Modelling of Substance Flows in Urban Drainage Systems
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STEFAN AHLMAN

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Cover: The user interface of the substance flow model SEWSYS

SEWSYS® is a registered trademark in Sweden

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Göteborg, Sweden 2006
Som vatten
Regn slickar hela staden
som en fuktig kall tunga
allt är asfalt smutsigt vatten
för lyktorna att spegla sig i
Går, Går förbi
alla människor är blanka som is
och du fastnar under ljusen
som ett fotografii

Kent (1995)
Modelling of Substance Flows in Urban Drainage Systems

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ABSTRACT
Stormwater is recognised as a large contributor of toxic substances to receiving waters. Different measures to manage stormwater quality have been proposed, including structural and non-structural best management practices (BMPs). Computer models have become useful tools for the analysis, evaluation and design of these BMPs. The main objective of this study was to develop a modelling framework that enables an analysis of the pollutant sources in urban drainage systems. In the modelling framework the sources of pollutants from different activities in the urban area were separated according to their origin, e.g. material corrosion, brake wear and tyre wear.

The model was named SEWSYS® and was developed in MATLAB/Simulink. SEWSYS simulates substance flows in urban drainage systems. At present the model contains 20 different substances, including nutrients, heavy metals and organic pollutants. The model can simulate both stormwater and domestic wastewater flows, in either combined or separate sewer systems. In the stormwater quality module, the pollutants from sources such as atmospheric deposition, traffic and construction materials are generated and accumulated on impervious surfaces during dry weather until they are washed away during rainfall.

Validation studies of the SEWSYS model were carried out using measurements of stormwater flow and quality. Calibration and validation were performed using a split-sample technique, i.e. with independent data sets for calibration and validation. The hydrological part of the model performed well in the validation but the quality part produced less reliable results.

Uncertainty analysis of the stormwater module in SEWSYS was carried out for the model outputs runoff volume, pollutant concentrations (EMCs and SMC), and pollutant load of heavy metals for an uncalibrated and calibrated model. Uncertainty assessment methods included Monte Carlo simulations, multi-linear regression and a Markov-Chain Monte Carlo method for parameter calibration. The results of the uncertainty analysis showed that predictions made with an uncalibrated model were associated with a considerable amount of uncertainty. It was also shown that by means of calibration this uncertainty could be reduced to an acceptable level.

The application of the SEWSYS model in different types of scenario studies has been an important part of the model development. The results from the application studies demonstrate that the model is a useful tool for simulating and evaluating pollutant source control measures.

Keywords: BMPs, diffuse pollution, modelling, source control, urban stormwater
Modelling of Substance Flows in Urban Drainage Systems

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SAMMANFATTNING

Dagvatten från urbana områden transporterar stora mängder toxiska ämnen till våra vattendrag. Denna avhandling presenterar en substansflödesmodell som utvecklats i syfte att beskriva föroreningstransport i urbana områden samt analysera olika scenarier med föroreningsminskande åtgärder och källkontroll. Datormodellen kallas SEWSYS® och är utvecklad i programvaran MATLAB/Simulink. SEWSYS beskriver uppbyggnad och transport av föroreningar i urbana avrinningsområden. Föroreningarnas källor är också beskrivna i modellen och inkluderar exempelvis korrosion av byggnadsmaterial, bromsslitage och däckslitage. För närvarande hanterar modellen 20 olika substanser från grupperna näringsämnen, metaller och organiska föroreningar. Det är möjligt att simulera både dagvatten och hushållsspillvatten, antingen i kombinerade eller i duplikata avloppssystem.


SEWSYS möjligheter demonstreras i avhandlingen genom olika tillämpade studier där modellen använts för substansflödesmodellering. Utifrån den detaljnivå som modellen använder i beräkningarna och de erfarenheter som de tillämpade studierna givit har SEWSYS visats vara ett mycket användbart verktyg för att simulera dagvattenföroreningar samt att utvärdera åtgärder som baseras på olika scenarier för källkontroll.

Nyckelord: avloppssystem, dagvatten, föroreningssaspekter, källkontroll, modellering, substansflödesanalys
LIST OF APPENDED PAPERS
This thesis is based upon the following papers, referred to in the text by their roman numbers (e.g. Paper I). The published papers are appended and reproduced with kind permission of the publishers.


Other publications by the author


ACKNOWLEDGEMENTS

The Swedish Foundation for Strategic Environmental Research (MISTRA) has granted financial support for this research and is gratefully acknowledged. Parts of the work presented in this thesis have been obtained within the framework of the European Commission funded research project DayWater “Adaptive Decision Support System for Stormwater Pollution Control”, contract no EVK1-CT-2002-00111, and the financial support given to this PhD project is gratefully acknowledged. The Göteborg Water and Wastewater Works is acknowledged for their financial support and help with the field measurements of stormwater.

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Working on the systems analysis project with Annika Malm and Henrik Kant (Göteborg Water and Wastewater Works) and Pascal Karlsson (City of Göteborg – Recycling) provided me with useful insights about the reality outside the university world. I also had the benefit of enjoying your company during the 2004 NOVATECH conference in Lyon.

I also want to thank my friends and family for support and encouragement. Thank you all for giving me good reasons to take necessary breaks from working on this thesis!

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Göteborg, April 2006

Stefan Ahlman
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1 INTRODUCTION

This chapter gives an introduction and overview of the problems relating to pollution in urban water systems, and especially the contribution from urban drainage systems. The introduction also provides arguments why modelling is relevant in pollution analysis of urban water systems. Furthermore, the aim and scope of the study as well as the outline of the thesis are presented.

1.1 Background

Water is our most common natural resource and necessary for all living things. It is therefore important to keep it clean. However, the present situation of water quality management in the world is not acceptable, mainly due to the forces of increasing population and economic development (Huang and Xia, 2001). This is especially evident for the world’s fastest growing cities (also called mega cities) which typically are located in low-income developing countries and characterised by poor water infrastructures and unsatisfactory wastewater treatment. Urbanization is without doubt one of the most characteristic global changes of today and of the coming decades (Varis and Somlyody, 1997). In the industrialised world the water situation is somewhat better but by no means satisfactory. Water stress, defined as pressure on the quantity and quality of water resources, is evident in many places throughout Europe, resulting in serious problems of water shortages, flooding, pollution and ecosystem damage (EEA and UNEP, 1997). However, in the last decades there has been much improvement in the protection and quality of Europe’s water and it is important that this positive trend continues.

The urban water system is a complex structure consisting of drinking water production from a raw water source (surface or groundwater), distribution of water to consumers in a pipe system, urban drainage (i.e. conveyance of wastewater and stormwater) and in the end treatment of the wastewater and discharge to receiving waters. In addition comes the issue of sewage sludge management. With all the involved areas mentioned above follows that there are a lot of stakeholders involved and affected by the urban water system which influences the society in environmental, social and economic dimensions. In addition, the present urban water system is heavily dependent on advanced technology. A relevant question is therefore: Is the urban water system of today sustainable?

It is not easy to give a straightforward answer to the question above, as there are considerable uncertainty and subjectivity in the definition of sustainable development and especially its implementation (Butler and Parkinson, 1997). But a good starting point is to look at the actual functions and services of the system of interest. The functions and services provided and the resources used in urban water management have been categorised by Larsen and Gujer (1997). Urban water systems in the developed world usually fulfil the functions of urban hygiene, drinking water and personal hygiene and prevention of flooding, while the function protection of natural resources (ground and surface waters, soil and air) is not entirely fulfilled. It can also be discussed whether urban water systems should be responsible for recycling nutrients in the sewage sludge between city and countryside. If so, Larsen and Gujer conclude that the present system is not fulfilling this function in a satisfactory manner.
The Swedish research programme *Sustainable Urban Water Management* has formulated a conceptual framework in order to facilitate systems analysis in urban water management (http://www.urbanwater.org). The framework has been used in the research programme to guide the evaluation of sustainability of urban water systems with applications in different model cities (Hellström *et al.*, 2000; Malmqvist and Palmquist, 2005). The conceptual framework shown in Figure 1 describes the urban water system as consisting of three elements: (1) Organisation, (2) Users, and (3) the Technology. These three system components interact with each other and form the dynamics of the system. Five groups of sustainability criteria are used in the systems analysis in order to integrate different research disciplines and to facilitate useful and creative syntheses of knowledge. With this holistic view the general aim of the Urban Water programme was to support strategic decisions about future water and wastewater systems, primarily on a national scale but also with international outlooks. The Urban Water programme was founded by The Swedish Foundation for Strategic Environmental Research (Mistra) and was running from year 1999 to 2005.

The work presented in this thesis was part of one of the technical projects in the Urban Water programme, with the primary goal to investigate stormwater management and provide knowledge and modelling tools for decision support in stormwater systems. The substance flow model SEWSYS was the main deliverable from this technical project (*Paper I*).

![Figure 1. The Urban Water conceptual framework](image)

Stormwater, here defined as runoff caused by rain and snowmelt in urban areas, and its handling in urban drainage systems is an intrinsic part in urban water management (Sundberg *et al.*, 2004). Urban drainage systems should be designed to handle wastewater and stormwater with the aim of minimising the problems caused to humans and the environment (Butler and Davis, 2004). Traditionally, wet-weather collection systems have been designed to move stormwater from the urban area as quickly as possible providing safe drainage and thus avoiding problems of local flooding. This traditional conveyance approach leads to problems with decreasing groundwater levels, high downstream discharges and release of pollutants to receiving waters.
Stormwater takes different pathways in combined and separate sewer systems. In combined sewers stormwater is conveyed together with domestic and industrial wastewater to a wastewater treatment plant (WWTP). Because of the limited storage capacity in the sewers, there is a need to have combined sewer overflows (CSOs) in the pipe system to cope with the increased flow during intense rain events. The diverted mixture of wastewater and stormwater is then discharged to the nearest water body which can have a detrimental effect on the water quality. The flow variations also cause problems with disrupted processes in the WWTP. Recycling of sewage sludge for agricultural use is another matter influenced by stormwater in combined systems. A considerable part of the heavy metals in sewage sludge comes from stormwater (Boller, 1997), which may prevent the sludge to be used as a fertilizer resource. The combined sewer system is predominant in many countries in Europe (Brombach, 2002) and in older parts of cities in the United States (Burian et al., 2000) and Japan (Fujita, 2002). In Sweden, about ¼ of the population lives in areas with combined systems, mainly in older parts of the larger cities (Stockholm, Göteborg and Malmö).

Separate sewer systems have been built in Sweden since the 1950s. In this system there are two pipes: one for domestic/industrial wastewater and one for stormwater. The drainage of groundwater to protect buildings is typically diverted to the stormwater pipe. The separate system was in a sense a response to the above-mentioned problems with combined systems and disturbances in the WWTPs, especially regarding the treatment capacity, and later on discharges from CSOs. However, the implementation of the separate system generated a paradox because in fact more untreated stormwater was discharged into urban waters. During the 1970s and 1980s there were several studies conducted around the world on stormwater quality issues and as a results it became known that stormwater alone can be a potentially large contributor of toxic substances to receiving waters (Ellis et al., 1987; Malmqvist, 1983; USEPA, 1983). Therefore different measures to manage stormwater quality have been proposed, commonly known as best management practices (BMPs).

Stormwater BMPs can be divided into: (1) structural (such as engineered and constructed systems) and (2) non-structural (institutional, education or pollution prevention practices) (Clary et al., 2002). Both types of BMPs have the ultimate purpose of improving the quality and/or controlling the quantity of stormwater runoff. Examples of structural stormwater BMPs are constructed wetlands, detention and retention ponds, swales and infiltration systems. These drainage components have been implemented all over the world, especially in the United States, Europe and Australia. Because of the vast number of possible solutions it is not always straightforward to decide on the most appropriate BMP for a specific case.

The European Union’s centralised research activities during the period 1998–2002 were set out in the European Commission’s (EC’s) Fifth Framework Programme (FP5). One of the sub-programmes is directed into energy, environment and sustainable development and has the objective “to help to meet the environmental challenges and strike a balance between economic development and environmental sustainability” (http://europa.eu.int/scadplus/leg/en/lvb/j23001.htm). The CityNet cluster has been an important part of the Key Action: Sustainable Management and Quality of Water, and has contributed to the application of decision support systems in
the water sector (http://citynet.unife.it/). CityNet is a network of six European research projects under FP5 focussing on Integrated Urban Water Management (IUWM):

- CARE–W, Computer Aided Rehabilitation of Water Networks
- CARE–S, Computer Aided Rehabilitation of Sewer Networks
- DayWater, Adaptive Decision Support System for the integration of stormwater source control into sustainable urban water management strategies
- AISUWRS, Assessing and Improving Sustainability of Urban Water Resources and Systems
- APUSS, Assessing Infiltration and Exfiltration on the Performance of Urban Sewer Systems

The work presented in this thesis has been a part of the DayWater project, which was running from year 2002 to 2005. The focus in DayWater was on stormwater that is handled locally in urban areas using various source control or BMP techniques. Source control measures can be divided in the same way as BMPs into structural and non-structural techniques (Rauch et al., 2005). The part of the DayWater project reported in this thesis had the primary goal to develop a new modelling tool for simulation of sources and fluxes in urban drainage systems. This model is called STORM/SEWSYS and is further presented in Paper II.

In Europe today, urban water management is highly effected by the implementation of the EU Water Framework Directive (WFD). The WFD claims that by the end of 2015 a “good status of surface water” and a “good status of groundwater” should be achieved (EC, 2000). One important consequence of the WFD is that water management has to be done on a catchment scale in an integrated manner. Sustainable urban water management should therefore include stormwater source control as a method to reduce runoff volumes and peak flows, and at the same time improve the stormwater quality. So far source control has not been widely adopted throughout Europe. This issue was addressed by the DayWater project and the main deliverable was a prototype of an Adaptive Decision Support System (ADSS) related to urban stormwater source control measures (http://www.daywater.org).

To ensure that the EU water policy will be successful, the assessment of emissions into receiving waters will be increasingly important. The WFD requires a better understanding regarding the concentrations and loads of contaminants entering surface waters and a prioritisation of ‘control at the source’ strategies (Rule et al., 2006). Assessment of chemical hazards is a related critical issue, which have to be dealt with when evaluating different strategies for sustainable handling of stormwater. In the DayWater project a methodology for identifying the most critical and representative chemical pollutants was developed (Eriksson et al., 2005). One of the deliverables was a list of selected stormwater priority pollutants (SSPP-list). The SSPP-list consists of 3 polyaromatic hydrocarbons (PAHs), 4 herbicides, 1 polychlorinated biphenyl (PCB) and 4 other xenobiotic organic compounds (XOCs) as well as 13 physical/chemical parameters, metals and inorganic trace elements. The DayWater SSPP-list has guided the selection of priority pollutants included in the STORM/SEWSYS model (Paper II).
The pollution load from priority pollutants and its environmental effects in receiving waters can be evaluated using mathematical models. At present computer models are widely used in the analysis, evaluation and design of BMPs, especially for structural stormwater BMPs. Quality source control is a necessary complement to the traditional end-of-pipe solutions and the integration of both strategies decides whether the decisions we make today will in fact be sustainable. Substance flow models that describe the substances in stormwater and their sources are therefore important components in the decision process for developing sustainable urban drainage systems. To be able to model scenarios related to non-structural BMPs and quality source control, i.e. reducing the pollutants at the source, it is necessary to incorporate a comprehensive pollutant generation and transport description in such a modelling framework. In addition, the sources for pollutants from different activities in the urban area have to be separated in their respective origin, e.g. material corrosion, brake wear and tyre wear.

1.2 Aim and scope of the study
The overall purpose of the work presented in this thesis is to develop a modelling framework that enables sources and flux modelling in urban drainage systems and thereby providing decision support in stormwater management. Specific objectives of the developed model are: (i) to include the relevant substances (priority pollutants) related to water quality problems in combined and separate sewer systems, (ii) to make the pollution load calculations based on the sources for each pollutant, (iii) to allow for evaluation of pollution by taking the dynamics of the system into account, (iv) to make the modelling framework flexible and the model environment user-friendly, and (v) to give modelling results that in a clear and pedagogical way can be used by decision-makers.

The research was divided in the following steps:

- Defining modelling aim and scope, formulating a conceptual model (Papers I, II)
- Building a model structure including components, the relevant processes and their descriptions (Paper I)
- Validation of the model using quantity and quality measurements of stormwater runoff (Paper III)
- Assessment of the model’s predictive uncertainty and parameter sensitivity (Paper III)
- Application of the model in case studies in order to give feedback to the development, and also to demonstrate the usefulness of the model (Papers IV, V, VI)

1.3 Outline of the thesis
This thesis is based on six appended papers. Chapter 2 contains a comprehensive literature review which includes the latest advances in urban drainage modelling and pollution control. Chapter 3 gives a brief description of the methods and tools used in the research, while in Chapter 4 the model development from the six appended papers is summarized and discussed in relation to the literature. The conclusions of the research presented in this thesis are presented in Chapter 5. Chapter 6 contains an outlook and suggestions for future work.
2 LITERATURE REVIEW

This chapter aims at giving a review of the relevant literature that concerns the topic of this thesis. The main focus of the literature review is on stormwater pollution and its modelling in urban drainage systems.

