for default values)	Section 4.2	Section 4.2	Section 4.2	Section 4.2
Compared to each other	Section 4.2	Section 4.2	Section 4.2	Section 4.2
Presentation of results	+	++	+++	++
Uncertainty in predictions	Section 4.2	Section 4.2	Section 4.2	Section 4.2
Model application				
Fields of application	++	+	+++	++
Case studies	+++	++	++	++

Table 18; Comparison of the tools according to evaluation criteria. (*) not possible to evaluate because of using a trial version for the case study. (**) Not a commercial tool in the same way as the other three and therefore not able to evaluate in the same way.

4.2 Results from Case study

4.2.1 Default simulation

The default simulation was made with the yearly rainfall event from May 2013 and with the corrected yearly precipitation from 2013. For Infoworks, SuDS studio and MUSIC no base flow was added in this simulation as the pipes were assumed to be non-leaking. For StormTac the base flow is calculated automatically and is therefore included.

4.2.1.1 StormTac

<u>Flows</u>

For the rainfall event the average runoff flow and average base flow is output (table 19). These values were compared to observed flows. For the yearly precipitation the average base flow is the same as during the rainfall event. The average annual runoff is also computed by the model. The model predicted average base flow is only one third of the observed base flow.

Table 19; Flows for the rainfall event 2013

	Modelled flows [l/s]	Observed flows [l/s]	Difference [%]
<u>Rainfall event May 2013</u>			
Average runoff flow	74.1	107	+ 31 %
Average. base flow	4.02	11.1	+ 63 %
<u>Yearly rainfall 2013</u>			
Yearly average runoff flow	5.58		
Yearly average total flow	9.6		
Average. base flow	4.02		

The total volume water from the rainfall is not an output from the model, but can be calculated as the average flow times the 9 hour duration of the rainfall. This gave a total runoff water volume of 2400 m^3 and with the base flow included 2530 m^3. The observed total flow was 3464 m^3 which is a difference from the volume in StormTac with 27 %. The total yearly flows are outputs from StormTac (table 20). Observed flows on a yearly basis were not available.

Table 20; Calculated event and yearly runoff and base flow volumes 2013.

Flow	Calculated event volume [m^3]	Yearly Volume [m^3]
Runoff flow	2400	176 010
Base flow	130	126 665
Runoff flow and base flow	2530	302 675

<u>Pollutants</u>

The average concentrations for the pollutants for the base, runoff and total flow are the same for the rainfall event as for the yearly precipitation. The runoff flow concentrations are higher than for the base flow. The values were compared to the observed monthly spot samples and also the Swedish guidelines (table 21). Compared to the Swedish guidelines simulated oil concentration exceeded the guidelines which is considered reasonable as it is an industrial area.

Table 21; Yearly average concentrations in column 1-3, Swedish guidelines and compared with observed data from the monthly spot samples

	StormTac Total flow	StormTac Runoff flow	StormTac Base flow	Swedish Guideline	Obs. data rainfall event May 2013 Average	Obs. data (monthly spot samples)	Difference between StormTacs total flow conc. And monthly spot samples (%)
P [µg/l]	90.1	127.3	38.8	160	-	-	-
N [mg/l]	1.48	1.93	0.86	2.0	-	-	-
Pb [µg/l]	6.38	10.2	1.22	8.0	1.2	2.33	+173
Cu [µg/l]	14.9	22.1	5.37	18.0	8	14.3	+5
Zn [µg/l]	66.1	97.0	22.9	75.0	77.13	71.6	-8
Cd [µg/l]	0.31	0.51	0.04	0.4	0.15	0.15	-107
Cr [µg/l]	3.6	5.58	0.85	10	1.94	5.69	-3
Ni [µg/l]	3.97	5.49	1.72	15	4.38	3.12	+2
Hg [µg/l]	0.03	0.04	0.01	0.03	0.05	0.03	0
Oil[mg/l]	0.52	0.86	0.08	0.40	-	-	-
BaP [µg/l]	0.03	0.05	0.003	0.03	0.005	0.02	+76
SS [mg/l]	30.6	49.2	5.4	40	7.25	10.1	+197

StormTac gives higher concentrations than the spot samples for all substances except for Zn and Cr (figure 25). The values for Mercury, Copper and Zink only differ with 3.3, 4.9 and 7.7 % respectively. The pollutant that differs the most between the model and the observed value is SS followed by Pb, Cd and BaP.

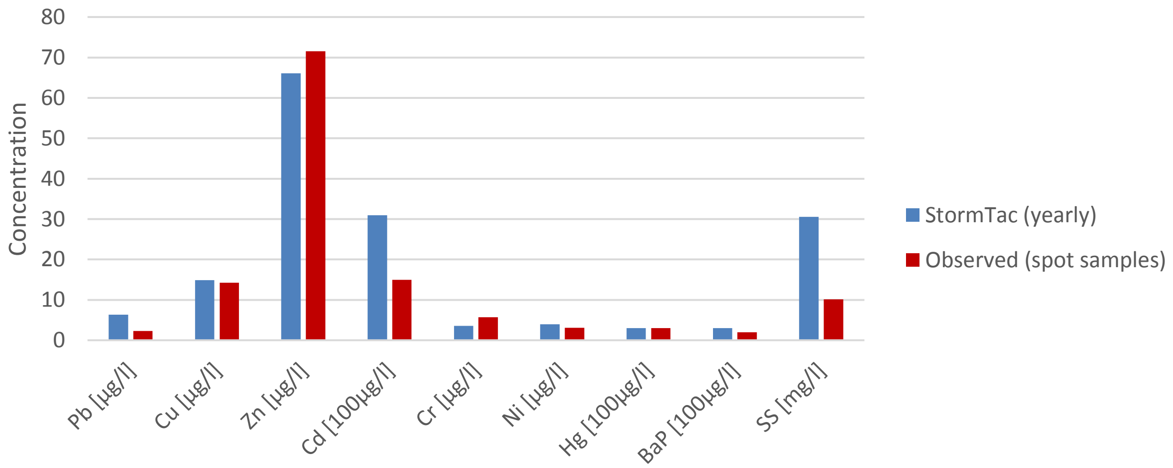

Figure 25; Observed average concentrations from monthly spot samples and the yearly average concentrations from StormTac.

The concentrations were also compared with the rainfall event from May 2013 (figure 26).

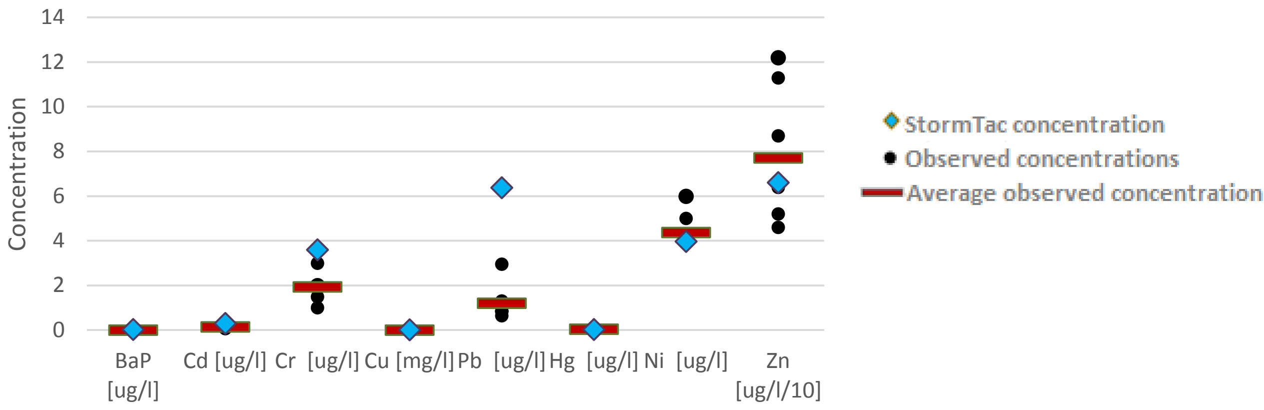

Figure 26; Observed concentrations for the rainfall event compared with values from the model in StormTac.

The loads for the rainfall event were calculated according to equation 8. The yearly based loads are obtained directly from StormTac (table 22). The concentrations and the loads are highest for nitrogen and suspended solids.

Table 22; Loads for the pollutants on a yearly basis and for the rainfall event.

	StormTac Load yearly [kg/year]	Load yearly (runoff flow) [kg/year]	Load yearly (base flow) [kg/year]	Load rainfall event [kg/event]	Load rainfall event (runoff flow) [kg/event]	Load rainfall event (base flow) [kg/event]
P	28	22.4	4.9	0.31	0.31	0.01
N	461	340	109	4.75	4.64	0.11
Pb	2	1.8	0.2	0.02	0.02	0.00
Cu	4.6	3.9	0.7	0.05	0.05	0.00
Zn	20.5	17.1	2.9	0.24	0.23	0.00
Cd	0.1	0.1	0	0.00	0.00	0.00
Cr	1.1	1	0.1	0.01	0.01	0.00
Ni	1.2	1	0.2	0.01	0.01	0.00
Hg	0.008	0.007	0	0.00	0.00	0.00
Oil	163	151	10.6	2.07	2.06	0.01
BaP	0.009	0.008	0	0.00	0.00	0.00
SS	9499	8662	680	22.8	22.1	0.70

4.2.1.2 Infoworks CS

Flows

Infoworks CS was run with the rainfall event and the time series flow output was compared to observed flow time series (figure 27). The simulation in Infoworks gives higher peak flows and does not show the same runoff pattern as the observed flow.

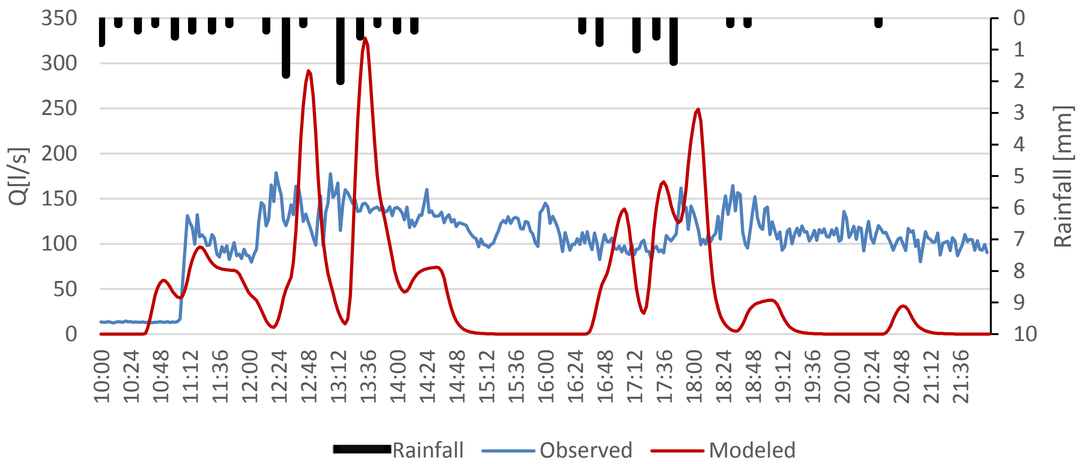

Figure 27; Flow from the default simulation in Infoworks and the observed flow for the rainfall event.

The water volume for the rainfall event was compared to observed data (table 23 and 24). The yearly simulation was run and results for volume of water was obtained (table 23 and 24) but no observed data was available for comparison with the yearly scenario.

The observed water volume is 38 % larger than the modelled water volume. In the Infoworks model the base flows is by default 0 l/s. The observed data however shows a base flow (figure 27).

Table 23; Output from the Infoworks model as well as the observed data.

	Modelled volume	Observed volume	Difference between model and observed [%]
Rainfall event May 2013			
Runoff Volume [m^3]	2145	3464	-38
Peak flow [l/s]	~330	~180	
Yearly rainfall 2013			
Runoff volume [m^3]	175 456		

Pollutants

Loads and concentrations of nitrogen for the rainfall event in May and for the yearly precipitation were output from the model. No observed data for nitrogen was available for comparison, but an intercomparison between the models were made, (section 4.2.4).

Table 24; Results of nitrogen concentrations and loads in the default simulation in Infoworks CS. Observed data was not available for comparison.

	Modelled
Rainfall event May 2013	
Load Nitrogen [kg]	0.237
Nitrogen average conc. [mg/l]	0.07
Nitrogen maximum conc. [mg/l]	0.99
Yearly rainfall 2013	
Load Nitrogen [kg]	384

4.2.1.3 SuDS Studio

For SuDS studio the default run was made with the event rainfall from May 2013 and for the yearly rainfall from 2013. The results from SuDS Studio that are relevant for this comparison are the loads of pollutants for each land use. The results presented in the following sections are calculated from these values.

The volumes of water from the rainfall event and on a yearly basis were calculated (table 25) assuming 100 % runoff from the impermeable surfaces.

Table 25; Calculated values for the rainfall event and the yearly corrected rainfall event.

	Volume water runoff flow [m^3]
Rainfall event	2691
Yearly corrected	197233

The pollutants analyzed in SuDS Studio are presented with predicted load ranges. The average predicted loads of the pollutants were calculated (table 26). No observed loads data for the pollutants were available, only observed concentration data so no comparison with observed data was made. An intercomparison with the results from StormTac was made (section 4.2.4).

Table 26; Results from SuDS studio for the rainfall event presenting the predicted load range and the calculated average predicted load.

	Average predicted load (rainfall event)	Predicted load range (rainfall event)
P [kg]	2.51	[0.46 4.55]
N [kg]	7.34	[1.53 13.2]
Pb [kg]	0.31	[0.012 0.61]
Cu [kg]	0.12	[0.11 0.12]
Zn [kg]	1.23	[0.14 2.31]
Cd [g]	10	[3 20]
Cr [kg]	0.03	[0.007 0.06]
Ni [kg]	0.22	[0.08 0.36]
Hg [kg]	0	[0 0]
Oil(MOH) [kg]	4.06	[0.59 7.52]
BaP [kg]	0	[0 0]

For Chromium the interval is largest with 100 % for the rainfall event. The loads with the interval for each pollutant was plotted (figure 28)

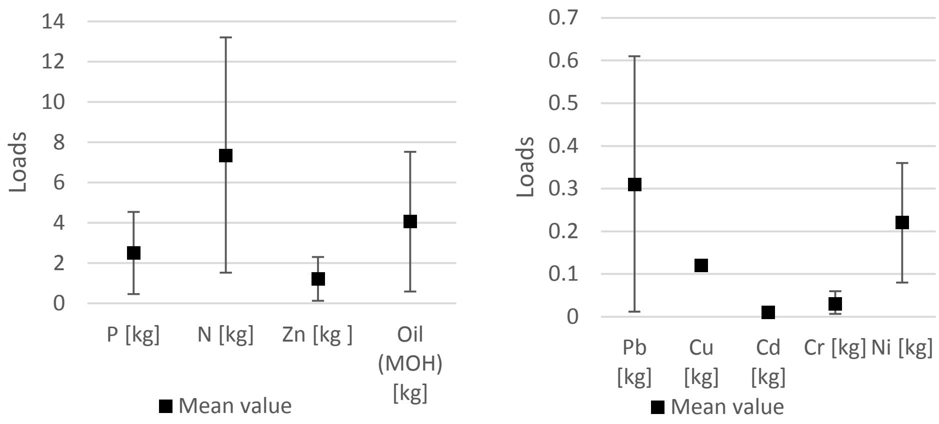

Figure 28; Intervals for the loads calculated in SuDS Studio for the rainfall event.

The same procedure was performed for the yearly precipitation (table 27).

Table 27; Results from SuDS studio for the yearly precipitation presenting the predicted load range and the calculated average predicted load.

	Average predicted load (yearly)	Predicted load range (yearly)
P [kg]	183	[33.4 333]
N [kg]	541	[112 970]
Pb [kg]	22.7	[0.9 44.5]
Cu [kg]	4.41	[0 8.8]
Zn [kg]	89.9	[10.2 170]
Cd [kg]	0.56	[0 1.1]
Cr [kg]	2.37	[0.5 1.1]
Ni [kg]	16.3	[0.4 32.1]
Hg [kg]	0	[0 0]
Oil (MOH) [kg]	297	[43.2 551]
BaP [kg]	0	[0 0]

The highest relative uncertainty is predicted for Cu and Cd although the largest difference in mass is for the loads of N and P.