2.1 Stormwater management

Stormwater, defined as runoff caused by rain and snowmelt in urban areas, and domestic wastewater are the main flows that are handled by the urban drainage system. Urban drainage systems should be designed to handle wastewater and stormwater with the aim of minimising the problems caused to humans and the environment (Butler and Davis, 2004). The available choices for handling the quantity and quality aspects of stormwater will be different depending on if the actual sewer system is of combined or separate type.

The hydrologic conditions, i.e. the natural cycle of water, are disrupted and altered when natural land is developed. Rainfall that once seeped into the ground now runs off the surface. The addition of buildings, streets and roads, parking lots and other surfaces that are impervious further reduces infiltration and increases runoff. Depending on the magnitude of changes to the land surface, the total runoff volume can increase considerably (Lee and Heaney, 2003). These changes not only increase the total volume of runoff, but also increase the rate at which runoff flows across the land. This effect is further intensified by drainage systems such as gutters and storm sewers that are designed to quickly convey runoff to rivers and streams, thereby providing safe drainage and avoiding problems of local flooding. This traditional conveyance approach leads to problems with high downstream discharges and decreasing groundwater levels (Burns et al., 2005).

Development and urbanization affect not only the quantity of stormwater runoff, but also its quality. Development increases both the concentration and types of pollutants carried by runoff. As it runs over rooftops and lawns, parking lots and industrial sites, stormwater picks up and transports a variety of contaminants and pollutants to downstream water bodies. In cities with separate sewer systems, stormwater runoff is recognised as the primary source of stream pollution (Walsh, 2000). In a study by Hatt et al. (2004) on the influence of urban density and drainage infrastructure on pollutant concentrations and loads in small streams, the authors propose that priority should be given to the concept of low-impact urban design (LID). This will minimise urbanisation-related pollutant impacts on streams, primarily due to a reduced drainage connection.

Measures to manage stormwater quality are commonly known as best management practices (BMPs). These are structural, non-structural and managerial techniques that are recognized to be very effective and practical means to prevent and/or reduce point source and non-point source pollution, in order to promote stormwater quality and protection of the environment (Clary et al., 2002). Examples of structural stormwater BMPs are constructed wetlands, detention and retention ponds, swales and infiltration systems. Non-structural BMPs comprise institutional, education or pollution prevention practices such as street sweeping. Terminologies for various stormwater measures have developed in different parts of the world, including Best Management

The term Sustainable Urban Drainage Systems (SUDS) was first introduced in Scotland as a concept to include source control, water quality aspects and socio-economic factors in the design and promotion of BMPs (D’Arcy and Frost, 2001). The SUDS concept recognises that the need of flood control and pollution control must be combined and considered together if the environment is to be adequately protected. And if the resulting stormwater facilities are to be acceptable for adoption and maintenance, they must also be attractive structures and cost-effective.

Water Sensitive Urban Design (WSUD) has been introduced in Australia as a sustainable approach to the management of urban water resources with the aim of minimising the impact of urban development on the natural water cycle (Lloyd et al., 2002). Fundamental to the application of WSUD is the adoption of best planning practices and BMPs. Best Planning Practices refer to the site assessment and planning component of WSUD. BMPs refer to the structural and non-structural control measures that perform the prevention, collection, treatment, conveyance, storage or reuse functions of a water management scheme. WSUD enables appropriate land-use requirements, including the layout and arrangement of a stormwater management scheme, to be harmonized with landscape characteristics.

Stormwater takes different pathways in combined and separate sewer systems. In combined sewers stormwater is conveyed together with domestic and industrial wastewater to a wastewater treatment plant (WWTP). Because of the limited storage capacity in the sewers, combined sewer overflows (CSOs) have been constructed in the pipe system. During intensive rain events the CSOs will divert the mixture of wastewater and stormwater to the nearest water body. The CSO discharges may have a detrimental effect on the water quality in the recipient (Marsalek et al., 1999b). The quality of sewage sludge leaving the WWTP is also influenced by stormwater coming from combined sewers. A considerable part of the heavy metals in sewage sludge comes from stormwater (Balmér, 2001; Boller, 1997; Palm and Östlund, 1996), which may prevent the sludge to be used as a fertilizer resource in agriculture. Other toxic compounds like PCBs and PAHs with stormwater as a significant source also affect the sewage sludge quality (Blanchard et al., 2001; Rossi et al., 2004).

Urban drainage systems in areas with cold climate conditions experience special requirements, arising from extended storage of precipitation and pollutants in the catchment snowpack, processes occurring in the snowpack, and changes in catchment surface and transport network by snow and ice (Marsalek et al., 2003). As a result, the hydrologic response and runoff quantity differ from conditions experienced in snow- and ice-free seasons. Cold climate conditions also add additional sources of pollutants, namely the application of de-icing and anti-skid agents (Marsalek, 2003). Urban snowmelt and winter runoff convey disproportionately high loads of specific pollutants at potentially acutely toxic levels; and ultimately, discharges of urban snowmelt and winter runoff may lead to reduced biodiversity in waters receiving such discharges (Marsalek et al., 1999a; Sansalone and Buchberger, 1997). Snow management in urban areas may also require local storage of fresh (unpolluted) snow and disposal of more polluted snow at central snow disposal sites (Reinosdotter and Viklander, 2006).
2.2 Urban stormwater pollution

As described in the previous section, the pollution aspect is an intrinsic part of stormwater management.

Diffuse or non-point source pollution is recognised as a major source of water quality problems in both surface and groundwater (Novotny and Olem, 1994). Pollution resulting from point sources has successfully been reduced by the efforts of regulators, whilst diffuse sources frequently remain as the dominant source of pollution. Stormwater, being such a diffuse source, is an important contributor to urban water pollution (Brezonik and Stadelmann, 2002; Buffleben et al., 2002; Uchimura et al., 1997). As stormwater runoff moves across the land surface, it picks up and transports pollutants directly into water bodies (separate system) or to a WWTP (combined system).

Urban surface runoff accounts for most of the negative effects observed in rivers, lakes and other receiving waters downstream or within urban areas. These negative effects include acceleration of the erosion of river banks, destruction of river habitats, increased eutrophication rates in lakes, and a general decline in receiving water quality. Observations show that a large storm event may shock the receiving water body many times greater than an ordinary sanitary effluent load (Lee and Bang, 2000). The effects of urban runoff on receiving water quality are highly site-specific (USEPA, 1983), which makes it difficult to predict impacts and design appropriate management and control practices without the access of site-specific data.

Several factors influence the generation and magnitude of stormwater pollution. Geographic and physical factors such as type and intensity of land use, degree of imperviousness, drainage connection and density, soil type and catchment slope are important determining factors in the generation of stormwater pollution. Climatic factors such as rainfall intensity and duration, storm frequency, and time since antecedent rainfall are also important conditions. The inter-event dry period is an important factor for the first-flush effect, which is the observed phenomenon that the initial part of a storm may have higher pollutant concentrations than the later part. The first-flush phenomenon has been investigated by several researchers to understand the characteristics of stormwater runoff discharge (Deletic, 1998; Lee et al., 2002; Saget et al., 1996). Lee et al. (2004) report a seasonal first-flush phenomenon occurring in Californian catchments due to several months of dry period during the summer season.

The type of urban land use plays an important role for the generation of stormwater pollution (Goonetilleke et al., 2005). Commercial and industrial land uses contribute with more pollutants than urban open space, parks, and low density residential land uses (Smullen et al., 1999). The sources and causes of urban stormwater pollution are widely known and closely related to human activities. The development and urbanisation of cities is increasing, traffic is increasing and more chemicals are used in the society. Increased vehicle traffic means that more pollutants on roads and streets are washed-off by stormwater and flow directly to local rivers and streams (Draper et al., 2000; Kayhanian et al., 2003; Legret and Pagotto, 1999). The wash-off process from roof surfaces has been pointed out as an important source of pollutants in several studies (Förster, 1999; Gromaire-Mertz et al., 1999; He et al., 2001).
Atmospheric deposition is reported in several studies as an important source of organic and inorganic contaminants to aquatic systems (Burian et al., 2001; Garnaud et al., 1999; Hu et al., 1998; Revitt et al., 1990). These studies highlight the links between air pollution and water quality. What starts as air pollution may end up as water pollution as hazardous compounds emitted into the air fall onto surfaces and directly into waters (Viard et al., 2004). Atmospheric deposition can be divided in wet deposition (particles attached to rain drops) and dry deposition (constant dry fallout). Dry deposition will accumulate on impervious surfaces until the particles are washed off during rainfall.

Not only pollutants are transported with stormwater to urban waters; stormwater can also carry higher water temperatures from streets, roof tops, and parking lots, which are harmful to the health and reproduction of aquatic life. Thermal pollution has been reported by Van Buren et al. (2000) in a study where they present a methodology for predicting the thermal enhancement of stormwater runoff from paved surfaces. In this study, measured temperature of stormwater from a parking lot area was higher than the temperature from an upstream catchment with mixed land use.

Here follows a compilation of common constituents found in urban stormwater. The constituents are discussed in terms of their environmental impacts and pollution sources.

### 2.2.1 Sediments
Suspended solids (SS) are one of the most common contaminants found in stormwater (USEPA, 1983). The soil particles are an important carrier of chemical pollutants and nutrients into the waters. In addition, the suspended soil particles in the water may reduce light needed for photosynthesis by plant life, clog the gills of fish and have other negative effects on aquatic life (Cheung and Shin, 2005; Wood and Armitage, 1997).

### 2.2.2 Nutrients
All plants require nutrients in order to grow and reproduce. When an oversupply of nutrients is present in streams, lakes and estuaries, algae and aquatic plants will grow to the point that they will compete for oxygen and space in the water; the water will become eutrophicated. Overgrown vegetation in lakes can eventually prevent recreational use for fishing and swimming. Such lakes are typically the result of nutrients from failing septic systems or fertilizers from agriculture and lawns that are carried into the lake by stormwater runoff. Nitrogen and phosphorus are the common nutrients found in stormwater. Nutrient loads from urban runoff are usually lower compared with other sources in the environment (USEPA, 1983). Malmqvist (1983) reported atmospheric deposition as the largest source of nitrogen in two investigated catchments in Göteborg, Sweden. The same study also assigned atmospheric deposition and animal droppings as the dominant sources for phosphorus. Other sources of phosphorus are reported by Thomson et al. (1997): leaching from tree leaves (peaks in fall and late spring), lawn fertilizer and automobile exhaust. The importance of automobile exhaust as a source for phosphorus in urban runoff has decreased with the introduction of catalytic converters. For decades, phosphorus, has been an effective antiwear/antioxidation agent in engine oils (Selby, 2002). But if an engine burns oil, phosphorus in the oil can contaminate the catalyst, and thus phosphorus-free oils have been introduced (Kaleli and Khorramian, 2000).
2.2.3 Heavy metals

Heavy metals are a group of highly toxic metals that generally are harmful to plants and animals. As trace elements, some heavy metals (e.g. copper, selenium, zinc) are essential to maintain the metabolism. However, at higher concentrations they can lead to poisoning. Heavy metals are considered a health threat because of their tendency to accumulate in the body and the food chain. Their negative impact on health may be acute, occurring quickly after exposure, or chronic, occurring over a long period of time. The most relevant heavy metals to include in stormwater studies are copper, zinc, lead, cadmium, nickel and chromium.

The National Urban Runoff Program (NURP) conducted by the U.S. Environmental Protection Agency, concluded that heavy metals are the most common priority pollutants found in urban runoff (USEPA, 1983). Copper, zinc and lead were found in more than 90% of the stormwater samples. Malmqvist (1983) appointed building materials and atmospheric fallout as the major sources for zinc and copper. For road runoff the major source of copper nowadays is brake wear since the shift of brake lining material from asbestos to copper that started in the mid 1980s. The phase out of lead in petrol has decreased the content of lead in stormwater.

In a study from the U.S., Davis et al. (2001) made estimations of lead, copper, cadmium, and zinc loadings from various sources in a developed area. The authors used information available in the literature, in conjunction with controlled experimental and sampling investigations. Important sources identified were building sidings for all four metals, vehicle brake emissions for copper and tyre wear for zinc. Davis et al. (2001) also attribute atmospheric deposition as an important source for cadmium, copper and lead. A conclusion from this study is that loadings and source distributions depend on building and automobile density assumptions and the type of materials present in the area examined. Tyre wear as an important source for zinc in road runoff is also reported in other studies. Councell et al. (2004) reported that zinc inputs from tyre wear to urban-suburban catchments can be significantly greater than atmospheric inputs. Drapper et al. (2000) monitored the water quality of road runoff at 21 sites around Brisbane, Australia. The authors found that sites incorporating exit lanes had higher observed concentrations of copper and zinc, which they suggest to support the hypothesis that brake pad and tyre wear caused by rapid deceleration contributes to the concentrations of these metals in road runoff. In the Netherlands Blok (2005) made estimations of emissions of zinc along roads originating from tyre wear, corrosion of safety fences (road furniture) and other traffic-related sources. The study showed that tyre wear and corrosion of safety fence are the main sources of zinc at the road.

High concentrations of heavy metals such as copper, zinc, lead and cadmium are easily removed in the form of soluble corrosion products of metal surfaces that are commonly used as roofing or gutter materials. Gnecco et al. (2005) reported high values of zinc concentration from measurements in roof runoff, which the authors appoint to the wash-off of corrosion products released by zinc gutters. Very high concentrations of zinc and lead were measured in roof runoff sampled in “Le Marais” catchment, an old residential district in Paris (Gromaire-Mertz et al., 1999). Athanasiadis et al. (2005) showed in their study that the cover material of the roof and the drainage system with gutters and downpipes are responsible for the high
concentration of copper in the runoff. This study also reports a linear correlation between the copper mass washed off the roof during a rain event and the runoff volume of the rain event.

In a study by Odnevall Wallinder et al. (2002) the release rates of chromium and nickel from stainless steel were determined during a one-year field exposure in the urban environment of Stockholm, Sweden. Complementary laboratory investigations on the influence of various rain parameters (pH and intensity) on the release rates were also performed. Major findings from this study were that nickel is generally released at a higher rate than chromium from stainless steel, and that no direct effect of rain intensity on metal release rate could be observed.

Davis and Burns (1999) evaluated painted buildings as a source of lead in stormwater runoff. In many cases, high lead concentrations were found. Lead concentration depended strongly on paint age and condition. Lead levels in runoff from older paints were much higher than from freshly painted surfaces. Lead from surface washes was found to be 70% or greater in particulate form, suggesting the release of lead pigments from weathered paints. Higher wash intensities were found to liberate more particulate lead than lower intensities.

Heavily populated areas may contribute larger amounts of anthropogenic contaminants to the atmosphere that would become part of the long-range transport or be deposited locally within the urban ecosystem (Conko et al., 2004). Sabin et al. (2005) investigated the contribution of atmospheric deposition to emissions of trace metals in stormwater runoff by quantifying wet and dry deposition fluxes and stormwater discharges within a small, highly impervious urban catchment in Los Angeles, USA. Based on the ratio of total deposition (wet and dry) to stormwater, atmospheric deposition potentially accounted for as much as 57–100% of the total trace metal loads in stormwater within the studied area.

### 2.2.4 Organic pollutants

Organic compounds are compounds that have long bonding structures, usually made up of carbon. The behaviour of organic compounds is dependent upon their molecular structure, size and shape and the presence of functional groups that are important determinants of toxicity.

There are many different types of organic pollutants, and three groups with special relevance for stormwater are discussed here:

- Hydrocarbons
- Polychlorinated biphenyls (PCBs)
- Pesticides

#### 2.2.4.1 Hydrocarbons

Hydrocarbons have bonds with carbon-hydrogen. They can be divided into two classes, the first being aliphatic hydrocarbons and the second being aromatic hydrocarbons, which contain ring structures (liquids or solids). Aromatic hydrocarbons such as polycyclic aromatic hydrocarbons (PAHs) are much more reactive than the aliphatic hydrocarbons. PAHs are usually reported as \( \Sigma_{16} \) (sum of the 16 U.S. EPA
priority listed PAHs). Concentrations of PAHs - comprising numerous carcinogenic compounds - have been increasing in recent decades in many urban lakes, particularly in areas undergoing rapid urban growth (Van Metre et al., 2000).

Aliphatic hydrocarbons in urban runoff samples from the well-documented "Le Marais" catchment in central Paris were investigated by Moilleron et al. (2002). The measurements suggest that aliphatic hydrocarbons were largely derived from anthropogenic petroleum sources, and the authors conclude that emissions from vehicles along with atmospheric fallout constitute the main part of hydrocarbon production.

Murakami et al. (2005) measured PAHs in road dust with the objective to identify the important fractions in urban runoff and to analyse their sources. In this study road dust was collected from a residential area and a heavy traffic area in Tokyo, Japan. Multiple regression analysis indicated that asphalt/pavement wear was the major PAHs source of road dust in the residential area, and that tyre wear and diesel vehicle exhaust were the major sources of PAHs in finer and coarser road dust from the heavy traffic area. Similar results were observed by Pengchai et al. (2005), who also studied road dust in Tokyo. In this study seven categories of PAHs sources were defined: diesel vehicle exhaust, gasoline vehicle exhaust, tyre, asphalt pavement, asphalt or bitumen, petroleum products excluding tyre and asphalt, and combustion products except for those in vehicle engines. Diesel vehicle exhaust, tyre and pavement were found to be the major contributors of PAHs in the fractionated road dust.

A previously unidentified source of urban PAHs is reported by Mahler et al. (2005). This study shows that parking lot sealcoat may dominate loading of PAHs to urban water bodies in the United States. Sealcoat is applied to many parking lots and driveways in an effort to protect the underlying asphalt pavement and enhance appearance. Previously identified urban sources of PAHs, such as automobile exhaust and atmospheric deposition, have been difficult to control or even quantify because of their non-point nature. But as the authors argue, sealed parking lots in contrast are point sources, and use of the sealant is voluntary and controllable.

2.2.4.2 PCBs
PCBs are stable and non-reactive fluids that previously were used as hydraulic fluids, coolant/insulation fluids in transformers, plasticizers in natural and synthetic rubber products, and as chemical stabilizer in paint (Walker et al., 1999). In many countries PCBs have been phased out from production. In Sweden all PCBs are forbidden since 1972 and within the European Union since 1985. Despite extensive regulatory actions PCBs remain a focus of environmental attention.

In a study by Rossi et al. (2004), the importance of PCBs in urban stormwater and the implication for urban water systems in Switzerland were determined. The authors conclude that urban stormwater is an important source of PCB contamination in the urban environment. Rossi et al. (2004) appoint atmospheric deposition, mainly wet deposition, as an important source of PCBs in stormwater. This is confirmed in another study by Blanchard et al. (2001) who investigated both PAHs and PCBs fluxes in urban effluents entering several wastewater treatment plants in the Paris area, France. The authors suggest that PCB inputs originate from the atmosphere whereas PAHs appear rather to be brought to wastewaters by urban runoff.
Recent investigations have revealed the presence of PCB sealant used in the construction of buildings as a potential PCB source (Andersson et al., 2004; Kohler et al., 2005). Sealants can be eroded or degraded so that PCBs are released into the environment, but the consequences for urban stormwater contamination are difficult to estimate.

2.2.4.3 Pesticides

Pesticides refer to all substances used to destroy unwanted vegetation (herbicides/fungicides), insects (insecticides) or other animals. Insecticides such as DDT are very dangerous because they accumulate in fat tissues of lower animals and then enter the food chain. DDT has gradually been phased out in Sweden and other industrial nations, but it is still used elsewhere (in the tropics, for example). Although pesticides are of major concern in pollution of agricultural runoff, urban runoff may also contain elevated concentrations of pesticides due to use in city park areas and lawns in suburban areas.

Asman et al. (2005) measured several pesticides in wet deposition in Denmark. Some pesticides were detected that are not allowed in Denmark. The authors conclude that they came from abroad and have been transported over at least 60-80 km, even longer distances for some of these compounds. This also implies that pesticides can be detected in urban stormwater. Ruban et al. (2005) investigated stormwater runoff from a small suburban catchment in Nantes, France. They found very high concentrations of the pesticides diuron and glyphosate in runoff, especially in spring and autumn when their use is at maximum. The authors suggest that measures to reduce the use of these pollutants should be considered.

2.2.5 Other

There are a number of other pollutants with relevance for stormwater that do not fall directly into the categories above.

Environmental contamination by platinum (Pt), palladium (Pd) and rhodium (Rh), which belong to the platinum-group elements (PGEs), is mainly related to the increased use of noble metal-based automotive catalytic converters (Palacios et al., 2000). Although the catalytic converters have reduced emissions of hydrocarbons, carbon monoxide and nitrogen oxides, the increased use of PGEs in automobile catalysts has led to concern over potential environmental and biological accumulation (Ek et al., 2004). Whiteley and Murray (2005) studied PGEs in sediments of infiltration basins and a wetland receiving urban runoff in Perth, Australia. They report PGE ratios in infiltration basin and wetland sediments that were within the typical range of catalytic converter compositions. However, comparisons of PGE ratios between parent road dusts and infiltration basin sediments revealed a systematic shift in Pt/Pd ratios. Thus, the authors suggest that PGE fractionation can occur during transport through the drainage system and that a small portion of Pd in road dust may be solubilised under natural conditions.

Disease-causing micro-organisms, or pathogens, are often present in human or animal faecal matter. Diseases that can result from exposure to faecal matter include dysentery, hepatitis, gastroenteritis (food poisoning), and parasitic infections. The
extent of pathogens in water is typically indicated by levels of faecal coliform, a type of bacteria found in human and animal faeces. Non-point sources of pollution for pathogens include stormwater runoff from pervious and impervious surfaces, failing septic systems, and direct deposition of animal faeces. Petersen et al. (2005) conducted a study of point and non-point sources of *Escherichia coli* and faecal coliform in a stream located in an urbanized catchment in Houston, United States. The authors undertook end-of-pipe sampling at wastewater treatment plant effluent and storm sewers discharging under dry weather conditions. They report relatively low concentrations of *E. coli* found in wastewater treatment effluent, while dry weather storm sewer discharges exhibited a 40 times higher mean concentration. Another study by Jeng et al. (2005) used faecal coliform, *Escherichia coli* and enterococci as indicator organisms to assess the microbial contamination resulting from urban stormwater runoff into the Lake Pontchartrain estuary, Louisiana, United States. During wet weather conditions, the authors found that urban stormwater runoff was responsible for elevated indicator organisms in both the water column and sediment, specifically in proximity to outfall discharges. This study also linked sedimentation as the main process of removal of the indicator organisms from the water column to estuarine sediment.

Oxygen is a natural component in all water bodies, and it is needed by all aquatic plant and animal life. Oxygen is needed by the micro-organisms that play an important role in cleansing polluted streams by breaking down complex organic pollutants into simple and harmless chemicals. However, the more polluted a stream, the more the micro-organisms and other aquatic life have to compete for the oxygen dissolved in the water. Thus, high levels of pollution cause high levels of oxygen demand and may cause such dramatic results as fish mortality (Magaud et al., 1997). The indirect indication of the amount of organic material in water can be derived from either the biochemical oxygen demand (BOD) or the chemical oxygen demand (COD) values. COD are more common in stormwater studies.

A summary of urban stormwater pollutants and their environmental effect is shown in Table 1.

<table>
<thead>
<tr>
<th>CONSTITUENTS</th>
<th>ENVIRONMENTAL EFFECT</th>
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<tbody>
<tr>
<td>Sediments – Total Suspended Solids</td>
<td>Turbidity changes</td>
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<td></td>
<td>Habitat changes</td>
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<td></td>
<td>Recreation/aesthetic loss</td>
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<td></td>
<td>Contaminant transport</td>
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<td>Nutrients – Nitrogen, Phosphorus</td>
<td>Algae bloom</td>
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<td>Eutrophication</td>
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<td></td>
<td>Recreation/aesthetic loss</td>
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<tr>
<td>Heavy Metals – Copper, Zinc, Lead, Cadmium, Nickel, Chromium</td>
<td>Aquatic toxicity</td>
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<tr>
<td></td>
<td>Bioaccumulation</td>
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<tr>
<td>Organic Pollutants – PAHs, PCBs, pesticides</td>
<td>Aquatic toxicity</td>
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<td></td>
<td>Bioaccumulation</td>
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<tr>
<td>Other Pollutants – PGEs, Pathogens, Oxygen demanding (BOD, COD)</td>
<td>Aquatic toxicity</td>
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<td></td>
<td>Dissolved oxygen depletion</td>
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<td></td>
<td>Infections</td>
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<td>Fish mortality</td>
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<tr>
<td>Thermal Pollution</td>
<td>Dissolved oxygen depletion</td>
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<td></td>
<td>Habitat changes</td>
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2.3 Stormwater modelling

A large number of mathematical models are available for simulating quantity and quality aspects in urban stormwater systems. The simplest models calculate pollutant loads from runoff volumes and event mean concentrations (EMC). Such models assume that the pollutant concentration is constant during the simulation (Charbeneau and Barrett, 1998). The EMC is defined as total pollutant mass \( M \) discharged throughout an event divided by total event volume \( V \), which is expressed mathematically as

\[
EMC = \frac{M}{V} = \frac{\int C(t)Q(t)dt}{\int Q(t)dt} \quad (\text{Equation 1})
\]

where \( C(t) \) is the pollutant concentration at time \( t \) and \( Q(t) \) is the stormwater discharge at time \( t \). Hence, the EMC is a flow-weighted average of pollutant concentration.

More complex models attempt to simulate the build-up and wash-off of pollutants from the catchment and the transport in the drainage system. Build-up and wash-off relationships are appealing for simulating constituent concentrations from impervious areas (Charbeneau and Barrett, 1998). In the build-up and wash-off model a supply of pollutants is assumed to build accumulate on the land surface during periods of dry weather. With a subsequent storm, part of this material is then washed off the surface into the drainage system. An exponential relationship between the amount of sediment on the surface and the time elapsed from the last rainfall was originally proposed by Sartor and Boyd (1972) for the assessment of build-up of sediment on urban surfaces during dry weather conditions. The exponential representation of the constituent load accumulated on the surface after a dry period \( P_t \) [g], takes the following form (Grottker, 1987):

\[
P_t = P_o \left(1 - e^{-k_1 t}\right) \quad (\text{Equation 2})
\]

where \( P_o \) is the maximum constituent load that can accumulate on the surface [g], \( k_1 \) is the build-up coefficient [d\(^{-1}\)] and \( t \) the number of dry days [d]. The build-up model has two parameters, \( P_o \) and \( k_1 \).

The pollutant removal from the surface by rainfall and runoff is commonly modelled as an exponential decay of the available surface pollutant load, with rainfall intensity, rainfall volume, runoff rate or runoff volume as the explanatory parameter(s) (Vaze and Chiew, 2002). The total load from wash-off for a storm is given by Alley (1981) as:

\[
L = P_t (1 - e^{-k_2 R_t}) \quad (\text{Equation 3})
\]
where $P_1$ is the initial load [g], $k_2$ is the wash-off coefficient [mm$^{-1}$] and $V_T$ is the total runoff from the storm event [mm].

A comprehensive review of urban stormwater models was made by Zoppou (2001). The reviewed models vary both in terms of complexity and input data requirements, and have been categorised in terms of their functionality, accessibility, water quantity and quality components and their temporal and spatial scale. Zoppou concluded that all the models can be used as planning models, some as design tools but very few as operational tools. The reason why few stormwater models are used in an operational way is explained by Zoppou to depend on the dynamics of the stormwater system that makes it difficult to implement complicated models and also collect reliable real-time data.

Models that simulate rainfall, runoff and transport of stormwater in urban areas are widely used in the water sector. These models that describe the quantity aspects of stormwater are seen as efficient tools in water management. But stormwater quality models on the other hand are not that commonly used in practice as pointed out by Ahyerre et al. (1998). The generation and transport of pollution are complex processes and including this complexity in quality models leads to some problems according to the authors. One problem is the discrepancy between the knowledge and the equations included in the models; another problem is the associated uncertainty of the input and calibration data. Ahyerre et al. (1998) suggest that a clear distinction should be made between management tools and research models. The management tools should include simplified models with just a few parameters, while research models are needed to improve the knowledge about the important processes.

2.3.1 Model development

In terms of model development, the chosen modelling approach will restrict the uses to which the model may be put. It is therefore important to define what purpose or purposes a model should have. Mulligan and Wainwright (2003) have identified seven purposes to which a general model is usually put:

1. As an aid to research
2. As a tool for understanding
3. As a tool for simulation and prediction
4. As a virtual laboratory
5. As an integrator of knowledge within and between disciplines
6. As a research product
7. As a means of communicating science and the results of science

Points 1-4 can be applied to most models and points 5-7 apply to models that are supposed to be used by end-users who are not the model developers themselves.

Urban stormwater models can be employed to meet many different objectives during the planning, design and operation phase, and thus different types of models can be more appropriate depending on the specific situation. Mathematical models in general can range from simple equations to complex software codes including many equations and conditions over the time and spatial domain. It is useful to define mathematical models into different types in order to know what purposes the model can be used for.
However, it is important to realise that models are usually a mix of different types. In terms of modelling mechanisms, Mulligan and Wainwright (2003) classify models as physically-based, empirical or conceptual. Combinations of these categories are also possible.

**Physically or process based models** should be derived from established physical principles and ideally produce results that are consistent with observations. Physically-based models use fundamental equations with model parameters that have direct physical meaning. This type of model has a high explanatory capacity, *i.e.* it is possible to find out in process terms why an outcome is as it is.

**Empirical models** describe the observed behaviour between variables using the observations alone and do not include any processes. Because of the direct link between input and output these models are also referred to as black box models. Empirical models have high predictive power but low explanatory depth. In terms of stormwater modelling, an empirical approach would be a model that relates runoff quantity or quality to a number of factors, such as rainfall or other characteristics of the catchment.

**Conceptual models** explain the behaviour of a system based on ideas of how the system works. The processes are explained by simplified conceptual formulations and described by equations using parameters that do not have a direct physical meaning. These parameters must usually be determined in a procedure of calibration and validation. Conceptual models have higher explanatory depth than empirical models.

Mathematical models can be further subdivided depending on how the equations are formulated and solved in the time domain, either **discrete** or **continuous**. Further subdivision can be made in terms of the mathematical type of the model. This explains the characteristics of the equations, whether the equations are **deterministic** or **stochastic**. In the deterministic approach, a single set of inputs will always produce the same output. In the stochastic approach, a single set of inputs will produce output that is not identical each time. This is achieved by introducing random processes in the governing equations of the model. Models are also of different spatial types and can be divided into **lumped** or **distributed** models. Lumped models simulate a spatially heterogeneous area or structure as a single value, while distributed models break the area or structure into discrete units. The spatial type of a model can be one-dimensional (1D), two-dimensional (2D) or three dimensional (3D). The 2D scale is usually used in the context of a geographical information system (GIS). Mathematical models can be further classified accordingly on their temporal scale. **Static** models have no time dependence while **dynamic** models include a time variation.

Finally, one additional classification is especially applicable to urban stormwater models. A stormwater model can be **event based** or **continuous** in terms of how it handles the input rainfall data. An event based stormwater model uses several discrete rainfall events as input to produce output like hydrographs and pollutographs. It can also be a single event model that uses a design storm with a given frequency and duration. A continuous stormwater model simulates a series of rainfall events including the dry periods between the events. The continuous model is therefore better equipped to describe the range of conditions that will occur over a longer time period.
This is confirmed in a study by Bouteligier et al. (2004) where a sensitivity analysis was performed of the water quality modules of two commonly used urban drainage modelling software packages. Bouteligier et al. conclude that water quality modelling is highly dependent on the initial conditions prior to the storm as well as to the model input. Given that the initial conditions vary from one event to another, water quality modelling using longer time-series will give the best overall results in terms of modelling and impact assessment.

As described above mathematical models can be classified as physically-based, empirical or conceptual. The following sections present a selection of urban drainage models reported in the literature that follows this classification.

2.3.2 Physically-based stormwater models
Physically-based stormwater models like SWMM (U.S. EPA), Mouse (DHI Software), HEC-HMS (U.S. Army Corps of Engineers) and InfoWorks (Wallingford Software) describe the physical processes related to water flow to a high degree and also require extensive measurements for calibration. The flow and characteristics of water are usually described using hydrodynamic theory, such as the St. Venant equations (Zoppou, 2001). All of the above-mentioned stormwater models are deterministic, i.e. no randomness is included.

A software tool developed for modelling of water flows should include the following main physical hydrological and hydraulic processes (Butler and Davis, 2004):

- rainfall to runoff formation
- overland flow
- flow in the sewer system

With these processes and additional relevant inputs (rainfall and wastewater flow) it is possible to describe the flow rate and depth within the system and at its outlets.

As mentioned earlier there are many physically-based deterministic flow models available but physically-based deterministic water quality models are not that widely used. It is also questionable if true comprehensive deterministic quality modelling is achievable because of the complex physical processes related to pollution generation and transport (Butler and Davis, 2004). The physically-based stormwater models mentioned above all include a water quality module but some of the processes usually have conceptualised elements.

2.3.3 Empirical stormwater models
Empirical or statistical stormwater models are usually based on regression analysis between water quantity and quality and relevant explanatory variables. Brezonik and Stadelmann (2002) developed predictive models of stormwater runoff volumes, loads, and pollutant concentrations from catchments in the Twin Cities metropolitan area, Minnesota, United States. In the study relationships between runoff variables and storm and catchment characteristics were examined. The best regression equation to predict runoff volume for rain events was based on rainfall amount, drainage area, and percent impervious area. For EMCs, Brezonik and Stadelmann conclude that the most
accurate models generally were found when the sampled sites were grouped according to common land use and size.

Kayhanian et al. (2003) evaluated correlations between annual average daily traffic (AADT) and stormwater runoff pollutant concentrations from highway sites in California, United States. They found no direct linear correlation between highway runoff EMCs and AADT. However, through multiple regression analyses the authors showed that AADT in conjunction with factors associated with catchment characteristics and pollutant build-up and wash-off had an influence on most highway runoff pollutant concentrations.

In summary, empirical models are able to analyse the input-output relationship of the urban drainage system. However, empirical models have one major disadvantage: they are site-specific.