4.2.1.4 MUSIC

Because of the limitations in the MUSIC trial version there are only results for the rainfall event in May 2013.

Mean average flow for the rainfall event given with a 30 minute interval and read from a result graph in MUSIC is 53.6 l/s. This gives a total flow of 1735.7 m^3 runoff flow for a 9 hour rainfall.

Concentrations for the three default pollutants were obtained from the run in MUSIC (table 28). The table also displays the load obtained in MUSIC for the rainfall event in May for the three default pollutants.

Table 28; Concentrations and loads for the simulation in MUSIC.

	Mean concentration during rainfall event[mg/l]	Load [kg]	Observed at Deans rainfall event [mg/l]	Measured at Deans from spot samples [mg/l]	Swedish guidelines [mg/l]
P	0.298	0.6	-	-	0.160
N	2.37	4.69	-	-	2.0
TSS	197	400	7.25	10.14	40

4.2.2 Model calibration and validation

The models in StormTac and in Infoworks were calibrated mainly against volume of water. The base flow seemed to be a factor contributing to a large difference in water volume and therefore the focus of the calibration was to add the base flow. For SuDS studio and MUSIC, no calibration was performed in the models. Instead the base flow was added separately to account for the established base flow.

4.2.2.1 StormTac

As StormTac calculated the amount of base flow automatically the parameter K_x in equation 7 was adjusted to retrieve the mean average base flow calculated from the observed data. K_x represents the part of the infiltrated water that contributes to the base flow. The default value of K_x is 0.7 and the maximum amount in the interval for K_x is 1, meaning that all the infiltrated water becomes base flow. The value K_x was given a value of 1.92 to obtain a base flow comparable to the observed, which is above the interval. This would mean that the base flow is almost twice as big as the infiltrated water and therefore have to origin from other sources. The base flow when K_x is set to 1.92 is 11.02 l/s. As K_x exceeded the interval this result was not used in the comparison.

4.2.2.2 Infoworks

A rainfall event from June 2013 was used for making a calibration according to the split- sample technique (see section 2.2.4) and the calibration was only made in regards to volume of water as the model built was a simplified model. The output flow time series from InfoWorks and the monitored flow data were compared to each other (figure 29).

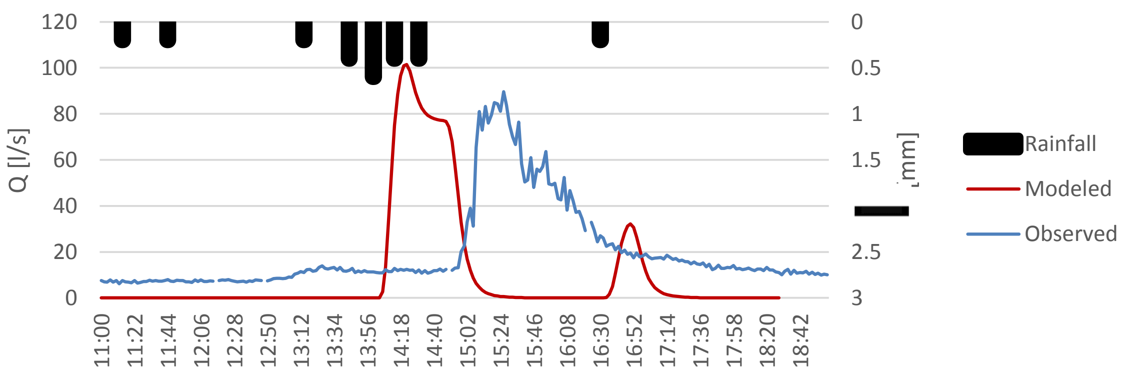

Figure 29; The Measured flow compared to the flow from the calibration simulation in Infoworks for the rainfall event in June 2013.

The volume of water from the model and the observed flow differed with more than 50 % (table 29).

Table 29; The volumes of water from the model and the observed flow for the calibration event.

	Infoworks output	Observed data	Error
Volume	251.1 m^3	556.9 m^3	54.9 %

The assumption of no base flow was not correct when comparing the results from the model with the observed values (figure 30). The first step in calibrating the model was therefore to add a base flow. The average base flow was calculated using the observed data as explained in section 3.4.5 and when added into the model it yielded a new hydrograph (figure 30) and a new water volume (table 30).

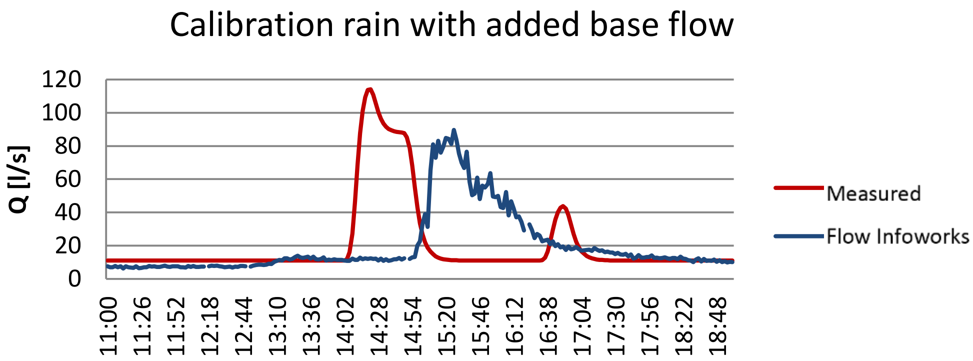

Figure 30; The calibrated rainfall with added base flow.

When doing this calibration the error rate of the water volume was instead 2.3 % which was considered an acceptable error rate.

Table 30; The volume water for the calibration event after adding the base flow into Infoworks gives a smaller error in comparison to the monitored data.

	Infoworks	Monitored data	Error
Volume	570 m^3	557 m^3	2.3 %

The model in Infoworks gives a quicker response than reality, which could be due to the model being a simplified model and the time of concentration could have changed as explained in section 3.4.3. As the volume now appeared to have a reasonable error some adjustments were made to try to minimize the response time difference. The Colebrook-White roughness coefficient was changed to 10 instead of 3. This was expected to reduce the response in the model. This did not change the volume more than 0.03 m^3 and the change in response time did also not change notably. The quick response is likely due to the simplifications in the network when building the model. Therefore no further calibration was done, as this was expected to be the main reason and also as the first intention only was to calibrate the model against the volume of water.

4.2.2.3 SuDS Studio

For SuDS Studio no calibration was performed. Instead the observed and calculated base flow of 11.06 l/s was added manually to the already calculated volume of water. The new total volume of water including both the runoff flow and base flow was 3050 m^3 of water.

4.2.2.4 MUSIC

In the same way as for SuDS Studio the base flow of 11.06 l/s was added to the runoff flow which gave a total flow of 2094 m^3.

4.2.3 Validation simulation

The only model for which a validation run was made was for the model in Infoworks (figure 31).The validation simulation was performed with the added base flow.

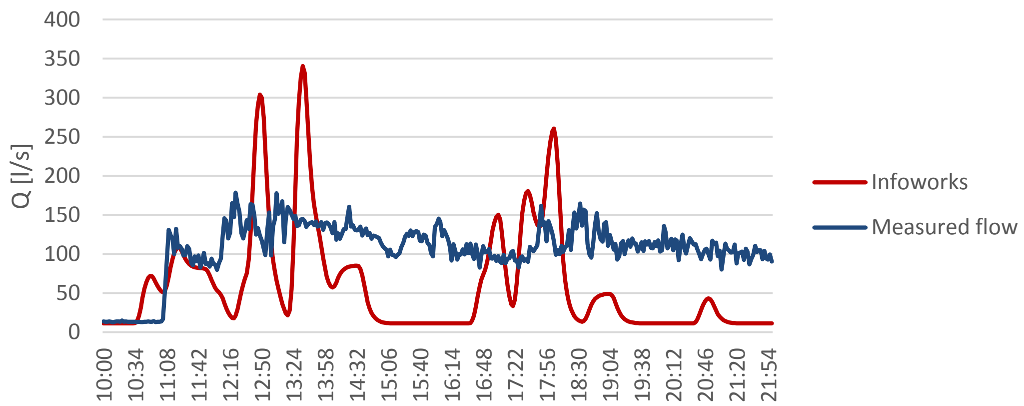

Figure 31; The modeled and observed flow when running the validation rainfall after calibrating the model with base flow.