2.3.4 Conceptual stormwater models

Conceptual models are normally based on simple yet sound physical concepts and relatively limited data resources. Compared to physically-based models they can be more efficient, i.e. timesaving and less data intensive (Achleitner and Rauch, 2005; Ruan and Wiggers, 1998). Conceptual models can also be used for developing “to be” scenarios or to solve “what if” problems, one of the limitations of empirical models. Here follows short descriptions for a selection of conceptual urban drainage models reported in the literature.

In Sweden, a commercial planning-level tool for quantification of pollutant transport and design of stormwater treatment facilities has been developed by Larm (2000b). The stormwater model in this tool (StormTac), uses land use specific input data, such as runoff coefficients, areas per land use and standard pollutant concentrations (EMCs). The model works with relatively simple equations for quantification of pollutant transport. Under the prerequisite that the objective is not to study the dynamic properties in the stormwater system, Larm considers the equations to be accurate enough for planning-level analyses. StormTac is further described in a case study of stormwater quantity and quality in a pond-wetland system (Larm, 2000a).

COSMOSS, a conceptual simplified model for sewer system simulation, has been developed in Italy (Calabro, 2001). The only substance simulated in the model is suspended solids. COSMOSS is conceptual both in the flow simulation (rainfall-runoff transformation) and in the qualitative aspect (build-up and wash-off of solids). The system (catchment, channels and conduits) is considered as a whole. Calabro states that the model seems to simulate the hydrographs and the pollutographs in a reasonably accurate way. Deviations between measured and simulated values could be explained by the fact that relatively small catchments were used for verification. Moreover, Calabro request improved knowledge of the washout rate, for which the information is scarce and to which the model is sensitive.

A conceptual CSO emission model called SEWSIM has been developed at Delft University of Technology in The Netherlands (Ruan and Wiggers, 1998). Ruan and Wiggers argue that the existing deterministic sewer models are not able to predict CSO emission effectively. The sewer system is described by an impervious catchment and a
sewer network, and in SEWSIM this is conceptualised with two linear dynamic reservoirs. The physical processes rainfall-runoff, solids buildup and washoff, sewer sediment erosion and deposition are likewise conceptually modelled. The model is suitable for both event-based and continuous simulations. Ruan and Wiggers conclude that in some cases SEWSIM can predict pollution load of CSO emission more effectively than deterministic models.

In Australia a tool called MUSIC (Model for Urban Stormwater Improvement Conceptualisation) has been developed. MUSIC predicts the performance of stormwater quality management systems. The operation of several stormwater BMPs like buffer strips, swales, wetlands and ponds can be simulated. BMPs can be configured in series or parallel to form a treatment train, and can be analysed by event or on continuous basis (Wong et al., 2002).

A simulation software called CITY DRAIN © has been developed with the EU project CD4WC and is described by Achleitner and Rauch (2005). This software differs from previous described models in the sense that the modelling framework includes not only the urban drainage system but also the WWTP and receiving water. The basic idea about CITY DRAIN reported by the authors was to create an open source toolbox for integrated modelling of urban drainage systems. Hydraulic routing and mass transport of conservative matter is described with conceptual models.

2.4 Calibration and validation of models

The calibration and validation of models with field measurements is important in model development and applications. Calibration is defined by Schnoor (1996) as a statistically acceptable comparison between model results and field measurements where tuning or optimisation of model parameters is allowed within the range of reported values in the literature. The simplest form of optimisation is iterative trial and error whereby model parameters are changed and a measure of goodness-of-fit between model results and calibration dataset is noted. However, many models include numerous parameters that also are highly interdependent and this will confound the definition of an optimum parameterisation (Mulligan and Wainwright, 2003). In these cases there are other automated techniques to define the optimal parameter set.

Haiping and Yamada (1996) explored different optimisation techniques to obtain accurate estimates of the parameters in a lumped stormwater quality model. The authors first used adaptive step-size random search procedures to find a rough global optimum, and subsequently employed the Marquardt method for more accurate results. Haiping and Yamada demonstrate the method in a catchment in Kyoto, Japan, and conclude that the simulated and measured data match quite well and that the calibration approach can generate accurate estimates efficiently.

Kanso et al. (2003) presented an application of the Metropolis algorithm, a general Monte Carlo Markov chain sampling method, for the calibration of a four-parameter lumped urban stormwater quality model. This method based on Bayesian theory differs from other optimisation techniques in the sense that it estimates the true posterior probability distribution of parameters rather than just the optimal parameter values. The posterior distributions of the parameters were analysed and the authors report a strong correlation between the dry weather parameters in the model. The
authors further conclude that the Metropolis algorithm provide information which would have been unreachable with classical calibration methods. The same algorithm is used in another modelling study by Mailhot et al. (1997), in which the authors came to conclusions in parity with Kanso et al. (2003).

Validation refers to the testing of the model output to confirm the results that should be produced in reality (Mulligan and Wainwright, 2003). Common methods of validation include comparison of a numerical model against the analytical solution (if available) or against measurement data. For validations with measured data split sample approaches, in which the available data is separated into a calibration set and a separate validation set, can be used. Calibration and validation of multiple regression models for stormwater quality prediction were carried by Mourad et al. (2005). The authors investigated the optimal split of available data into calibration and validation subsets, and the effect of dataset size and characteristics on calibration and validation results. In the study three multiple regression models were calibrated and validated and the authors found the models case sensitive to calibration data. Few data used for calibration infers bad predictions despite good calibration results. Mourad et al. also found that the random split of available data into halves for calibration and validation was not optimal; more data should be allocated to calibration. The part of data to be used for validation increases with the number of available data and reaches about 35% for around 55 measured events.

2.5 Uncertainty in modelling

Uncertainty is an avoidable and inherent part of stormwater modelling. Physically based models have shown great ability to simulate reality, however significant uncertainty is inherent in lack of knowledge about model structure, input functions and parameter estimations. Harremoës and Madsen (1999) propose that the application of a model must also include the estimation of uncertainty of prediction. This is also supported by Spear (1997), who emphasizes practical procedures for assessing the impact of parametric uncertainty and variability as being increasingly important to the application of simulation models, either in the support of policy decisions or for furthering scientific understanding.

A definition of uncertainty analysis is given by McIntyre et al. (2002) as “the means of calculating and representing the certainty with which the model results represent reality”. Model errors that are responsible for differences between model result and reality consist of:

- Model parameter errors ($\varepsilon_1$)
- Model structure errors ($\varepsilon_2$)
- Numerical errors in the model implementation ($\varepsilon_3$)
- Boundary condition uncertainties ($\varepsilon_4$)

Field measurements are only an approximation of reality and data errors arise from:

- Sampling errors (i.e. data not representing the required spatial and temporal conditions) ($\varepsilon_5$)
- Measurement errors ($\varepsilon_6$)
• Human reliability ($\varepsilon_7$)

If an error-free model would equal the error-free field data, the actual model result $M$ and the actual observations $O$ can be summarised as

$$M - \varepsilon_1 - \varepsilon_2 - \varepsilon_3 - \varepsilon_4 = O - \varepsilon_5 - \varepsilon_6 - \varepsilon_7$$

where $\varepsilon_1 - \varepsilon_4$ is the model error and $\varepsilon_5 - \varepsilon_7$ the data error (McIntyre et al., 2002).

The modeller is generally not in control of $\varepsilon_2 - \varepsilon_4$, so the aim is to compensate as much as possible for $\varepsilon_2 - \varepsilon_4$ by identification of the optimum effective parameter values. As such, the model parameters are used as error-handling variables and are identified according to their ability to explain both $\varepsilon_2 - \varepsilon_4$ and $\varepsilon_5 - \varepsilon_7$.

Lei and Schilling (1996) introduce the concept of preliminary uncertainty analysis. Given some preliminary estimates of the uncertainty of model parameters, the associated model output uncertainty of a physically based rainfall-runoff model was calculated in this study by the use of Monte-Carlo simulation and subsequent multi-linear regression. When the calculated model output uncertainty is compared with the relative error between model output and observed data, this method can detect errors in observation data, validate the model structure and identity the most sensitive parameters. If the calculated model output uncertainty is unacceptably large the most sensitive parameters should be calibrated to reduce the uncertainty.

The previously described (in Chapter 2.4) Bayesian approach for calibration and validation by Kanso et al. (2003) has been further developed to also include uncertainty analysis (Kanso et al., 2005a; Kanso et al., 2005b). The methodology uses the Metropolis algorithm to assess parameter uncertainty, and a Monte Carlo procedure to assess the model’s predictive uncertainty. Kanso et al. (2005a) used the Bayesian approach for the calibration and uncertainty analysis of a stormwater quality model. The tested model uses a hydrologic/hydrodynamic scheme to estimate the accumulation, the erosion and the transport of pollutants on surfaces and in sewers. The quality model was calibrated for four different initial conditions of in-sewer deposits in combined sewer systems. Calibration of the model resulted in a large variability in the model’s responses with respect to the initial conditions. The authors conclude that the predictive capacity of the tested model was very low. In Kanso et al. (2005b), the effectiveness and efficiency of the methodology are illustrated for different configurations of accumulation/erosion models, tested on different subcatchments. The authors demonstrate with calibration results that the Metropolis algorithm produces reliable inferences of parameters that will help the improvement of the mathematical concept of model equations.

Another method to assess uncertainty in models conditioned by the observations of the modelled system is the Generalised Likelihood Uncertainty Estimation (GLUE) procedure. The GLUE procedure works with multiple sets of parameter values and allows that, within the limitations of a given model structure and errors in boundary conditions and field observations, different sets of values may be equally likely as simulators of the conditions in a catchment (Beven and Binley, 1992). The GLUE procedure has been used in several hydrologic modelling studies with the aim of
3 RESEARCH METHODOLOGY

This chapter describes the materials and methods used in the conducted research. The focus of this thesis is on analysing the substance flows passing through the urban drainage system to identify critical pathways of pollution, as well as assessing the effectiveness of pollution reduction measures. Thus, the rationale chosen for this study is based on substance flow analysis and its implementation in a mathematical model called SEWSYS. The development of the model was divided in the following steps:

- Defining modelling aim and scope, formulating a conceptual model based on substance flow analysis (Paper I, II)
- Building a model structure including components, the relevant processes and their descriptions (Paper I)
- Validation of the model using quantity and quality measurements of stormwater runoff (Paper III)
- Assessment of the model’s predictive uncertainty and parameter sensitivity (Paper III)
- Application of the model in case studies in order to give feedback to the development, and also to demonstrate the usefulness of the model (Paper IV, V, VI)

The steps above describe a logical progression in time of the model’s development process. The process is however in reality not linear since there are interconnections and loops of feedback between the different steps.

3.1 Substance flow analysis

The concepts of material flow analysis (MFA) refers to accounts in physical units (usually in terms of mass) comprising the extraction of production, transformation, consumption, recycling and disposal of materials (e.g. substances, raw materials, base materials, products, manufactures, wastes, emissions to air, water or soil) in a specific region. According to different subjects and various methods, MFA covers approaches such as substance flow analysis, product flow accounts, material balancing, and overall material flow accounts (Fischer-Kowalski and Hüttler, 1999). Substance flow analysis (SFA) is a method for mapping flows of a substance in a company or in geographical regions. SFA usually deals with chemically defined substances, as opposed to bulk materials flows such as wood, air or construction materials used in MFA. Typical examples of SFA applications include studies of nitrogen flows in a region or flows of a specific metal in a country (Finnveden and Moberg, 2005).

The procedure in an SFA is usually the following:

- Identify which substances that are to be included in the study
- Identify the temporal and geographical system
- Identify where the flows of these substances are within the selected system
- Quantify the flows
- Draw conclusions and propose solutions such as substitutions, collection systems, etc.
The last step above would for applications in the urban drainage system include for example choices of structural and/or non-structural BMPs. Within the area of systems analysis, SFA combined with mass balance approaches has been used in studies of the urban water system to highlight pressures on the environment, i.e. on the receiving water, and to identify information gaps (Benedetti et al., 2005; Jeppsson and Hellström, 2002). Systems analysis has been the core of the Urban Water research program, with the aim of synthesizing results from the other research projects and analysing results with respect to the overall visions and the goals of the program (Hellström et al., 2000). The methodology of the systems analysis in Urban Water has involved studies of different combinations of model cities, system structures (technical systems) and scenarios (future events in society directly or indirectly affecting the water and wastewater systems).

In this study, SFA will be incorporated in the developed model for describing the pathways of diffuse pollution in urban drainage systems.

3.2 Model building
Sustainable management of water resources requires integration, and recognition of interconnections between systems at different levels of scale. In order to understand the sources of and the solutions to complex problems, linear and mechanistic thinking should be replaced with non-linear and organic thinking, more commonly referred to as systems thinking (Hjorth and Bagheri, 2006). Systems thinking includes studying things in a holistic way, rather than through purely using techniques of reductionism. It aims to gain insights into the whole by understanding the linkages and interactions between the elements that comprise the whole system. The system at focus in this thesis, the urban drainage system, is seen as a dynamic and complex whole, interacting as a structured functional unit. Information flows between the different elements that compose the system. Furthermore, the urban drainage system is situated within an environment, and communicates with the surrounding environment via the system boundaries.

The design of a conceptual model of the system at focus is an important part in model development. Conceptualisation is the process of going from observation and understanding of an existing system to a concise description, the conceptual model, of the factors and processes needed to solve a specific problem (Mulligan and Wainwright, 2003). The conceptual description is a simplification of the real world, thus introducing some uncertainty whether the conceptualisation is sufficiently complex for the actual problem to solve. With an acceptable conceptual framework consisting of the relevant components, the processes and their descriptions, the formulation of the mathematical model can begin. The process of model building incorporates three sub-stages: developing the modules, testing the modules and verifying the modules.

Model building can take place in either graphical building environments or using high level computer programming languages like FORTRAN, C++ or Java. In this study the graphical modelling environment MATLAB®/Simulink® (www.mathworks.com) was chosen. MATLAB is a technical computing language and interactive environment for algorithm development, data visualization, data analysis, and numeric computation. It provides a developing environment in Simulink with possibilities to add
compartments and flows, linking them with dependencies and entering the appropriate equations into the relevant compartments, flows or variables. MATLAB can also be used to build graphical user interfaces (GUIs) with the GUIDE tool. Several models based on MATLAB®/Simulink® with applications in the urban water sector have been reported in the literature (Achleitner and Rauch, 2005; Frehmann et al., 2002; Jeppsson et al., 2005; Ruan and Wiggers, 1998).

3.3 Model validation

The overall purpose of validation is to determine whether the model is suitable for its intended purpose. Validation can be defined as any process which is designed to assess the correspondence between the model and the system (Van Horn, 1971). Model validation encompasses statistical techniques for testing the goodness-of-fit of empirical data. The empirical data is usually observations of the system in the form of field measurements. Model evaluation requires some measure of how well the model represents the actual field data. The measures are often called objective functions, or goodness-of-fit statistics (Mulligan and Wainwright, 2003).

The root mean square error (RMSE) is a statistical estimator to show how much the model over or under-estimates the observations. RMSE is the mean square difference between the modelled and the measured value as

\[ \text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (O_i - M_i)^2} \]  

(Equation 4)

where \( O_i \) is the observed value, \( M_i \) is the predicted value, and \( n \) is the number of observations. The RMSE presents an average error in the original unit.

The coefficient of determination \( (r^2) \) is a statistical measure commonly used in model evaluation (Mayer and Butler, 1993). The coefficient of determination is the square of the Pearson’s Product Moment Correlation Coefficient and describes the proportion of the total variance in the observed data that can be explained by the model. It ranges from 0 (poor model) to 1 (perfect model) and is given by

\[ r^2 = \left( \frac{\sum_{i=1}^{n} (O_i - \bar{O})(M_i - \bar{M})}{\sqrt{\sum_{i=1}^{n} (O_i - \bar{O})^2} \cdot \sqrt{\sum_{i=1}^{n} (M_i - \bar{M})^2}} \right)^2 \]  

(Equation 5)

where \( M_i \) is a sequence of \( n \) model outputs to be compared to \( n \) observed system values \( O_i, \bar{M} \) is the mean model output and \( \bar{O} \) the mean observed value. This measure is insensitive to constant proportional deviations, i.e. a perfect agreement will occur if the model consistently under- or overestimates by a specific proportion. In addition, the coefficient of determination is sensitive to outliers.
A dimensionless statistic which directly relates model predictions to observed data is the modelling efficiency, $EF$ (Nash and Sutcliffe, 1970), defined as:

$$EF = 1 - \frac{\sum_{i=1}^{n} (O_i - M_i)^2}{\sum_{i=1}^{n} (O_i - \bar{O})^2}$$

(Equation 6)

The modelling efficiency $EF$ is a measure of the mean square error to the observed variance and theoretically ranges from 1.0 to $-\infty$. If the mean square error is zero, then $EF=1$ and indicates a perfect model. If the error equals the observed variance, then $EF=0$ which indicates that the observed mean value is as good as any model. With increasing error the measure will become more negative. The modelling efficiency $EF$ is not affected by proportional effects as the $r^2$, but is still sensitive to outliers.