Error for the water volume is now 24 % which is a larger error rate than in the calibration rainfall (table 31). The load of nitrogen for the rainfall event has not changed notably from the default simulation.

Table 31; the output from the Infoworks model as well as the monitored data after calibration.

	Rainfall event May 2013	Observed	Percentage difference
Water Volume [m^3]	2622	3464	24 %
Load Nitrogen [kg]	0.24	-	-

4.2.4 Intercomparison of model results

The type of output from the models differ and in some cases a like for like comparison was therefore not possible to make. For the parameters that were comparable between the models, a comparison was made.

All models can give volumes of water as an output. As a trial version was used for MUSIC, only the volume water for the rainfall event was obtained. In the full version it would have been possible to get a time series output with the flows and in that way get results for the entire year.

For StormTac, Infoworks and SuDS Studio the volume of water is obtained on a yearly basis from the runs with the yearly precipitation. The runoff volumes from the three modelling tools on a yearly basis are similar especially for StormTac and Infoworks where the difference for a year in runoff is about 2000 m^3, which is about 5.5 m^3/ day during the year (figure 32). For SuDS Studio and StormTac the difference is bigger, with about 21200 m^3per year and 58 m^3 per day.

The difference in volume is larger when looking at both runoff + base flow (figure 32). Notable in this figure is that both Infoworks and SuDS Studio have the same calculated base flow for the runoff + base flow. The calculated base flow for Infoworks and SuDS studio is the base flow calculated from observed data as explained in section 3.4.5. It is added as a single value of 11.1 l/s. The automatically calculated base flow for StormTac is much lower than the base flow from observed data used for Infoworks and SuDS Studio.

Observed flows on a yearly basis are not available. If the yearly volume was calculated as the amount of rainfall fallen into the catchment and assuming no infiltration the total volume of water during 2013 would be 511 974 m^3. The calculated volume is only 1.6 % difference from Infoworks CS and 6 % from SuDS Studio, but 41 % difference from StormTac for the total flow with both runoff and base flow.

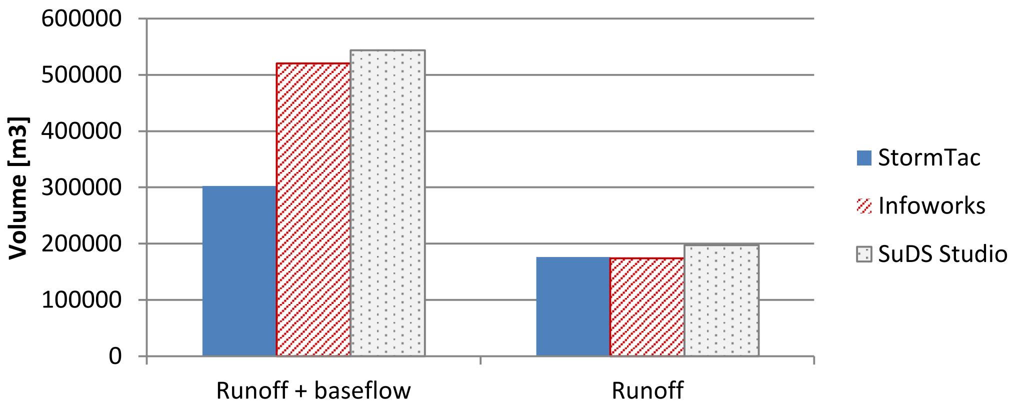

Figure 32; Runoff and total volumes of water (runoff and base flow) on a yearly basis for the Default run (without calibration).

The volumes of water for a single event from May 2013 were also compared to see the different responses for the flow from a particular rain. This was also compared to the measured volume of water for that single event (figure 33). The observed volume of water is larger than all of the output water volumes from the four modelling tools. For the modelling tools, SuDS Studio gave the largest volumes of water and MUSIC the lowest volumes of water. Important to notify in the graph is that for the measured flow, the runoff flow is the total flow with the average base flow subtracted from it.

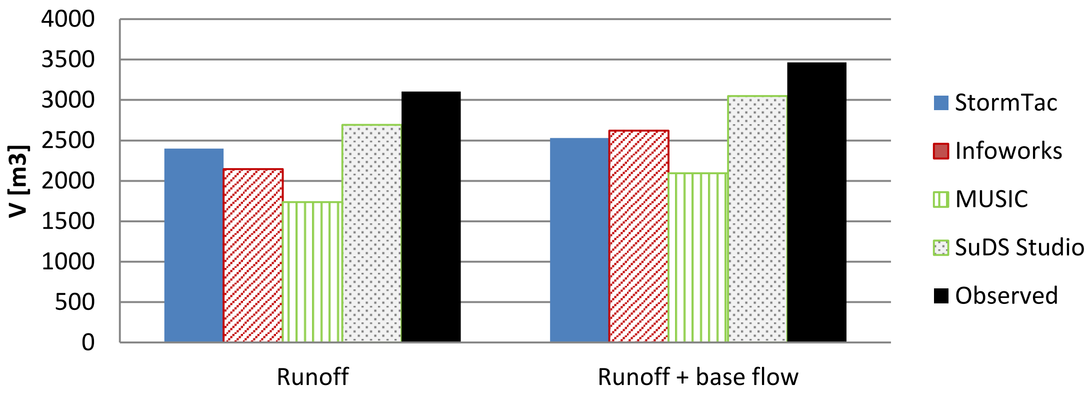

Figure 33; Runoff and total volumes of water (from runoff and base flow) for the rainfall event in May 2013. The volumes of water are also compared with observed volume of water.

A brief water balance calculation was made, see Appendix 5, showing that the volume water in the system would be around 2240 m^3 which is more similar to the modelled water volumes than the observed water volume.

The yearly amount of Nitrogen was possible to compare as this was calculated for all modelling tools except for MUSIC (figure 34). The value for SuDS studio is the same for both total and runoff flow as there was no base flow included in the model, and therefore the amount of pollutants were the same. The yearly amount of nitrogen is highest for SuDS Studio and lowest for Infoworks regarding the total flow (runoff and base flow). The yearly amount of nitrogen is highest for SuDS Studio and lowest for StormTac regarding the runoff flow.

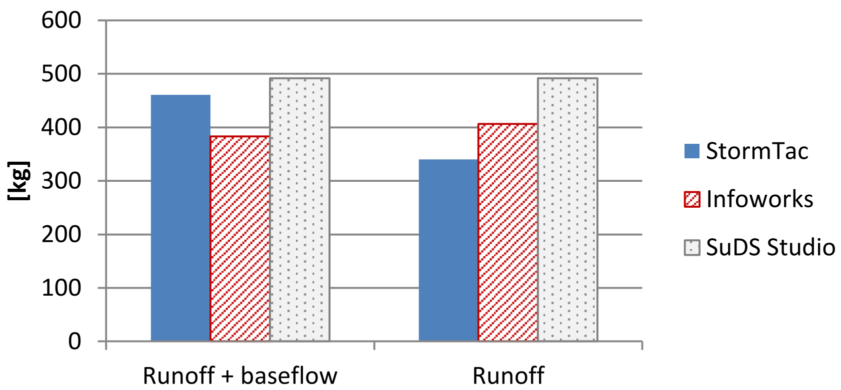

Figure 34; The yearly amounts of nitrogen.

From all four models loads of nitrogen for the rainfall event, May 2013, were obtained (figure 35). Infoworks gave a much lower pollutant load than the others. The outputs from StormTac and MUSIC were similar with only 0.2 kg difference. SuDS studio gave the largest load of nitrogen for the rainfall event.