The field measurements used in this study for model evaluation are from a measurement campaign of stormwater quantity and quality in a sub-catchment in the city of Göteborg, Sweden. The sub-catchment is part of the larger catchment used in Papers IV-VI. The purpose of the sampling campaign was to obtain knowledge about stormwater quality in the city centre, and to use the measurements in evaluation of the SEWSYS model. The measurements were performed by the author of this thesis.

### 3.3.1 Study site

The catchment is located in Vasastaden, a district in the city centre of Göteborg, Sweden. This area is densely populated and consists mainly of commercial and residential buildings, built in the late 19th century and beginning of the 20th century. The Vasastaden catchment is shown in Figure 2, with the monitored sub-catchment shaded. The local water body for the catchment is called Vallgraven (Swedish word for moat) and can be observed in the upper left corner of Figure 2. The total size of the catchment is 75 ha, and there is a mix of both separate and combined sewers. However, the separate sewers are drained to a large trunk sewer parallel to Vallgraven with several CSOs connected. The monitored sub-catchment has a total area of 6 ha and a separate sewer system.

The Göteborg Water and Wastewater works (GWWW) has made classifications of the water bodies in the city that are influenced by stormwater in terms of their sensitivity, and the characteristics of the drained catchments in terms of their pollutant load contributions (GWWW, 2001). The classifications are used by the GWWW in planning and prioritising stormwater treatment measures. The water system that Vallgraven is part of is placed in Category 2 and the area Vasastaden in Category 1. This means a relatively sensitive water recipient and a catchment with a large potential pollutant generation.
The city of Göteborg, situated on the west coast of Sweden, has a coastal temperate climate with a mean annual rainfall of about 750 mm evenly distributed throughout the year (See Figure 3). The mean maximum and minimum air temperatures for Göteborg are 11 and 4 °C, respectively.

Figure 2. The Vasastaden catchment, with the monitored sub-catchment shaded

Figure 3. Climate (rainfall and temperature) in Göteborg, Sweden
The area Vasastaden has been one of the model cities in the Urban Water research program. In the program a model city, together with a system structure, scenarios and system boundaries, are the components that define the total system to be analysed and evaluated (Hellström et al., 2000). A model city represents all aspects of a city that have an influence on the urban water system without actually defining the urban water system structure itself. Five conceptual priority model city types were selected in the program to cover the majority of the Swedish urban environment. Vasastaden represents the “old urban area in or near the city centre”.

3.3.2 Field sampling
Monitoring of stormwater runoff took place in Vasastaden in April-May 2002. An ISCO 6700 automatic water sampler was installed in the vicinity of a manhole to take samples in a φ400 mm concrete stormwater pipe. The sampler had a flow meter connected, which forced the sampler to take flow-weighted samples. The flow meter was an ADS 3600 equipped with ultrasonic sensors for level and velocity, and a pressure depth sensor for backup. Each storm event included several flow-weighted samples (up to 24 bottles containing five flow-weighted sub-samples each). A tipping bucket rain gauge (HoBo/MJK) was installed approximately 60 meters from the sampler on the boundary of the catchment.

3.3.3 Laboratory analyses
Within 8 hours after the rain events, collected stormwater samples were transported to the laboratory, where they were directly prepared or analysed. All samples were analysed for pH, conductivity, total suspended solids (TSS), chemical oxygen demand (COD) and heavy metals (copper, zinc, lead and cadmium). This yielded valuable intra-event data for these parameters. pH and conductivity were analysed according to Swedish standard methods. The content of TSS was analysed by filtering stormwater through a GF/C glass fibre filter according to Swedish standard methods SS-EN 872-1/SS 02 81 12. COD was analysed with the HACH method. Total content of heavy metals was determined by inductively coupled plasma mass spectrometry (ICP-MS). Composite samples were analysed at a commercial lab for total phosphorus (TP), total nitrogen (TN), polyaromatic hydrocarbons (PAH-16) and polychlorinated biphenyls (PCBs). The methods used were TRAACS for TN and TP, GC-MS for PAH-16 and EPA 3510-808 for PCB. Some samples were also analysed for acute toxicity with the Microtox® method.

3.4 Model uncertainty
Uncertainty assessment methods the SEWSYS model have included Monte Carlo simulations in combination with multi-linear regression, the Bootstrap method and a Markov-Chain Monte Carlo method to estimate and analyse the posterior parameter distributions.

The prediction uncertainty and sensitivity is assessed using Monte Carlo sampling in combination with multi-linear regression and correlation analysis as proposed by Lei and Schilling (1996). This method assumes that there is no uncertainty in the input data or in the model structure. Instead all the uncertainty is put on the model parameters, here seen as stochastic variables. For each parameter a statistical probability distribution is assumed. The expected uncertainty for a specific model output, e.g. total
stormwater volume, is calculated by Monte Carlo simulation followed by multi-linear regression. The Monte Carlo simulation technique means using \( n \) numbers of random parameter sets taken from their distributions in \( n \) numbers of simulations. To avoid excessive computational load, an efficient sampling technique is needed. In this study, the Latin Hypercube Sampling (LHS) technique (Iman and Conover, 1982) was used. LHS is a stratified sampling technique used to generate multivariate samples of statistical distributions. In the multi-linear regression the model output is linearised with the mean values of the stochastic parameters. The most sensitive parameters for a specific model output are identified by calculating sensitivity coefficients. The sensitivity coefficients for a parameter show the relative contribution of its variance to the total variance in model output.

For automatic calibration of the model the function `fminsearch` in MATLAB was used. This function is based on the Nelder-Mead simplex algorithm which is a direct search method for multidimensional unconstrained minimization (Lagarias et al., 1998).

One limitation of using automatic calibration is that it does not give any additional information about the parameters regarding their probability distribution. Such information can be obtained by the Markov-Chain Monte Carlo (MCMC) method and the Bootstrap method. Kanso et al. (2005b) propose using the MCMC method together with the Metropolis algorithm to find the true posterior distribution of parameters. The calibration of the water quality module in SEWSYS is performed with a random walk Metropolis-Hastings algorithm in order to assess the uncertainties and correlations of the model parameters.

### 3.5 GIS analysis

The use of geographical information systems (GIS) has been an essential part of the model development, mainly in preparing input data for the SEWSYS model regarding characteristics of the studied catchments. The GIS software used in this study was MapInfo Professional\textsuperscript{®} (http://www.mapinfo.com). GIS provides an ability to efficiently gather spatial data and present the information in a graphical way. Background data on different structures (buildings, streets, parking lots, parks etc.) was used to estimate the impervious area. GIS data on traffic counts was utilised to calculate the traffic load in the catchments. To enhance the data, field studies were performed with the purpose of identifying the roofing materials in the different catchments. The roofs were categorised by their material into galvanised, painted sheet steel, copper and other. The category other comprises tile and fibre roofs. All this data was added to the MapInfo layer with building structures.
4 MODEL DEVELOPMENT

In this chapter the results from the model development in the appended papers are summarised and discussed in relation with the literature review. Some complementary material has been added. The structure of this chapter principally follows the research methodology as outlined in Chapter 3.

4.1 Modelling objectives

The overall purpose is to develop a modelling framework for analysing the substance flows passing through the urban drainage system. The modelling framework is intended to provide decision support and be used as a simulation tool for assessing the effectiveness of pollution reduction measures. Additional specific objectives of the model are:

- to include the relevant substances (priority pollutants) related to water quality problems in combined and separate sewer systems
- to make the pollution load calculations based on the sources for each pollutant
- to allow for evaluation of pollution by taking the dynamics of the system into account
- to make the modelling framework flexible and the model environment user-friendly
- to provide modelling results that in a clear and pedagogical way can be used by decision-makers.

The developed model should be flexible and generic, and be able to describe the different structural parts of the stormwater system. To make the model applicable to different spatial scales, it is necessary to take into account the various typologies of urban catchments and making it possible to adjust the model complexity to the available input data and the available process knowledge. The modelling objectives are discussed in further detail in Papers I and II.

4.2 Conceptual model

The model development proceeds with the process of going from observation and understanding of the urban drainage system to a concise description - the conceptual model - of the factors and processes needed to achieve the modelling objectives outlined in Chapter 4.1. The conceptual description of the urban drainage system is shown in Figure 4. It shows the parts that have to be included in order to be able to perform the desired substance flow analysis. Outside the system boundary are the surrounding urban water system, the society and the environment. The central area for the research presented in this thesis is also highlighted in the figure, i.e. sources, generation, and characteristics of stormwater pollution. Paper II contains a simplified conceptual model that was used for the implementation of the stormwater pollutant generator in STORM/SEWSYS.

In summary, the conceptual model outlines the sources, sinks and pathways of pollutants in the urban drainage system.
4 MODEL DEVELOPMENT

4.3 Model structure

With the conceptual model as the underpinning idea the next step in the development of SEWSYS was to build the model structure. **Paper I** describes the structure and the processes in the SEWSYS model. The development of the sources and flux model STORM/SEWSYS was made in a different way as described in Chapter 4.3.2 below and in **Paper II**.

4.3.1 SEWSYS

The conceptual model outlined in Figure 4 specifies which components and processes that are needed to include in the framework of the substance flow model. To achieve the modelling objectives the chosen model structure of SEWSYS follows a conceptual design because it keeps the model reasonably simple and easy to use. A physically based description of the system would require a lot more input data, higher level of process descriptions and yield longer simulation times. An empirical approach is not employed because, although it could simulate the pollutant load quite efficiently, the flexibility of the model would be limited. Choosing a conceptual design facilitates the possibility to further enhance the model as new knowledge becomes available about the processes.

Figure 4. The conceptual model used in development of SEWSYS
The equations in the model will be solved and expressed in discrete form, following the time step size of the rainfall data. As one modelling objective is to be able to study the characteristics of pollutant generation, this calls for a continuous dynamic approach with a build-up and wash-off formulation. This approach provides the abilities to calculate the mass of pollution per event and to represent the shape of the pollutographs and the dynamics of the phenomenon. It is up to the user to decide on the spatial resolution in the model. The basic module is lumped, but several small catchments could be connected to create a distributed system. Finally, the structure of the developed model is deterministic, with no randomness or probabilities included in the input data or parameters.

Precipitation that falls like snow and the accumulation of pollutants in the snowpack is a process that has been left outside the scope of this thesis. No attempt has been made to model snowmelt and hence all precipitation is considered to be in the form of rain. This will not affect pollution load calculations over longer time periods; however, seasonal effects during snowmelt will be less evident. The processes that may occur during transport in the sewer system have not been implemented in the model. No attempt has been made to model the in-sewer sediment transport and the erosion/deposition of sediments. The transport of substances is considered for conservative matter only. This will especially influence pollution load calculations over short time periods, i.e. while looking at a few rain events when the initial conditions are important. In-sewer processes are also more important in combined sewers and for degradation of organic material.

The basic representation of the urban drainage system was made in the Simulink component of MATLAB. Previous findings by Engvall (1999) was used in the development of the stormwater pollutant generator. Two Simulink structures were built as default models, one for a typical combined sewer system and one for a separate system. The top-levels of the two models are shown in Figure 5, seen as variants interpreted from the conceptual model. By clicking the boxes the user can reveal more details of the underlying structure. The Simulink environment provides total flexibility to change the structure by rearrangement or adding new boxes and links. A block library is also provided with commonly used model components (Figure 6).

Figure 5. Simulink models of combined sewer system (left), and separate sewer system (right)
The substances included in the SEWSYS model are shown in Table 2. Two criteria have guided the selection of substances. First, the relevance for the urban drainage system mainly from the viewpoint of pollution sources and environmental impact as discussed in the literature review of Chapter 2. Second, the requirement of certain substances to be able to simulate the characteristics of the wastewater treatment plant. The list of substances covers a majority of the priority pollutants outlined in the literature review of this thesis. A limiting factor for the addition of other substances has been the data availability.

It should be noted that the mass flow simulations are for the total fraction of each substance, except for nitrogen in domestic wastewater. Hence, it is not possible to observe the dissolved phase of the pollutants. For heavy metals it is mainly the dissolved phase that is bio-available and hence determines the toxicity. However, many factors such as pH, residence time and solids concentration influence the metal partitioning and these processes have been left outside the scope of the model.

Table 2. The substance vector in SEWSYS

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<thead>
<tr>
<th>Nr</th>
<th>Substance</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>H₂O</td>
<td>Water</td>
</tr>
<tr>
<td>2</td>
<td>Tot-P</td>
<td>Total Phosphorus</td>
</tr>
<tr>
<td>3</td>
<td>Tot-N</td>
<td>Total Nitrogen</td>
</tr>
<tr>
<td>4</td>
<td>NH₃/NH₄⁺ -N</td>
<td>Nitrogen in ammoniac and ammonium</td>
</tr>
<tr>
<td>5</td>
<td>NO₃ –N</td>
<td>Nitrogen in nitrate</td>
</tr>
<tr>
<td>6</td>
<td>N₂O –N</td>
<td>Nitrogen in nitrous oxide</td>
</tr>
<tr>
<td>7</td>
<td>SS</td>
<td>Suspended Solids</td>
</tr>
<tr>
<td>8</td>
<td>BOD</td>
<td>Biochemical Oxygen Demand</td>
</tr>
<tr>
<td>9</td>
<td>COD</td>
<td>Chemical Oxygen Demand</td>
</tr>
<tr>
<td>10</td>
<td>Tot-C</td>
<td>Total Carbon</td>
</tr>
<tr>
<td>11</td>
<td>Phase Index</td>
<td>Part VS (Volatile Solids) of SS</td>
</tr>
<tr>
<td>12</td>
<td>Cu</td>
<td>Copper</td>
</tr>
<tr>
<td>13</td>
<td>Zn</td>
<td>Zinc</td>
</tr>
<tr>
<td>14</td>
<td>Pb</td>
<td>Lead</td>
</tr>
<tr>
<td>15</td>
<td>Cd</td>
<td>Cadmium</td>
</tr>
<tr>
<td>16</td>
<td>Hg</td>
<td>Mercury</td>
</tr>
<tr>
<td>17</td>
<td>Cr</td>
<td>Chromium</td>
</tr>
<tr>
<td>18</td>
<td>Pt</td>
<td>Platinum</td>
</tr>
<tr>
<td>19</td>
<td>Pd</td>
<td>Palladium</td>
</tr>
<tr>
<td>20</td>
<td>Rh</td>
<td>Rhodium</td>
</tr>
<tr>
<td>21</td>
<td>PAH</td>
<td>Polyaromatic Hydrocarbons</td>
</tr>
</tbody>
</table>

*) Unit in [gram per time step], except for water [m³ per time step]
Data is fed to the Simulink model from two sources: (1) the main user window, and (2) background data files on emission factors. The main user window, developed using the GUIDE tool, is where the user enters specific input data about the studied catchment. This is also the panel from where the user controls the model. Figure 7 displays the main user window in SEWSYS with some sample data entered. The main window also controls which type of sewer system is to be used in the simulation, either combined or separate. This choice determines which of the models in Figure 5 that will be used in the simulation. The user also has the possibility to choose a user-defined Simulink model.

Descriptive input data for the generation of sanitary/domestic wastewater is needed in the form of the number of people living in the catchment. Background data on emission factors for domestic wastewater are given in per capita values, hence the requirement for the number of people. Input data for stormwater include total impervious area, annual rainfall, traffic load and the part of heavy traffic.

The distribution between roads, roofs and other impervious areas is also required. The direct input that drives the stormwater simulation is a time series of rainfall data. This is loaded into the model with a rain file, which has to be specified from the SEWSYS main window. Additional wastewater, e.g. from industrial activities, can also be added to the simulation.

Background data in the form of emission factors for domestic wastewater and stormwater are stored in MATLAB data files and loaded into the Simulink model for each simulation. Data for the pollutant sources in the stormwater and domestic wastewater modules have been obtained from the literature as well as other existing Swedish models.
4.3.2 STORM/SEWSYS

The development of the sources and flux model STORM/SEWSYS was made in a different way compared with SEWSYS. A description of the structure and features of STORM/SEWSYS can be found in Paper II. STORM/SEWSYS is one of the deliverables from the research project DayWater and the model was developed in cooperation with one of the partners in the project, the consulting company IPS in Berlin, Germany. The main purpose of the proposed sources and flux modelling (SFM) tool is the ability to simulate different scenarios of stormwater source control practises. This was achieved by combining the modelling approaches from the two models STORM and SEWSYS.

The STORM model, originally developed as an in-house model at IPS, has been used for several years in Germany as a conceptual hydrological model for simulation of stormwater runoff and pollution load (IPS, 2003). STORM contains classical drainage elements (e.g. overflows and tanks) to set up models for both combined and separate sewer systems. Alternative stormwater management by structural BMPs and source control can be simulated using infiltration devices, green roofs and sedimentation ponds. For the calculation of pollutant loads STORM uses standard concentrations (EMCs). The user interface of STORM is shown in Figure 8.

![Figure 8. STORM/SEWSYS user interface](image)

To enhance the stormwater quality part of STORM, the concept of pollution generation from SEWSYS has been integrated into the STORM interface. This means that there are two choices in the STORM/SEWSYS model for calculation of pollutant loads, either the classical way with standard concentrations or by using SEWSYS as the pollutant generator. By choosing SEWSYS the model provides the user with
information about the sources of each pollutant and the opportunity to simulate different scenarios on quality source control.