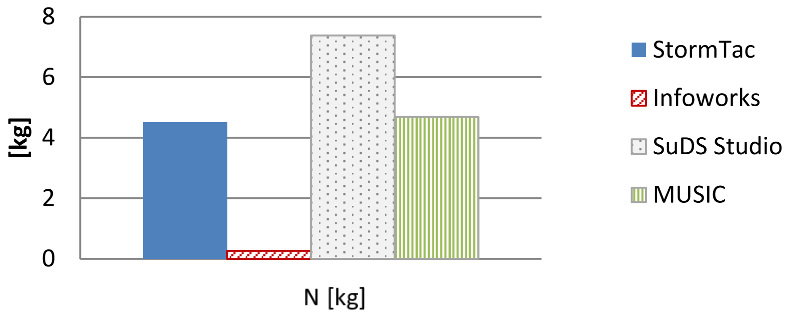

Figure 35; Loads of Nitrogen from the rainfall event. SuDS Studio gave the highest load nitrogen for the rainfall event, and Infoworks gave the lowest.

For StormTac and SuDS Studio other pollutant loads were comparable (figure 36 and figure 37). The loads for SuDS studio are obtained straight from the program, while in StormTac they are calculated from the concentrations and volume of water. The pollutant loads for Hg and BaP are not included in this figure but the results can be compared in table 22 and 26.

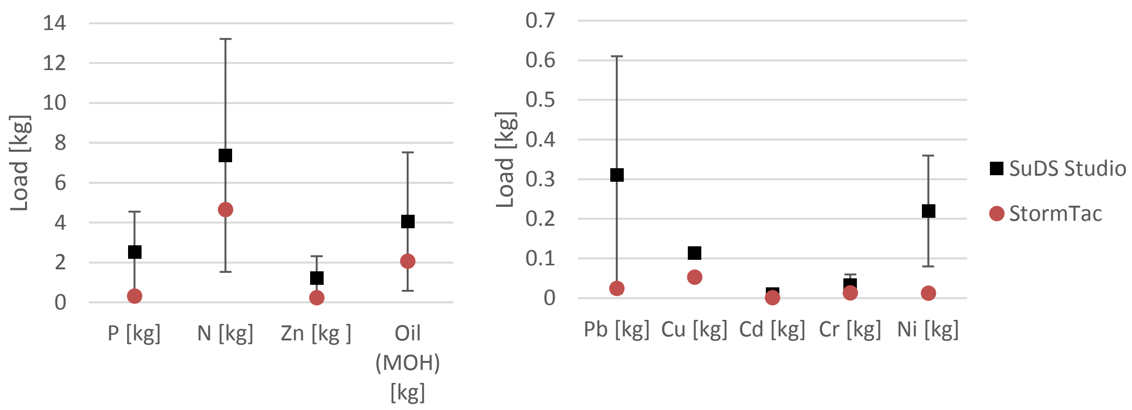

Figure 36; Pollutant loads predicted by SuDS Studio compared to predictions from StormTac for the rainfall event (May 2013).

For N, Zn, Oil, Pb, Cr and Hg are StormTac within the interval of the results from SuDS Studio. For P the concentration of StormTac is just below the interval in SuDS Studio.

The load intervals on a yearly basis from SuDS Studio were also compared with the load from StormTac on yearly basis (figure 37). For the yearly rainfall are the loads of N, Zn, Oil, Pb, Cu, Cd, Cr and Ni calculated in StormTac inside the intervals from SuDS Studio. The only substances outside of the interval are the loads for P, Hg and BaP. The load Nitrogen for Infoworks was also added in the figure to see the compliance. The load nitrogen from Infoworks CS is also inside the interval from SuDs Studio. For Nitrogen there is therefore a compliance for all three models, in the way that they are all inside and close to the middle of the interval from SuDS studio.

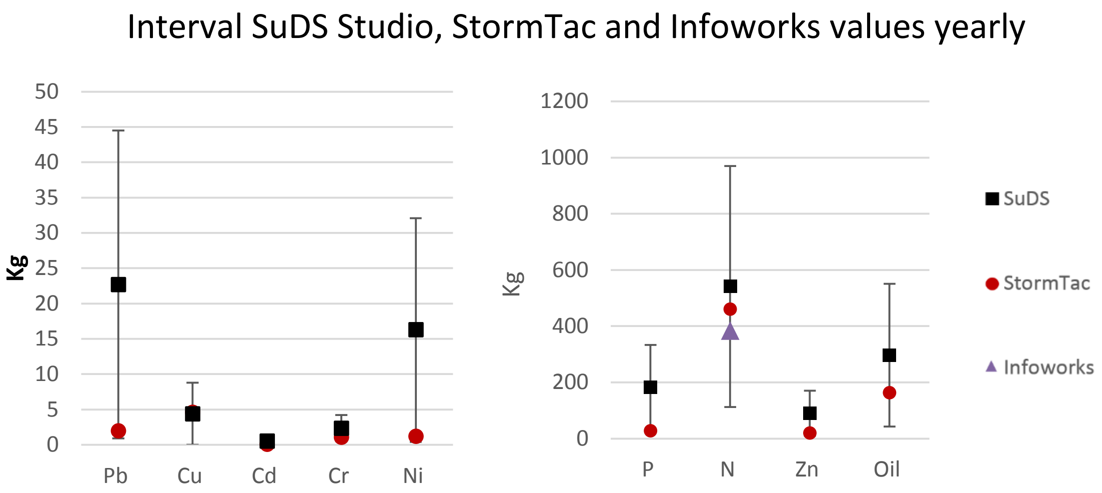

Figure 37; Pollutant loads predicted by SuDS Studio compared to predictions for StormTac on a yearly basis (2013). The value for N on a yearly basis for Infoworks as also compared.

The average nitrogen concentrations during the rainfall are comparable between the models (figure 38). The values for SuDS Studio and MUSIC are higher than the Swedish guidelines while the values obtained from Infoworks are much lower.

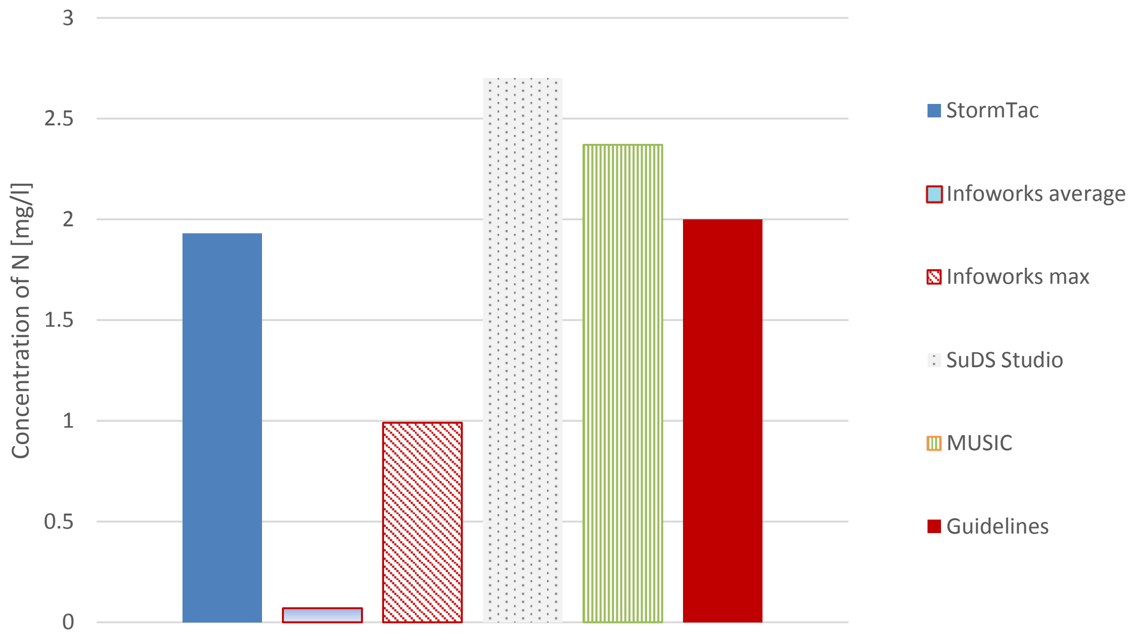

Figure 38; Concentrations of Nitrogen for rainfall event for all models and compared with Swedish Guidelines (table 21).