The emission factors for each pollutant source have been compiled in a separate database outside STORM/SEWSYS. Work started in the DayWater project to fill the database with emission factors from different countries and regions in Europe. So far, data sets with pollutant source data has been compiled for catchments in Sweden, Germany and Denmark. The data on emission factors is imported into STORM/SEWSYS each time the user sets up a new model with SEWSYS as the pollutant generator. The idea behind the database is to provide a flexible and open environment to add new data for pollutants and their sources.

STORM/SEWSYS is a compiled software developed in Visual C++ and can be installed on any computer running Microsoft Windows. This is an advantage compared to the original SEWSYS model which requires a MATLAB/Simulink license. STORM/SEWSYS is one of the external tools of the Adaptive Decision Support System (ADSS) developed in DayWater. The web based ADSS can be found at www.daywater.cz.

### 4.4 Process description

Here follows a summary of the major processes as they are described in the SEWSYS model. Further details can be found in Paper I.

#### 4.4.1 Domestic wastewater generation

Sources for domestic wastewater content are divided into grey water, urine and faeces. The default values for water consumption per capita which is assumed to equal the wastewater generation are set to 150 l/d for grey water and 50 l/d for toilet use. In Table 3 a selection of the emission factors for domestic wastewater substances are listed. These values originate from different Swedish studies where the content of domestic wastewater was investigated (Dalemo, 1999; Sundberg, 1995; Vinnerås, 2002).

<table>
<thead>
<tr>
<th>Source</th>
<th>P-tot</th>
<th>N-tot</th>
<th>BOD</th>
<th>COD</th>
<th>Cu</th>
<th>Zn</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grey water</td>
<td>0.52(^1)</td>
<td>1.37(^3)</td>
<td>26(^2)</td>
<td>52(^3)</td>
<td>0.008(^3)</td>
<td>0.01(^3)</td>
<td>g/person, day</td>
</tr>
<tr>
<td>Urine</td>
<td>1.0(^2)</td>
<td>11(^2)</td>
<td>3(^1)</td>
<td>3.5(^1)</td>
<td>0.0001(^2)</td>
<td>0.000045(^2)</td>
<td>g/person, day</td>
</tr>
<tr>
<td>Faeces</td>
<td>0.5(^2)</td>
<td>1.5(^2)</td>
<td>17(^2)</td>
<td>43(^3)</td>
<td>0.0011(^2)</td>
<td>0.0108(^2)</td>
<td>g/person, day</td>
</tr>
</tbody>
</table>

\(^1\)Dalemo (1999), \(^2\)Sundberg (1995), \(^3\)Vinnerås (2002)

For simulations with domestic wastewater, SEWSYS generate the flow with a diurnal variation.

#### 4.4.2 Hydrology and hydraulics

The rainfall–runoff process describes the generation of stormwater flow at the outlet of the catchment. Two phenomena are included in this hydrologic process: (1) the losses during runoff generation and (2) transformation of the resulting effective rainfall into an overland flow hydrograph. The generation of stormwater is calculated by considering the initial loss and only the impervious area is included. The amount of maximum initial loss in the SEWSYS model is determined by the parameter LOSS. If there is less rain volume available than the initial loss, all the rain volume will be
withdrawn and no runoff is produced. For the remaining amount of rain, a constant fraction of the impervious area will produce runoff. This fraction corresponds to the volume runoff coefficient $\phi$. The calculation of rainfall-runoff in SEWSYS follows the conceptual model shown in Figure 9.

![Figure 9. Conceptual model for rainfall-runoff formation in SEWSYS, exemplified for $\phi=0.8$ and LOSS=1 mm](image)

Overland flow is computed by means of a conceptual non-linear reservoir model. The hydraulic conditions in the sewers are not described explicitly by the model. But the hydraulic routing effects in the sewers within the catchment can be included as a lumped process together with overland flow in the non-linear reservoir model. The combined sewer overflow (CSO) is described by a discharge limit value set by the user in the SEWSYS main window. If the wastewater flow from the catchment described by an incoming hydrograph exceeds the discharge limit, this volume will be bypassed and discharged to the water recipient. The CSO is furthermore considered as a completely mixed tank.

### 4.4.3 Stormwater pollutant generation

The selection of stormwater pollution sources to include in the model framework is supported by the findings reported in the literature review if Chapter 2.

The net continuous rainfall and mean annual rainfall, together with emission factors for wet deposition, give the amount of pollutants that come with the rain. The pollution that builds up on impervious areas is divided in SEWSYS into three parts: roads, roofs and other areas. Dry deposition is calculated separately for each of the area categories with emission factors. The other sources for pollutants from road areas consist of tyre and road wear, brake wear, exhaust, oil spillage, catalysts and street-furniture corrosion. The tyre and road wear differ between cars and heavy vehicles. Brake linings are made of copper or brass and plastic. The brake wear contains mainly copper and zinc particles, with emission factors of 1,500 and 650 $\mu$g/km, respectively (Landner and Lindeström, 1999). Zinc corrosion takes place on the galvanised surfaces of street furniture in the vicinity of the road, e.g. railings and lampposts. The zinc
surfaces by roads are entered as a percentage of the total road area in the main window of SEWSYS. A realistic value of zinc surfaces by roads (if no other information is available) is 2%, based on rough estimates of Swedish conditions.

The pollution from roofs originates mainly from corrosion processes that occur when the metallic surface is exposed to air and water. Copper and zinc corrosion in SEWSYS are modelled separately, with emission factors constant over time. The emission factors used are the corrosion rates that are reduced with a runoff rate factor. This is due to the fact that the release of metals in the roof runoff is lower than the corrosion rates because a part of the metal is retained on the surface in corrosion products of low solubility (Persson and Kucera, 2001).

The build-up process of pollutants on impervious areas is modelled as a function of pollutant generation and removal (Overton and Meadows, 1976). Generation from the pollutant sources is assumed to be constant over time while removal is dependent on the accumulated amount which can be expressed as

\[
\frac{dL}{dt} = C - k_a \cdot L
\]  
(Equation 7)

where \( L \) is the accumulated load (\( \mu \)g), \( C \) is the deposition rate (\( \mu \)g/s) and \( k_a \) the rate constant of pollutant removal (s\(^{-1}\)). The deposited material is removed by winds and other means, so the accumulation rate slows down after some time giving the accumulation an exponential form.

The process of pollution accumulation requires an initial start value, which is the amount of pollution generated during the last 4 days (default value) before simulation.

The accumulated pollutants are washed out during rainfall. The removal by wash-off is assumed to be proportional to the accumulated amount and to the rain intensity (Overton and Meadows, 1976) and given as

\[
\frac{dP}{dt} = -k_w \cdot r \cdot P
\]  
(Equation 8)

where \( P \) is the amount of pollutant remaining on the surface (\( \mu \)g), \( k_w \) is the washout rate constant (mm\(^{-1}\)) and \( r \) is the rainfall intensity (mm/s).

The differential equations above are expressed in discrete form as they are implemented in the SEWSYS model.

**4.4.4 Wastewater treatment plant**

The wastewater treatment plant (WWTP) is a modified version taken from ORWARE, a Swedish model for management of municipal organic waste (Dalemo, 1999). The original model has been modified to suit the SEWSYS structure and substance vector. The WWTP sub-model consists of screen, sandtrap, pre-sedimentation, biological purification (activated sludge treatment) and chemical
purification. The model offers the choice of including nitrogen purification in the activated sludge process. Sewage sludge is thickened and then led out of the model. The WWTP used in SEWSYS greatly simplifies the complexities of pollutant treatment, but as the aim of the model is to describe the substance flows of wastewater and not to provide detailed simulation and design of treatment processes, the simplified approach is held appropriate.

4.4.5 Stormwater pond

The removal of pollutants in the stormwater treatment pond is modelled according to a USEPA-method, with a dynamic phase during wet weather conditions and a quiescent phase during dry weather (USEPA, 1986). The particulate bound pollutants are removed through sedimentation which is the predominant process in reduction of pollutants in treatment ponds (Walker and Hurl, 2002). The sedimentation process depends on factors such as size of the pond, the water flow, size and density of the suspended particles.

The dynamic phase is calculated with the following equation

\[
R_d = 1.0 - \left[ 1.0 + \frac{1}{n} \cdot \frac{v_s}{Q/A_{pond}} \right]^{-n}
\]

(Equation 9)

where \( R_d \) is the removal rate of particles, \( v_s \) is the settling velocity (m/s), \( Q \) is the inflow (m\(^3\)/s), \( A_{pond} \) is the pond area (m\(^2\)) and \( n \) is a turbulence constant. An n-value of 1 specifies poor pond performance which is the case under variable inflow and consequently used as default in this module.

The quiescent phase uses the equation

\[
R_q = 1.0 - e^{-v_s \cdot t/d}
\]

(Equation 10)

where \( R_q \) is the removal rate of particles, \( t \) is the inter-event dry period (s) and \( d \) is the pond depth (m).

4.5 Results from field measurements

Field measurement of stormwater quantity and quality took place in Vasastaden in the period from April 27 to May 29, year 2002. In the period of 33 days the installed rain gauge recorded a total rainfall of about 70 mm, of which 16 storm events were chemically analysed. The rainfall characteristics for the analysed events are shown in Table 4. The rainfall was distributed rather evenly throughout the period with one exception of a longer dry period between the 1\(^{st}\) and 9\(^{th}\) of May.
Stormwater flow measurements were running continuously in the period, ensuring a flow-weighted water sampling. The analysis of stormwater in Vasastaden shows an average pH of 6.8 and a conductivity of 64 μS/cm. The results of the chemical analyses for heavy metals and total suspended solids (TSS) for each rain event are shown in Table 5. The event mean concentrations (EMCs) in the table have been calculated with a number of flow-weighted sub-samples for each event. For example, the EMC for rain event vasa020429 is calculated with 14 sub-samples. The site mean concentrations (SMCs) in Table 5 are calculated as the flow-weighted average of EMCs. Total nitrogen (TN) and total phosphorus (TP) were only analysed in 7 composite samples with SMCs of 1.6 mg/l and 0.14 mg/l, respectively.
PAH-16 was analysed in 19 sub- and composite samples. For the carcinogenic PAHs, all the samples were lower than the detection limit (0.02 μg/l). In the group of other PAHs, pyrene, fluoranthene and naphthalene were detected just above the detection limit for 13 samples. PCB-7 were analysed in 3 composite samples and were not found above the detection limit (0.01 μg/l). Acute toxicity with Microtox was analysed in six sub-samples. The toxicity was classified as Zero or Slight for all samples except one which was classified as Moderate.

The content of copper and zinc in stormwater from Vasastaden shows higher SMC values compared to studies found in the literature. To eliminate the possibility for errors in the chemical analysis, a few duplicate samples were sent to an external laboratory. Using the same analysis method (ICP/MS), the external laboratory reported the same concentrations. Therefore, the concentrations for zinc and copper shown in Table 5 are believed to be correct. For zinc the measured SMC (437 μg/l) is fairly high compared to other studies with mixed urban land use. Gnecco et al. (2005) report a median EMC for zinc of 408 μg/l for runoff from a roof covered with slate and with zinc gutters. Runoff from a heavily trafficked highway is reported by Pettersson et al. (2005) to have a median zinc EMC of 290 μg/l, and copper 82 μg/l. Gromaire-Mertz et al. (1999) report extremely high concentrations of zinc with a median EMC of 3200 μg/l for runoff from a roof with zinc sheets and gutters.

4.6 Model validation

The SEWSYS model was calibrated and validated with data from the field measurements in Vasastaden. A random split-sample technique was used where the 16 rain events were split in two halves by randomisation, and the first 8 events were used for calibration and the remaining events for validation. The model parameters were calibrated automatically using the *fminsearch* function in MATLAB. The function to minimise was the sum of squared errors between measured and simulated data. For calibration of the rainfall-runoff module the event runoff volumes were used, and for the water quality module the event mean concentrations (EMCs) were used. Four measures of performance were used to judge the model's simulation ability: Bias, RMSE, coefficient of determination *r*² and model efficiency EF.

The model parameters $\phi$ and LOSS were used in calibration of the rainfall-runoff module. Table 6 presents a summary of the simulation performance for the calibration and validation periods. The rainfall-runoff module in SEWSYS is able to predict the runoff volume well, as it is implied by the goodness-of-fit measures. This is also observed in Figure 10, showing a graphical comparison between calibration and validation data. It was possible to calibrate the model very accurately using the calibration data set, where all the variance in the observed data could be explained by the model ($r^2=1.0$) and with a very low mean square error (EF=1.0). Using the calibrated model and evaluating the validation data shows only minor reductions in the goodness-of-fit measures ($r^2=0.99$ and EF=0.99).
Table 6. Model calibration and validation results for rainfall-runoff simulation

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Bias</th>
<th>RMSE [m³]</th>
<th>r²</th>
<th>EF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vasastaden</td>
<td>CAL</td>
<td>VAL</td>
<td>CAL</td>
<td>VAL</td>
</tr>
<tr>
<td>Volume</td>
<td>1.00</td>
<td>1.00</td>
<td>5</td>
<td>12</td>
</tr>
</tbody>
</table>

Figure 10. Calibration data (left) vs. validation data (right) for event runoff volumes

However, by putting together all the events from one site and then perform a calibration means that the prediction of runoff volume for some events will be good and some will be not so good. It is not enough to only study the runoff volumes and the corresponding goodness-of-fit; the actual appearance of the hydrographs is equally important. Two rainfall events have been chosen to point out the importance of including the hydrographs in the model validation and are shown in Figure 11 and Figure 12. The chosen rain events represent different conditions: the event from 020429 has a longer duration and higher flows, whereas the event from 020525 has shorter duration and lower peak flow. In both cases the rainfall-runoff module in SEWSYS produces hydrographs consistent with the flow measurements.

Figure 11. Observed and modelled hydrographs for rain event 020429
The model parameters $k_a$, $k_w$ and EFs were used in calibration of the water quality module. Table 7 presents a summary of the simulation performance for the calibration and validation data for copper EMCs. The water quality module in SEWSYS is able to predict the EMCs reasonable well, as it is implied by the goodness-of-fit measures. This is also observed in Figure 13, where the calibration and validation data are compared. It was possible to calibrate the model quite well, where 75% of the variance in the observed data could be explained by the model ($r^2=0.75$). Using the calibrated model and evaluating the validation data reveals considerable reductions in the goodness-of-fit measures ($r^2=0.22$ and EF=0.57), and especially poor predictions of the higher EMCs.

Table 7. Model calibration and validation results for water quality simulation (Copper EMC)

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Bias</th>
<th>RMSE [µg/l]</th>
<th>$r^2$</th>
<th>EF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vasastaden</td>
<td>CAL</td>
<td>VAL</td>
<td>CAL</td>
<td>VAL</td>
</tr>
<tr>
<td>Cu EMC</td>
<td>0.96</td>
<td>0.71</td>
<td>74</td>
<td>171</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 13. Calibration data (left) vs. validation data (right) for copper EMCs
4.7 Model uncertainty

A comprehensive uncertainty analysis of the stormwater module in SEWSYS is reported in Paper III. The uncertainty analysis is performed for three cases. In Case I the uncertainty is analysed for total volume over the whole simulation period and for volumes for each rain event. In Case II the uncertainty is assessed for predictions of the event mean concentrations (EMCs) and the site mean concentration (SMC). Finally, in Case III the uncertainty is analysed for total pollution load over the whole simulation period. The measurements of stormwater quantity and quality in Vasastaden are used in the model calibration step.

As the first step in the preliminary uncertainty analysis of Case I (uncalibrated model) the parameters reduction factor ($\phi$) and initial loss ($LOSS$) was declared as stochastic variables with log-normal distributions. 1000 simulations were run with SEWSYS using the parameter sets for $\phi$ and LOSS. The results of the preliminary uncertainty analysis for event runoff volumes are shown in Figure 14. The uncertainties are expressed in a relative scale as 2 times the coefficient of variance (CV). For the larger rain events the uncertainty is about 40% of the mean value. For total modelled runoff volume the uncertainty is 36% of the mean value.

![Event Runoff Volumes (uncalibrated LHS)](image)

Figure 14. Modelled and measured event runoff volumes (Case I, uncalibrated), uncertainty bound for modelled values is $\pm2CV$

The parameter sensitivities calculated with data from the multi-linear regression show which parameters that are most efficient to calibrate. In this case the hydrological reduction factor and initial loss are both sensitive parameters with regards to output uncertainty of stormwater event runoff, and hence included in the calibration step.

In calibration of the rainfall-runoff module the Bootstrap method was used. The parameter sets for the calibrated case were then used in a Monte Carlo simulation followed by multi-linear regression to evaluate the uncertainty propagation. The results from the uncertainty analysis for event volumes for the calibrated case are shown in Figure 15.
For the event volumes the uncertainty is reduced by about 40 percentage units compared with the uncalibrated case, with larger reductions for the smaller rain events. For total runoff volume the predictive uncertainty is reduced from 36% to 5%.

For the results of the uncertainty analysis of Case II and III, please refer to Paper III.

4.8 Systems analysis and SFA in Vasastaden

A methodology consisting of a scheme of methods and principles to be used for systems analysis of wastewater management is presented in Paper V. The methodology was developed and evaluated in a cooperative research project between the Urban Water program and the City of Göteborg. The methodology was tested in a case study for the Vasastaden catchment, one of the model cities in the research program. Three different system structures for management of wastewater were compared: a combined sewer system, a conventional separate sewer system, and a separate system with source control. The sustainability aspects covered in the methodology are technical function, substance flows, economy and risks.

The SEWSYS model was used in this study in a substance flow analysis (SFA) with the purpose of quantifying the flows, the kind of substances present in the sewer system and the pollutant sources. SEWSYS also provided input for the environmental impact assessment (EIA) of the different system structures. Environmental impacts were assessed from the viewpoint of the local water body Vallgraven, local sediment (sediment in Vallgraven and sediment in the retention pond) and the sewage sludge. In addition, the SEWSYS model was used in a scenario study to evaluate the efficiency of non-structural BMPs. The scenario study is presented separately in Paper VI and is summarised in Chapter 4.9.

Figure 16 shows the Vasastaden catchment divided into six sub-catchments and the surface distribution. The different surfaces were determined using GIS analysis and a complementary field study on roofing materials. The results from the GIS analysis provided input data for the SEWSYS model, see Table 8.
There are two different kinds of sewer system in the catchment at present: a separate system and a combined system. In the separate system, sanitary wastewater is diverted directly to the WWTP and stormwater is conveyed to the nearest combined sewer. The reason for having this system is that the stormwater is considered too polluted to be diverted directly to the local water body Vallgraven. The catchment was divided into six sub-catchments depending on their system structure. Sub-catchments 1-3 have a sanitary wastewater active separate system and sub-catchments 4-6 have a combined system. This means that the present sewer system in principle can be defined as a combined system, because all the stormwater generated in the catchment is influencing the CSO discharges.

Eight substances were included in the SFA: copper (Cu), zinc (Zn), lead (Pb), cadmium (Cd), phosphorus (P), nitrogen (N), polyaromatic hydrocarbons (PAH) and biological oxygen demand (BOD). A long-term perspective is of importance when using time-series of rainfall data in simulation models. Therefore a one-year rain series
is used that describes well a normal hydrological year in the Göteborg region. The rain series, called Lundby1926, gives an annual precipitation of 685 mm.

4.8.1 Present sewer system (combined)
The present sewer system is described by the Simulink-model in Figure 17. The representation of the system is the result of the evaluation of technical function, the first step in the systems analysis. Sub-catchments 1-3 are described as a sanitary wastewater active separate system and catchments 4-6 as a combined system.

The recipient Water is divided into CSO discharges and WWTP effluent, where Vallgraven is the receiving water body for the CSO volume and the WWTP effluent is discharged into the coastal waters. The recipient Landfill receives material from the treatment steps screen and sand trap in the WWTP, which is transported to a landfill. The recipient Sludge consists of sewage sludge from the pre-sedimentation and the biological and chemical treatment steps. The recipient Air receives substances (N₂) from the nitrification and de-nitrification processes in the WWTP.

4.8.2 Conventional separate sewer system
Figure 18 shows the Simulink-model for an alternative system, where all the present combined catchments now have a separate sewer system.
In this alternative all stormwater is discharged without any treatment to the recipient Vallgraven and the WWTP effluent is still discharged into the coastal waters.

### 4.8.3 Separate sewer system with source control and treatment

Figure 19 shows the Simulink-model for the structure where all catchments have a separate sewer system and source control is applied for stormwater. This system addresses the problem of direct discharge of untreated stormwater as in the case of the conventional separate system. The source control strategies consist of different structural BMPs. Stormwater from streets is regarded as heavily polluted and needs treatment before it can be discharged into the receiving water. In this case a retention pond was used for stormwater treatment.

From catchments 1, 2, 4 and 5 the stormwater is considered too polluted to be infiltrated, therefore all stormwater is diverted to the retention pond. From catchments 3 and 6 the stormwater from roofs and other areas is infiltrated in the ground, while
the stormwater from roads is considered to be too polluted. Two additional recipients are introduced in this system structure: the soil as recipient for infiltrated stormwater and local sediment in the pond. If careful consideration of the groundwater is taken into account when stormwater is infiltrated, the soil can be seen as a relatively stable recipient. However, in both cases there is a need to handle the contaminated soil and sediment which may pose a potential solid waste disposal problem (Mikkelsen et al., 1997).

4.8.4 SFA results

The simulations with SEWSYS give that the whole catchment (sub-catchments 1-6) generates in total 735,000 m$^3$ of wastewater per year, where sanitary wastewater and stormwater contributes with 474,000 and 262,000 m$^3$, respectively. The generated sanitary wastewater volume was first calculated with a specific domestic water use of 150 l/person/day but was changed later in the study to 200 l/person/day, a more realistic value. However, this does not affect the total substance flows generated from the area. Figure 20 shows the simulation results for the pollution sources, in relation to the total load from Table 2 in Paper V. The results show that the largest part of phosphorus and nitrogen can be found in urine and faeces, where phosphorus and nitrogen in the urine fraction is 50% and 80%, respectively. Grey water is a significant source for heavy metals and BOD, whereas stormwater contributes mainly with heavy metals and PAH. For copper in stormwater the two main sources are copper roof corrosion and brake wear with contributions to the total load with 31% and 24%, respectively. The pollution of zinc in stormwater comes from several sources, where corrosion of zinc roofs (painted and galvanised) together with tyre wear contribute with almost 1/3 of the total pollution. For both lead and cadmium the dominant sources are greywater and atmospheric deposition.

![Figure 20. Total substance flows divided in sources for domestic wastewater and stormwater](image)

The results of the SEWSYS simulations for the three system structures for each of the sinks Vallgraven and Sewage sludge are displayed in Figure 21 and Figure 22,
respectively. The pollution load to *Vallgraven* increases for all substances in the case of the conventional separate system where all stormwater is directly discharged to the recipient. On the other hand, the WWTP receives no stormwater at all and the sewage sludge contains less heavy metals and PAH. The reductions for heavy metals and PAHs in sewage sludge are about 50% and 75%, respectively. These reductions are also valid for the separate system with source control. Source control (SC) measures of infiltration and treatment in the pond decreases the pollution load to *Vallgraven* for all substances.

![Figure 21. Pollution load to Vallgraven](image1)

![Figure 22. Pollution load to Sewage sludge](image2)

### 4.8.5 EIA results

The results from the SFA with SEWSYS were used in the environmental impact assessment (EIA) in the form of simulated site mean concentrations (SMCs). The results from the EIA show that none of the systems would entirely satisfy the Swedish
EPA’s environmental quality criteria (EQC) for heavy metals. When applied to the recipient Vallgraven the EQC showed that copper was the critical metal for the combined system, and for the conventional separate systems the critical metals were copper, zinc and lead.

**4.9 Evaluation of BMPs using SEWSYS**

The usefulness of using SEWSYS in the evaluation of different stormwater best management practices (BMPs) are presented in Papers IV and VI. Here follows a summary of the main results.

**4.9.1 Source control by combinations of structural and non-structural BMPs**

Paper IV presents a case study of an SFA where different abatement strategies concerning stormwater quality were simulated, comprising both structural and non-structural. This study was the first SFA performed within the scope of this thesis. The study object was the Vasastaden sub-catchments 1-4 as outlined in Figure 16, with sub-catchments 1-3 defined as sanitary wastewater active separate system and sub-catchment 4 as combined. The objectives of the study were three-fold: (1) to use SFA to evaluate the present situation, (2) evaluate an alternative system structure where the separate sewer systems are conveyed to the local recipient Vallgraven, and (3) to simulate and evaluate four different abatement strategies for improving the stormwater quality.

Different alternatives for improving the stormwater quality and decreasing the discharges of polluted stormwater to Vallgraven have been used for the simulations, and combined into four scenarios:

Scenario 1 – Reduction of the construction material pollutant sources. This is simulated with an 80% decrease in copper and zinc surfaces, together with a 50% decrease in substances from asphalt.

Scenario 2 - Reduction of the movable pollutant sources (emissions from vehicles). This is simulated with a 50% decrease in substances from tyres, zero copper emission from brake linings, 50% decrease in oil spillage, along with an overall 30% decrease in traffic load.

Scenario 3 –Infiltration of stormwater. In the simulations, it was assumed that all stormwater from roofs and 50% of other areas could be infiltrated. No part of the stormwater from road areas is infiltrated.

Scenario 4 – Treatment in a stormwater pond. Stormwater is lead to a sedimentation basin.

The simulation results of the SFA for the alternative system structure show that the pollution load to the water recipient Vallgraven increases with an order of magnitude of about 18 compared with the present system. As Vallgraven is classified as a sensitive recipient with recreational values it is important to reduce the pollution load. The relative pollution reductions obtained from Scenarios 1 and 2 are presented in Figure 23 for the selected substances copper, zinc, phosphorus and PAH. The simulations show that:
4 MODEL DEVELOPMENT

- Reducing the construction material sources (Scenario 1) has considerably decreased the pollution load of copper (by 30%) and zinc (by 42%). Lead, cadmium and PAH have decreased by less than 15%, whereas phosphorus and nitrogen have no reduction at all.

- Reducing the movable pollutant sources (Scenario 2) has considerably decreased the pollution load of copper (by 56%). Zinc has decreased by 22%; phosphorus and PAH by 15% and 12%, respectively. Lead and cadmium have both been reduced by less than 10%.

- If Scenario 1 was combined with Scenario 2, very high reductions of the pollution loads from copper and zinc would be obtained.

![Reduction of pollutants](image)

**Figure 23. Reductions of total pollution load to Vallgraven for Scenarios 1-2**

The results for the simulation of Scenario 3 (stormwater infiltration) show reductions of the pollution load to Vallgraven in the range of 23-42% for the studied substances. If Scenario 3 is compared with the modified system, the overall reduction is about 96%.

In Scenario 4 simulations were made with the separate catchments connected to a stormwater pond. Comparing the results from Scenario 4 with the simulation of the modified system, *i.e.* where all stormwater from the separate catchment is directed to Vallgraven, show considerable reductions of the discharges to the receiving water for some of the substances, where pollution load of PAH is reduced by 77%, lead by 66% and phosphorus by 53%. The discharge of copper and zinc would be reduced by 41%, whereas the reduction of cadmium and nitrogen would be 15% and 9%, respectively.
In a comparison between the present situation and Scenario 4 the pollution load to the receiving water increases in the ranges of a factor 4 (for PAH) to a factor 16 (for nitrogen).

4.9.2 Efficiency of non-structural BMPs

Paper VI describes a modelling study where SEWSYS was used for evaluating the efficiency of different non-structural best management practises for stormwater management. This study was a part of the systems analysis presented in Paper V, which means that Papers V and VI use the same area in Vasastaden (sub-catchments 1-6 in Figure 16).

In year 1999 the Swedish Parliament agreed on 15 environmental quality objectives (EQOs), which form the basis for the ongoing and future environmental work in Sweden (SEPA, 2006). The overall goal is to solve the major environmental problems we currently face, and to achieve this goal within one generation. This implies that all key measures required in Sweden must be implemented by the year 2020. To guide efforts to achieve the EQOs, national authorities such as the Swedish Environmental Protection Agency (SEPA) have suggested environmental quality criteria (EQC) for different fields of environmental management. EQC play an important role in the management framework by providing the quantitative benchmarks for measuring success in achieving EQOs. The aim of this modelling study with SEWSYS was to evaluate how the modelling approach could be used to simulate different non-structural BMPs in combination with management by objectives using EQC.

The modelling approach chosen for this study uses the SEWSYS model from the viewpoint of two cases:

1. For management by objectives, i.e. aiming towards specific environmental quality criteria (EQC).
2. For the evaluation of source reduction practices, i.e. a source control scenario with different non-structural BMPs.

First, management by objectives was introduced to meet EQC given by the Swedish Environmental Protection Agency (SEPA) with respect to environmental effects in recycling sewage sludge (SEPA, 2002) and surface water discharges (SEPA, 1999). In detail this implies measures to achieve: (a) acceptable sewage sludge quality for agricultural use according to SEPA’s proposed action plan for the year 2020 and (b) acceptable stormwater quality for direct discharge of stormwater to the local water body. The results from the SFA and EIA performed in Paper V showed that copper, zinc and lead were the critical substances in stormwater discharges directly to the local water body, taking the dilution effect into account. The reductions required for copper, zinc and lead were 90 %, 55 % and 50 %, respectively. Also, the characteristics of the sewage sludge from the local wastewater treatment plant were taken into consideration in the EIA. The EIA for sewage sludge showed that copper and lead need to be reduced by about 10 %, but this reduction was assumed to be achieved without any specific prevention measures. Instead, cadmium posed the greatest challenge and must be reduced by 62 % to comply with the proposed EQC associated with the use of sewage sludge as fertilizer.
Second, the SEWSYS model was used to simulate a scenario with different non-structural BMPs. The scenario is based on a hypothetical control program that includes prevention, education and regulations and that would be fully adopted by the year 2020. The effects of the control program are simulated using the following assumptions on pollution reduction from:

- copper roofs by 80 %, using material replacement, painting and copper filters in down-pipes.
- painted roofs by 20 %, by using paint with a lower zinc content.
- brake wear by 80 %, by banning the use of copper in brake linings within seven years.
- galvanised areas (*e.g.* street furniture) by 20 %, through painting and replacement.
- tyre wear by 80 %, by using more environmentally friendly tyres.
- road wear by 60 %, by different studs in tyres and a change in driving patterns.
- atmospheric deposition (wet and dry) by 1 percentage unit per year, *i.e.* in total 17 %.

In addition, the traffic load in the catchment is assumed to decrease 10 % by the year 2020 by the introduction of tolls in the inner city.

The simulations with SEWSYS for the present situation as compared with the hypothetical control program comprising different non-structural BMPs, are shown in Figure 24. The total pollution load (100%) in the figure corresponds to the total substance flows of stormwater as presented in Paper V and VI. The simulations show relatively high reductions in copper and PAH, 77 % and 50 % respectively, whereas the reductions for the other substances range from about 15 to 30 %.

![Figure 24. Simulated reductions with source control measures](image-url)
In a comparison between the pollution reductions required by the EQC and the simulated reductions achieved using the control program it is observed that a simulated cadmium reduction of 23 % falls very short of the required of 62 %. Furthermore, the simulated reductions in copper, zinc and lead do not meet the required reductions in surface water discharge. There is a clear need to further reduce the pollution load for the critical heavy metals.

The total reductions were also evaluated in terms of the distribution among the different sources of stormwater pollution incorporated in the model. As seen in Figure 25, the reductions in copper corrosion and brake wear contribute most (about 98 %) to the total reduction of copper, and reductions in brake wear and roof corrosion are the largest contributors to reductions of zinc load. The lower lead level is a result of the reductions in road wear and dry deposition.

Figure 25. The respective source and its relative contribution to the total pollution reduction

Figure 26 shows the distribution of the sources that contribute to the remaining stormwater pollution in the system. From this figure it can be seen that the greatest sources for copper pollution is still copper corrosion and brake wear, for zinc it is zinc corrosion and tyre wear. Since the road wear has been reduced dry deposition is now the greatest contribution to lead pollution.

Figure 26. The respective source and its relative contribution to the remaining pollutants
4.10 Substance flow modelling as decision support

This section aims at putting the developed model in a wider context in terms of its usefulness in supporting decisions regarding urban stormwater management.

**Paper V** in this thesis presents a methodology for systems analysis of wastewater systems in a catchment in Göteborg, Sweden. The methodology was developed and evaluated in a cooperative research project between the Urban Water research program and the City of Göteborg, represented by the Recycling Office and the Water and Wastewater Works. The results presented in the paper show that the methodology provides useful information about the systems, which can be used in decision support. The SEWSYS model is a fundamental part of the proposed methodology and was used in the project for substance flow analysis and evaluation of scenarios. SEWSYS also provided input for the environmental impact assessment of the different systems. The project has also been reported in full in a Swedish report (Ahlman *et al.* , 2004). This report was the basis for the material used in an exercise performed with different stakeholders in the City of Göteborg in order to make comparative evaluations between different stormwater management alternatives. The stakeholder dialogue exercise was performed in co-operation with the Urban Water MIKA-project, which worked with knowledge management support within complex planning processes. The results of the exercise will be presented in an Urban Water report in spring 2006 (Kärrman *et al.*, in prep).

Positive experiences from the systems analysis project described above lead to the decision to include SEWSYS as the SFA tool in a larger project on long-term wastewater planning for the whole of Göteborg. In this project SEWSYS was used for quantification and source identification of pollutant loads emanating from the combined and separate sewer systems.

A study on the pollutant load from road runoff to different receiving waters in the city of Göteborg was included as a part of the larger long-term planning project (German *et al.*, 2006). The study was initiated by the City of Göteborg and the National Road Administration with the aim to quantify the pollutant loads and the sources of pollutants from roads in Göteborg. The results from the road runoff study will be used to support decisions regarding in which catchments it is most effective to introduce pollution reduction measures on road runoff, depending on pollution load and sensitivity of the receiving water.

Many aspects have to be considered when making decisions about the future water management systems: the environment, hygienic considerations, chemical risks, economy, and organisational aspects. The Urban Water toolkit, one of the main deliverables from the research program, contains tools for analysing these central aspects. The tools range from computer models to hands-on advisory services. The substance flow model SEWSYS is one of the components in the toolkit.