5 Discussion

5.1 Method

The overall choice of method was considered to give a comprehensive picture of the modelling tools as it was possible to evaluate all developed evaluation criteria by doing both a literature study and by testing the tools on a case study. To be able to draw more conclusions of model predictions more simulations with the tools would have been needed including simulations with more rainfalls, with other study sites and conducting a more extensive calibration.

As only a trial version of MUSIC was used, the results from the case study was not emphasised in the evaluation as this was considered to give non-representative information of the model.

This study was conducted by a modeller with no previous experience in any of the four selected tools. A more experienced modeller might not have evaluated the tools in the same way.

5.1.1 The model selection

From the market research, four tools that differed considerably in layout and design were selected for further studies. The selection of such diverse tools was a central part of this study as all the tools provide different features that can benefit from various studies. This made the comparison more difficult than if more similar tools would have been selected as the tools needed various input data and mainly produced various types of output data to be compared by intercomparison and against observed data. At the same time this selection was rewarding as the modelling tools different fields of applications was more enlightened and most likely easier to distinguish and emphasis than if the tools would have been more similar and had more similar fields of application.

5.1.2 Evaluation criteria

This evaluation of stormwater modelling tools is entirely dependent on the evaluation criteria. If other evaluation criteria had been developed and used for this study the conclusions regarding the tools strengths and weaknesses might have been different. The importance of each evaluation criteria in section 3.1 depends on the purpose of the study. For a short study where the goal is to make rough estimations of pollutants and flows in an area and where no observed data is available, the possibilities to calibrate the model will not be as important as for a detailed study where observed data is available. For a detailed study where a model is built to design stormwater facilities or to watch dynamics in a system for various seasons for example, the ability for calibration and validation in the modelling tool will be highly important to the study.

5.2 Literature study

The results from the literature study presented in table 18 highlighted that Infoworks CS is the only of the three tools applicable for design and studies of systems where the dynamics in a sewer system is central. It is also the choice for wastewater and combined systems. Features that were not found in any of the other three tools which is then a clear strength with the tool compared to the other three. On the other hand Infoworks was given low scores for required input data and learning period implying that Infoworks has weaknesses regarding *User friendliness* and *Required input*. This might not necessary mean that Infoworks CS is not as good as the other modelling tools for all users. For a modeller with previous experience of

Infoworks the learning period is not an important evaluation criteria. The same applies for a study where all the necessary input data such as pipe and manhole dimensions and coordinates, precipitation, material of the pipes and observed base flow data is available. In such a study the amount of required input data might be given a higher score as it is possible to make the model more site specific than in the other models. However, in this study the tools were evaluated by a user with no previous experience and therefore the learning period was an important criteria and also availability of input data and amount of required input data were important.

StormTac was given a high score for Pollutants as it includes around 70 predefined substances. More predefined pollutants are not necessarily a strength with a tool if the model predictions are not good. If the model predictions are not good, the number of predefined pollutants does not matter as the model will be useless. In such a case it is better that the user can define its own pollutants even if it requires more time and efforts. In the case where the predefined pollutants give good model predictions, it will be a strength. In this study more pollutants were given a high score, as this was later tested in the case study. If the model predictions for the pollutants in StormTac would have been poor, this feature would not have been concluded as an advantage. MUSIC was given a low score as it only includes three predefined pollutants and if the user wishes to define more, one of the existing (P, N, SS) has to be exchanged and only three pollutants can be modelled at the same time. This was considered a weakness since in Sweden, Stockholm County for example, have guidelines for twelve pollutants and it was considered an advantage to be able to model as many of these at the same time to save time and money.

5.3 Case study

The implementation of the case study differed between the models and so did the output. A model always provides a simplified picture of the system. None of the models gave good predictions for all parameters.

5.3.1 Site

The area of Deans Catchment consisted of an Industrial and residential area. The pollutant concentrations in stormwater from industrial areas depends on the type of industries in the area and for example the management of chemicals and amount of transportation. As could be seen in table 1 all 12 pollutants with Swedish guidelines have traffic as one of their main sources so the amount of traffic will be decisive for the concentrations in the water. The model predictions could have been different if another type of area would have been used in the case study such as a forest area.

5.3.2 Flow predictions

In general none of the models were able to make good predictions for the base flow, which had an impact on the results for flows, volumes of water and this might also affect the predictions of pollutants. StormTac was the only tool that automatically calculates base flow, but the result was only 30 % of observed base flow. The observed data for Deans catchment had a constant base flow event when no rainfall events occurred or had occurred for days. This implies that there might be pipe leakage somewhere in the system or that extensive water enters the system in other ways. For the yearly precipitation the base flow was about 40 % of the total amount of water for StormTac and about 70 % of the total amount of water for Infoworks CS. This shows how important calibration of base flow is and the importance of observed data of base flow for the models. It is important to remember that the base flow from Infoworks was assumed from observed data and StormTacs was calculated in the model.

5.3.3 Water volume

All four models predicted a smaller water volume than observed, which is concerning as this could imply that all models underestimate the actual water volumes. StormTac predicted a water runoff volume that was 30 % lower than observed. However the difference in runoff volumes predicted by StormTac and Infoworks CS and the calculated runoff water volume for SuDS Studio were similar which could also suggest that the observed data was not correct or that some assumption that was made for all models during the implementation was incorrect. This is further discussed in section 5.4 – Sources of error.

To see if the results from the models gave realistic amount of water volumes a rough calculation of the total amount of water fallen into the catchment during a year was calculated from the amount of corrected precipitation over the catchment multiplied with the area of the catchment, Appendix 5. If base flow was added it was considered to be realistic as SuDS Studio and Infoworks gave volumes that only differed with 2-6%.

With the water balance calculation in Appendix 5, the calculated total amount of water in the pipes from the rainfall event of 2240 m^3 is rather good compared to the modeled predictions, but not good if compared with the observed values. This could imply that the precipitation data or observed data was not matching.

5.3.4 StormTac

In the default simulation the average runoff flow, base flow and total flow for the rainfall event was lower than observed flows. The water volume was 30 % lower than observed for the rainfall event. For the yearly comparison when compared with the other three models (figure 32) the total water volume including the base flow was 60 % of the water volume for Infoworks CS for example. This might suggest that StormTac does not give good model predictions for flows and water volumes in areas with high base flows and that calibration is needed, further studies would be needed to confirm this. In a sensitivity and uncertainty study of parameters and indata in StormTac by Stenvall (2004), Stenvall concludes that runoff and base flows are most sensitive to errors in precipitation data (Stenvall, 2004). The precipitation data used for this case study was measured a few kilometres away from the study site where the flow was observed. This could have affected the result.

Model predictions in StormTac regarding pollutant concentrations were considered good. The model gave a better prediction for yearly values compared with the monthly spot samples than with the concentrations for the rainfall event. This was expected as StormTac is designed for long-term predictions and not for short term predictions and single event rainfalls (section 2.3.11).

5.3.5 Infoworks CS

The model predictions for the rainfall event in May with Infoworks CS were not considered to be good compared with observed flow time series as the graphs did not resemble each other. Infoworks CS was the tool that required most input data and assumptions by the modeller, which could have been one reason of the poor modelling result. The model built with Infoworks CS was also a simplified model where several pipes and manholes where removed to simplify the model. This could affect the flows, but the same water volume should still be in the modelled system. In comparison with the model predictions from the other three tools the model predictions for water volumes were in the same range as the others. For the calibration rainfall the hydrographs resembled each other more than for the event in May and the water volumes only differed with 2.3 %. More rainfall simulations would be needed to establish whether there might be something wrong with the observed data in comparison with measured rainfall as mentioned in section 5.2.4 and further discussed in section 5.4.

Infoworks only simulated the substance N out of the 12 guideline substances. For N no observed data was available but in the intercomparison of N concentrations (figure 35) Infoworks CS predicts a concentration much lower than the others. Infoworks CS simulates Total Kjeldahl Nitrogen which does not include nitrite and nitrate nitrogen. In stormwater nitrogen mainly appears as nitrate or as organic compounds (Andersson, et al., 2012). This might be the reason for this poor model predictions compared with the other models predicting Total Nitrogen that includes both nitrate and nitrite.

5.3.6 SuDS Studio

SuDS Studio gave large intervals for pollutant loads. This can be a strength with the tool as this provides a worst case scenario and a best case scenario. At the same time this can also allure into false safety for the user as the intervals sometimes were rather large. No observed pollutant loads were available and therefore the loads predicted by the model could not be validated against measured data but only compared with the loads in StormTac. To validate this model prediction observed load data would have been desired. This could have been calculated from observed concentrations in comparison with observed water volumes. However the concentrations were measured with time controlled sampling and the time-steps were considered too big to give enough information to calculate the actual loads. SuDS Studio does not give pollutant concentrations as an output which would be preferable if using the model in Sweden as the Swedish guidelines are given as concentrations and not loads.

In figure 36 and 37 pollutant loads for the rainfall event and the annual pollutant loads were compared between StormTac and SuDS Studio. The load for Infoworks on a yearly basis was also added in figure 37. The loads from StormTac for the rainfall event, fall into the interval in SuDS Studio for N, Pb, Zn, Cr, Hg and oil. For P the load from StormTac is just below the interval. For the annual loads are N, Pb, Zn, Cr, Oil, Cu, Cd and Ni inside the interval. The only Substances outside of the interval are P, Hg and BaP.

5.3.7 MUSIC

For the simulation in MUSIC the concentration of N was in the same order as StormTac with a difference of less than 20 %. As StormTac gave good model predictions for the other substances this was considered to be a good model prediction. Predictions for P with MUSIC were 230 % larger than the concentrations in StormTac and for TSS it was as much as 400 %. For the models that have calculated concentration of suspended solids i.e. from StormTac and MUSIC, the result differs significantly from the observed values. The calculated concentrations for SS showed no compliance between the models. This could mean that concentrations of suspended solids are difficult to model for an industrial area

5.4 Sources of error

5.4.1 Catchment, land use and runoff coefficients

The definition of the catchment and subcatchments was made from land use, stormwater network, property boundaries and from the slight inclination towards the watercourse. The definition of the catchment boundaries is essential for calculating water volumes, flows and pollutants. If the assumed catchment used for modelling is larger than the actual catchment area the total amount of runoff water in the system will most likely be larger than observed runoff volumes and the base flow will most certainly also be larger. In this study observed water volumes were larger than predicted by all model which could be due to an incorrect defined catchment. If the defined catchment is correct, the division into subcatchment will not affect the total amount of water in the system, but the peak flows might not be the same due to changed times of concentration.

5.4.2 Runoff coefficients

The division into land use classes is an essential part for calculating both pollutants and flows. If the land use classes would have been decided in a different way, this would have resulted in other runoff coefficients used in the models. If larger runoff coefficients would have been used the predicted volume water in the models would have been larger. According to Jansson 2013 a sensitivity study conducted by Ahlin (2012) with MIKE Urban and another sensitivity study by Kleindorfer (2009) with MUSIC concludes that the runoff coefficients are the most sensitive model parameter (Jansson, 2013).

5.4.3 Observed data

As the models all predicted smaller water volumes than observed, this implies that either the models give poor predictions, the implementation was wrong or that the observed data is not correct. As all models where given similar input data and all gave similar predictions of water volumes this might imply that the input data in correlation with observed flows could be incorrect. The rainfall was measured a few kilometres away from Deans Catchment and the SWO where the flow was measured. The rainfall might have been larger over Deans catchment than the rainfall measured a few kilometres away which would make the comparison of input data and observed data uncertain.

The pollutants where measured with spot samples and time controlled samples. These two sampling methods can both miss pollutant peaks and lows in concentrations. If flow proportional samples would have been used instead the results could be different.

5.5 Further studies

For further studies it would be interesting to do a comparison of results from a non trial version of MUSIC with StormTac, Infoworks CS and SuDS Studio. To further evaluate these models simulations with other rainfalls could be made and compared with observed data. It would also be interesting to test the models on other case studies with catchments with other land use to see if this affects the model predictions. StormTac might for example not give as good pollutant concentrations with a non industrial and residential area.

All models included in this study have an extensive range of applications and not all functions have been evaluated in this study. A function not evaluated is the design of stormwater treatment facilities and local disposal possibilities such as infiltration facilities, ponds and ditches. These are important functions as these kind of systems are becoming more and more state of the art to use today in Sweden and would therefore be interesting to study.

6 Conclusions and recommendations

Today, there exists various computer-based modelling tools for modelling stormwater quantity and quality. The four selected modelling tools; StormTac, Infoworks CS, SuDS Studio and MUSIC differ significantly in structure, layout and focus. The modelling tool that is best suited for a study will be completely dependent on the goal of the project.

There are benefits with using Infoworks CS for projects with the goal to design stormwater, wastewater or combined sewer systems. It is also an appropriate tool to study risks of flooding in the network, movements of water, contaminant and sedimentation in the network as the tools is fully distributed. Infoworks can also be used to study point source pollutants. Infoworks CS is applicable for both short term and long term predictions. Infoworks can also be used for surface pollutants, however only five default pollutants are included in the model. The results from the case study did not give good model predictions for the pollutant concentrations of nitrogen for a short term rainfall. Infoworks does not calculate base flow automatically.

Projects that benefits from using StormTac are projects with main focus on long term predictions of pollutants. StormTac is also applicable for calculations of long term runoff flows. The model does not require much input data and can therefore be used when not much input data is available. StormTac gave good model predictions when compared with observed spot sampled pollutant data in the case study. StormTac has a comprehensive approach on stormwater systems and includes the recipient. It was not considered good for calculating base flow for catchments with large base flow. StormTac can also be used for studies of stormwater treatment facilities.

SuDS Studio is a unique tool for defining suitable options for retrofitting SuDS solutions such as for example green roofs and ponds. As of 2013 there were no other such tool available. SuDS studio can also be used for looking at the impact of the SuDS solutions on water quality and water quantity. SuDS studio provides an interval for pollutant loads from surfaces. The interval can provide information regarding the worst case scenario of pollutant loads. In the case study the intervals were large for some pollutants which makes the result for these pollutants uncertain. SuDS Studio does not give pollutant concentrations as an output which would be preferable for use in Sweden as the guidelines are given as concentrations.

MUSIC is a tool used for decision making of stormwater systems. Its main focus are pollutants and treatment of pollutants through treatment facilities such as ponds and wetlands for example. MUSIC should not be used for detailed design. In the case study the trial version of MUSIC did not give good predictions for TSS concentrations when compared to observed concentrations but the predictions of nitrogen concentration was considered good when compared to results from StormTac.

The strengths and weaknesses are summarized in table 32.

Table 32; Strengths and weaknesses with the modelling tools.

	StormTac	Infoworks CS	SuDS studio	MUSIC
Strength	-User friendly and few input data needed to run the model, short learning curve -Good model predictions for pollutant concentrations in case study -Automatic calculation of base flow. -Treatment, detention and Recipient sub models -More than 70 pollutants included in the model	-Complete buildup of Network -Studies of flood risks -Simulate pollutant point sources -Sedimentation in pipes -Time varying results, with various ways of presenting the results -Fully distributed	-Unique tool for defining SuDS options - New version includes 85 SuDS solutions -Gives interval for pollutant loads - Worst case scenarios for pollutant loads -User friendly to run, few input data needed	-User friendly -Requires a short learning period -Treatment facilities
Weakness	-Not appropriate for single event studies -No buildup of a network. -Base flow contains uncertainties and needs calibration.	-Few default pollutants and poor model predictions of N in the case study -Requires many input data and a model is time demanding to build -Base flow need manual input	-Time demanding to analyze data -Large interval for some pollutants	-Requires pollutant concentrations to be manually defined if the land use is not a typical urban, forest or agriculture node -Only the three default pollutants: N, P, SS

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Appendix 1 – Methods for calculating design flows

The rational method

The rational method is used to compute design flows, $Q_{d\ dim}$ [l/s], at various points in the sewerage system. Rational method was developed in the 1800's and only accounts for the catchment area A [ha], the runoff coefficient φ that is a value between 0-1 and the rainfall intensity i [l/s·ha] for a certain duration of a rain t_r [s] as shown in equation 1.

$$Q_{d\ dim} = A\varphi i(t_r) \tag{8}$$

When the rational method is used it is assumed that the rainfall intensity is evenly distributed over the catchment and the time of concentration is about the same over the entire area and equal to the duration of the rain (Svenskt Vatten, 2011b). The method is very simple and is therefore best suited for rough calculations or for small and evenly spaced areas. If the time of concentration differs much throughout the catchment it is better to use the time-area model, see next section (Arnell, 1980; Svenskt Vatten AB, 2004).

Time –Area model

The Time-area model is used for calculating the design flow at various points in the network system. Unlike the rational method, it accounts for the time of concentration in the catchment and in the network. The model divides the catchment into smaller parts, with approximately the same time of concentration (Hendriks, 2010). With this method it is possible to generate runoff hydrographs. However, this method sometimes shows response to the rain that is to slow (Arnell, 1980). The problem with this method is that it assumes that the time of concentration is the same for all areas, regardless of the amount of water draining (Beven, 2003) .

Appendix 2 – Comparison of features

Table 33; Features of the modeling tools in the market research.

	StormTac	**SWMM 5.0**	**PCSWMM**	**MIKE Urban**	**Infoworks SD**	**InfoWorks ICM**
Developer/Publisher	StormTac AB	EPA	CHI	DHI	Innovyze	Innovyze
Water systems						
Stormwater	Yes	Yes	Yes	Yes	Yes	Yes
Wastewater	-	Yes	Yes	Yes	-	Yes
River systems	-	-	Yes	-	-	Yes
Area of use						
Water quantity	Yes	Yes	Yes	Yes	Yes	Yes
Water quality	Yes	Yes	Yes	Yes	Yes	Yes
Sewer system	-	Yes	Yes	Yes		Yes
LID/SuDS/LOD/WSUD	Yes	Yes	Yes	Yes	Yes	Yes
Long term predictions/single event	Long term	Both	Both	Both	Both	Both
Simulation of 1D pipeflow	-	Yes	Yes	Yes	Yes	Yes
2D overland flow	-	-	Yes	Yes	Yes (optional module)	Yes
Import/Export/Connections						
GIS	Results from StormTac can be integrated with a GIS-model	Interchange	Integration	Complete Integration	Integration/ Import	Integration/ Import/export
CAD	-	-	Yes (various formats)		Import and Export of some formats	

Table 34; Features of the modelling tools in the market research.

	MUSIC	**XPSWMM**	**XP STORM**	**StormCAD**	**CivilStorm**	**Civil 3d - storm och sanitary analysis**	**SEWSYS**
Developer/ Publisher	eWater	XP Soultions	XP Solutions	Bentley	Bentley	Autodesk	
Water systems							
Stormwater	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Wastewater	-	Yes	-	-	-	Yes	Yes
River systems	-	Yes	Yes	-	-		-
Area of use							
Water quantity	Yes	Yes	Yes	Yes	Yes	Yes	
Water quality	Yes	Yes	-	-	Yes	Yes	Yes
Sewer system						Yes	-
LID/SuDS/L OD/WSUD	Yes	Yes	Yes	-	Yes	BMP's	
Long term predictions/ single event	Both	Both	Both			Both	
1D pipeflow	-	Yes	Yes	Yes	Yes	Yes	-
2D Overland flow	-	Yes	Yes			-	-
Import/Export/Connections							
GIS	-	Import/expo rt	Import/expo rt	Some conversion utilities from GIS databases	Some conversion utilities from GIS databases	Import/expo rt various GIS database structures, shape files	-
CAD	-	Import/expo rt	Import/expo rt	Can be used within AutoCAD	Can be used within AutoCAD	Yes (bidrectional data exchange)	-

Appendix 3 – Guidelines for pipe dimensions and gradients

The guidelines and requirements that Svenskt Vatten has regarding minimum gradients of pipelines that should be self-draining (Svenskt Vatten AB, 2004).

Table 35; Minimum gradients of pipelines from Svenskt Vatten P90.

Dimension [mm]	Minimum gradient ‰	Flow [l/s]
160	5.0	2.0
200	4.5	2.5
300	3.0	6
400	2.5	9
500	2.0	14
600	1.5	25
800	1.0	60
>800	1.0	-

Appendix 4 – Pollutant concentrations for StormTac and MUSIC

Standard concentrations for each pollutant and land use for StormTac and MUSIC.

StormTac

The standard concentrations for the pollutants evaluated in this thesis, for each of the four

Table 36; The standard concentrations for each pollutant and for each land use. (StormTac, 2014)

	P	**N**	**Pb**	**Cu**	**Zn**	**Cd**	**Cr**	**Ni**	**Hg**	**SS**	**Oil**	**BaP**
	mg/l	mg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	µg/l	mg/l	mg/l	µg/l
Road (1000 v/d)	0.14	2.4	3.9	23	43	0.28	7	4.4	0.08	66	0.78	0.011
Industrial area	0.30	1.8	30	45	270	1.50	14	16	0.07	100	2.50	0.15
Roof	0.026	2.0	2.0	10	33	0.08	0.17	0.4	0.01	10	0	0.01
Mixed Green Area	0.12	1.0	6.0	12	23	0.27	1.8	1.0	0.01	43	0.17	0

MUSIC

These values for the pollutants were used for the Residential area, table 37.

Table 37; Values from Blacktown city council guidelines and the standard deviation (Blacktown City Council, 2013).

Land use	**TSS runoff**	**TSS base flow**	**TP runoff**	**TP base flow**	**TN runoff**	**TN base flow**
Roof	1.30 std 0.32	1.20 std 0.17	-0.89 std 0.25	-0.85 std 0.19	0.30 std 0.19	0.11 std 0.12
Manmade	2.15 std 0.32	1.20 std 0.17	-0.6 std 0.25	-0.85 std 0,19	0.30 std 0.19	0.11 std 0.12
Road	2.43 std 0.32	1.20 std 0.17	-0.30 std 0.25	-0.85 std 0,19	0.34 std 0.19	0.11 std 0.12
Landscape	2.15 std 0.32	1.20 std 0.17	-0.60 std 0.25	-0.85 std 0,19	0,30 std 0,19	0.11 std 0.12

For the manmade surfaces in Deans Industrial estate the values were exchanged to values comparable with an industrial area according to the MUSIC user guide (table 38) (eWater, 2013b).

Table 38; The values for the Industrial area from MUSIC User guide (eWater, 2013b).

	TSS	**TP**	**TN**
Industrial	2.17 std 0.52	-0.523 std 0.3	0.4 std 0.22

Appendix 5 – Water balance

A brief water balance was made to estimate the amount of water from the area to see if the results from the models were reasonable. The estimation was made with equation 9, where p is the precipitation [m], A[m^2] the catchment area and φ the runoff coefficient. A joint weighted runoff coefficient was calculated to 0.32 according to equation 10 (Svenskt Vatten AB, 2004) and with the runoff coefficients from table 39, in accordance with Svenskt Vattens publication P90. The total amount of water fallen over the catchment was 6986 m^3 and with the joint φ the volume water was 2242 m^3.

$$V = p\varphi A \qquad (9)$$

$$\varphi_{total} = \frac{(A_1\varphi_1 + A_2\varphi_2 + .. + A_n\varphi_n)}{(A_1 + A_2 + .. + A_n)} \qquad (10)$$

Table 39; Land use from the case study, area for each land use and the assumed corresponding land use from Svenskt Vatten P90 and the runoff coefficients.

Land use	Area [ha]	Svenskt Vattens land use	φ
Roads	4.49	Asphalt	0.8
Man-made surfaces	7.49	Closed buildings, industrial area	0.5
Buildings	7.98	Roof	0.9
Green area	29.94	Grass area	0.05 (0 -0.1)

Water volume for a year

A brief calculation to see how much rain that theoretically falls over Deans catchment in a year. This was calculated to see if the total yearly runoff water volume from the models were reasonable.

V = $p_{corrected*}$A= 511974 m^3