The Urban Water tools and methods have been tested and developed in a number of model cities, which represent different types of Swedish urban environments. The research was shaped through the interaction between the Urban Water researchers and the local stakeholders in the model cities. The research program was concluded
with the use of the tools and methods in several projects in one of the model cities, the city of Uppsala. One of the projects dealt with evaluation of possibilities for alternative stormwater management, particularly focusing on the beneficial use of stormwater. The SEWSYS model was used here for SFA in the studied catchments and with the intention of providing decision support for the City of Uppsala concerning their future stormwater management strategy (Ahlman, 2006).

The research presented in this thesis has also been part of the European research project DayWater. The main product of the DayWater project is a web-based adaptive decision support system (ADSS) called Hydropolis. The ADSS is intended to provide guidance and support in decision making regarding projects on urban stormwater management in order to find the best suitable measures by adapting to different stakeholder's problems. The sources and flux model STORM/SEWSYS is one of the external tools linked with the ADSS. As such, the model is used for calculating facts to be used in multi-criteria decision making.

Climate change due to human activities has the possibility of changing both the natural and built environment over the coming decades. With the increase in global population and the associated urbanisation, stakeholders have an urgent need for tools to assess the impacts of global warming on urban water resources. As a reaction a research project was initiated with the aim to investigate the relative effects of climate change and changes in management of wastewater and stormwater in central Helsingborg, southern Sweden (Semadeni-Davies et al., 2005). The study used an approach of sensitivity analyses with the urban drainage model MOUSE and the substance flow model SEWSYS. Scenarios were developed for changes in both regional climate and urban drainage. The latter were based on current trends in Sweden and ranged from no change to complete rehabilitation of existing pipes and use of local stormwater volume and quality controls in new housing areas.

The SEWSYS model is also being used in the ongoing research project NORIS (No Rain in Sewers). NORIS is an EU funded Interreg North Sea Region project running from 2004 to 2007 with the aim of improving water quality and reduce other quality and quantity-related problems by reducing the excess water entering the sewers. This will ultimately improve water quality by reducing sewer overflows, and enable wastewater treatment plants to work more efficiently. Two-in-one sewer relining technique and source control measures with filtration devices will be implemented and tested in different catchments. Simulations of runoff from different types of sealed areas with different treatment measures will be made, which makes it possible to evaluate different scenarios. The simulations will be done with the STORM/SEWSYS model. Additional information about the NORIS project is found on the web site http://www.noris.co.uk/.
5 CONCLUSIONS

In this chapter conclusions from the work presented in this thesis are presented.

The main objective of the work presented in this thesis is to develop a modelling framework that enables a source based pollution analysis of urban drainage systems. The developed mathematical model is called SEWSYS and is intended to be used for simulation of substance flows in combined and separate sewer systems.

The substance flow model SEWSYS is able to predict pollutant loads and concentrations that are consistent with measured and literature values, and thus the model is considered acceptable for the intended purposes. Furthermore, the validation studies indicate that it is possible to quantify the pollutant load from an urban catchment through the study of different diffuse sources of pollution present in the area. The model is also considered useful for understanding the processes of generation and spreading of the included substances.

Although some of the results from the model can be collected in an alternative way by using a simpler analysis of the land uses and associated unit loads in a catchment, the developed SEWSYS provides a more generic tool. The use of MATLAB/Simulink and the open-source code facilitate future development and adaptation of the model. The wider range of purposes for the SEWSYS model includes:

- Analysing alternative pollution control measures
- Modelling the impact of future changes in an urban catchment
- Prioritising abatement measures on the basis of catchment characteristics

This study shows that a substance flow modelling approach for estimation of urban runoff pollutant loads can be efficiently developed to provide important information for analysing reductions of pollutants. The SEWSYS model, together with GIS analysis to provide geospatial input data, forms a modelling framework that is a useful aid in setting up non-point source pollution management plans. If targeted against certain environmental quality criteria (EQC), SEWSYS can be a useful tool in providing catchment-specific pollution data, and identifying the important sources and how great the reduction in pollution must be to meet the desired EQC. SEWSYS also makes it possible to study the efficiency of the pollution reduction measures taken, i.e. what reduction in pollution the measures actually give as well as it makes it possible to identify which sources have the greatest effect on reductions in pollution.

In Paper VI it was shown that for the specific catchment at study, the applied non-structural BMPs did not achieve a sufficient reduction in pollution to meet the desired EQC. To do so requires the implementation of additional BMPs, both non-structural and structural. To be able to achieve a significantly higher reduction in pollution, there is a need to implement structural BMPs. Such measures may be stormwater retention ponds, filters and infiltration devices.

A methodology for systems analysis of alternative wastewater systems was developed and evaluated in Paper V. The results presented in the paper demonstrate that the methodology can provide useful information about the sustainability of the systems,
which then can be used in decision support. The SEWSYS model was used in this study for the substance flow analyses of the different system structures and provided quantifications of the substance flows, the kind of substances present in the sewer system and the pollutant sources. SEWSYS also provided input for the environmental impact assessment (EIA) of the different systems. In summary, the model was a fundamental part of the overall systems analysis.

A reliable estimate of the prediction uncertainty of a model is essential for making efficient decisions based on the model simulations. The uncertainty analysis of SEWSYS presented in Paper III shows that predictions made with an uncalibrated model are associated with a considerable amount of uncertainty. It is also shown that by means of calibration this uncertainty can be reduced to an acceptable level. The rainfall-runoff module in SEWSYS can predict total runoff volumes and hydrographs with high accuracy and low uncertainty. The uncertainties for predictions of event runoff volumes and event mean concentrations (EMCs) are higher, compared with predictions of total runoff volume and site mean concentration (SMC). When using the model for comparing alternatives or scenarios the relative uncertainty in the difference between alternatives is probably lower than the absolute uncertainty in model prediction.

The use of MATLAB/Simulink as the model interface for SEWSYS provides both possibilities and limitations. The user-friendly environment in MATLAB/Simulink facilitates future development and adaptation of the model. One limitation is that SEWSYS requires MATLAB/Simulink to run. This problem has been solved by the integration of SEWSYS into the STORM model as described in Paper II. The STORM/SEWSYS model combines two modelling approaches into a stand-alone tool containing simple and well-established hydrological and hydraulic principles. STORM/SEWSYS is a powerful simulation tool with a wide range of applications within stormwater management. It has the ability to simulate and evaluate quality source control measures as well as structural BMPs such as swales, infiltration devices, wetlands and ponds.

The effects of non-structural and structural BMPs on pollution reduction were evaluated in Paper IV. If measures for the reduction of pollutant sources as suggested in the source control scenarios were combined with structural BMPs as suggested in the treatment scenarios, very high reductions of the discharges to the receiving water would be obtained. This highlights the importance of combining the two approaches. The source control measures are however recommended as a first choice since they can be seen as being more sustainable from an environmental point of view. Source control measures prevent the substances from entering the water system. Such measures are by definition sustainable. A decreased use of metals and minerals from the crust of the earth is a step towards a more sustainable society. The treatment facilities should only be used when the pollutant sources have been reduced as much as it is practically possible.
The most important findings of the work presented in this thesis can be summarised in the following points:

- The conceptual stormwater model called SEWSYS, developed for substance flow analysis of urban drainage systems, has the ability to follow substances in terms of their sources, pathways and sinks.
- The validation studies of SEWSYS indicated that it is possible to quantify the pollutant load from an urban catchment through the study of different diffuse sources of pollution present in the area.
- The hydrological module in SEWSYS performed generally well in the model validation but the quality part produced less reliable results.
- The results of the uncertainty analysis showed that predictions made with an uncalibrated model are associated with a considerable amount of uncertainty. It was also shown that by means of calibration this uncertainty can be reduced to an acceptable level.
- SEWSYS is appropriate for systems analysis and decision support in stormwater management.
- The model is a useful tool for simulating and evaluating pollutant source control measures.
- SEWSYS is a pedagogical tool that explains the links between the “polluters”, *i.e.* pollution sources, and the consequences for the “receivers”, *i.e.* where the pollution will end up.
6 OUTLOOK AND SUGGESTIONS FOR FUTURE WORK

The main product from this thesis is a substance flow model called SEWSYS that enables a source based pollution analysis of urban drainage systems. The modelling framework has been developed to be generic and flexible in order to facilitate future development and adaptation of the model. An outlook is presented here to identify the current trends and needs for pollution analyses. From this follows suggestions for future work regarding development of the SEWSYS model.

In year 1999 the Swedish Parliament agreed on fifteen environmental quality objectives (EQOs), which form the basis for the ongoing and future environmental work in Sweden (SEPA, 2006). The overall goal is to solve the major environmental problems we currently face, and to achieve this goal within one generation. This implies that all key measures required in Sweden must be implemented by the year 2020. The task of monitoring and evaluating progress towards these goals has been entrusted by the Swedish Government to the Environmental Objectives Council, which consists of representatives of central government agencies, county administrative boards, local authorities, non-governmental organizations and the business sector. In 2004 the Council put forward an evaluation report describing the progress towards the objectives (SEPA, 2004). The Council judged four of the fifteen environmental objectives to be particularly difficult to achieve, and three of these have special relevance for urban water management. In the case of the goal Zero Eutrophication, pressures on the environment are admittedly decreasing, but the natural systems concerned will take a long time to recover. As regards to A Non-Toxic Environment, the Council identified a major problem in that releases of toxic substances are diffuse and difficult to deal with, at the same time as many of the substances in question are persistent. As for the objective Reduced Climate Impact, far-reaching international agreements are recognized by the Council as being essential, the Kyoto Protocol being no more than a first step.

The prospects of reducing the environmental impacts of chemicals in Sweden depend to a very significant degree on the chemicals policy adopted by the European Union (EU). The EU is changing its general approach for chemical regulation by introducing the new programme REACH (Registration, Evaluation and Authorisation of Chemicals). The aims of the proposed new regulation are to improve the protection of human health and the environment while maintaining the competitiveness and enhancing the innovative capability of the EU chemicals industry. REACH will require producers and users of chemical substances to register any use in a volume-triggered system. Mandatory submission of chemical assessment reports containing information on the hazards, exposures and risks associated with the uses of the chemical substances will be reviewed by government appointed expert committees (Petry et al., 2006).

The European Water framework directive (WFD) is probably the most important environmental management directive that has been enforced over the last decade in the European Union (Achleitner et al., 2005). The directive aims at achieving an overall good ecological status in all European water bodies (ground and surface waters) by organising water management on a river-basin scale, and applying a combined emission and water-quality based approach.
The implementation of the EU WFD and the anticipated Sludge Directive requires the water industry to better understand the flow of priority substances entering and being discharged from wastewater treatment works (Rule et al., 2006). In order to assess the potential treatment options required to meet new legislation a detailed understanding of the load and sources of priority substances entering WWTPs is necessary in order to identify possible reduction measures. In November 2005 the Swedish Parliament passed the Environmental Bill 2004/05:150. This bill presents an evaluation of the environmental quality objectives and proposes new measures to ensure the achievement of the goals. One amendment concerns the recycling of nutrients from sewage sludge and states that by 2015 at least 60% of phosphorus in sewage should be brought back to productive land. To achieve this goal the sewage sludge must be of such quality that there will be no environmental risks associated with its spreading on farm land.

The federal Clean Water Act in the United States regulates two types of water protection instruments, TDML and NPDES. TMDL or Total Maximum Daily Load is a calculation of the maximum amount of a pollutant that a water body can receive and still meet water quality standards, and an allocation of that amount to the pollutant’s sources. Water quality standards are set by individual states and they are also responsible for identifying the uses for each water body, e.g. drinking water supply, swimming, and fishing (USEPA, 2006b). A TMDL is the sum of the allowable loads of a single pollutant from all contributing point and non-point sources. TMDLs identify the pollutant load reductions that are necessary from point and non-point sources and are also a guidance tool for the implementation work.

To comply with the 1987 amendments to the Clean Water Act, the USEPA established a permitting framework under the National Pollutant Discharge Elimination System (NPDES) program to address stormwater discharges associated with urban areas including transportation facilities. Under the NPDES stormwater program, operators of large, medium and regulated small municipal separate storm sewer systems require authorization to discharge pollutants under an NPDES permit. The NPDES permit procedure is a mechanism to require the implementation of controls designed to prevent harmful pollutants from being washed by stormwater runoff into local water bodies (USEPA, 2006a).

The flow of chemicals in the society affects the urban water system in many ways. The chemical composition of grey wastewater (domestic wastewater without any input from toilets) depends on sources and installations from where the water is taken, e.g. kitchen, bathroom or laundry. The chemical compounds present originate from household chemicals, cooking, washing and the piping system. In a study by Eriksson et al. (2002), the authors identified 900 different xenobiotic organic compounds (XOCs) as being potentially present in grey wastewater by using tables of contents of household chemical products. In another study by Palmquist and Hanæus (2005), hazardous substances were analysed in separately collected grey wastewater and blackwater (urine, faeces and flush-water from toilets) from typical Swedish households. 81 XOCs (nonylphenol- and octylphenol ethoxylates, brominated flame-retardants, organotin compounds, PAH, PCB, phthalates, monocyclic aromatics, and triclosan) were selected and measured in both fractions. 46 organic substances were
found in grey wastewater and 26 in blackwater. PCB was the only group found in neither fraction.

The development of a methodology for identifying the most critical and representative chemical pollutants is reported by Eriksson et al. (2005). The developed methodology consists of five steps; (1) source characterisation, (2) receptor and exposure identification, (3) hazard and problem identification, (4) hazard assessment and (5) expert judgement. Hazard assessment is divided into exposure assessment and effect assessment. The exposure can be represented by predicted environmental concentrations (PEC), where the values can be based on measured data or model simulations. Assessment of the effects can be characterised by predicted no effect concentrations (PNEC). PNEC represent estimated concentrations for which unacceptable effects are not likely to occur, and these can be found in the literature (databases and handbooks). Comparison between the PEC and PNEC values are made in order to determine if the compound should be considered as hazardous for organisms in the environment. The pollutants that receive a PEC/PNEC ratio above one (1) are classified as priority pollutants.

The chemical hazard identification and assessment tool has been applied for evaluation of different strategies for sustainable handling of stormwater (Eriksson et al., 2005). The authors’ literature survey revealed that at least 656 XOCs could be present in stormwater. In the next step, 233 XOCs were evaluated with respect to the potential for being hazardous towards either aquatic living organisms or humans, or causing technical or aesthetical problems. 121 XOCs were found to have at least one of these negative effects, while 26 XOCs could not be assessed due to the lack of data. The hazard assessment in this study showed that 40 XOCs had a PEC/PNEC ratio above one, e.g. they should be considered as priority pollutants.

The outlook presented above clearly indicates a general concern about the chemical flows in the society and the need for new assessment tools regarding water quality issues. The SEWSYS model has the potential for being part of such a toolkit for long-term and cost-effective evaluation of substance flows of priority pollutants. To achieve this there is a need for expanding the list of substances currently present in SEWSYS. The majority of the traditional stormwater pollutants outlined in the literature review of this thesis are already covered in the modelling framework. However, additional XOCs are required to reflect the present needs of pollution analysis. The potentially damaging effects of XOCs, including their persistence and bioaccumulation in the environment, necessitate their consideration in stormwater management strategies. Some XOCs also represent a carcinogenic, mutagenic reproductive and endocrine disruption hazard. A limiting factor for the addition of other substances in SEWSYS is the data availability. Additional measurements of XOCs should be done for stormwater in different types of areas and the measurements should be coupled with identification of sources and finding relevant emission factors.

A new PhD project started in spring 2006 at Water Environment Technology, Chalmers University of Technology, entitled “Sources and fluxes of new organic substances in urban stormwater”. One part of the PhD project deals with the adaptation of SEWSYS for simulation of organic pollutants. Measurements will be performed in two catchments and used in validation of the model. Seven specific
substances have been selected in the groups of alkylphenols, antioxidants and phthalates, based on an initial literature study. This PhD project is also part of a larger co-operation project run by the Stockholm Environmental Office and the Stockholm Water Company called “New pollutants – new tools”.

One interesting future development of SEWSYS would be the ability to model the fate, behaviour and removal potential of XOCs in stormwater BMPs. It is clear that the assessment of chemical hazards will be a key aspect in future urban stormwater management. A tool for chemical hazard identification and assessment has previously been developed within the research project DayWater (Eriksson et al., 2005). This generic tool can be applied for evaluation of different strategies for sustainable handling of stormwater, focussing on identification and assessment of problematic or hazardous compounds. The aim of the hazard assessment step would then be to generate data for site specific comparison of different stormwater handling scenarios, preferably using the PEC/PNEC ratio. PECs can be calculated using either measured data (if available) or by modelling.

In a modelling approach, determination of PEC (exposure assessment) or PNEC (effect assessment) requires mathematical formulations and the modelling tool has to be an integrated part of the environmental risk assessment. The proposed fate modelling in SEWSYS for XOCs in stormwater BMPs would be used for long and short-term emission management in unsteady-state conditions. This requires a dynamic exposure model that takes temporal variability into account. Since the toxicity of a chemical compound depends on the duration and frequency of exposure it is only by a dynamic exposure model that the violation of the PNEC value can be described. The key pollutant removal processes for modelling XOCs in BMPs are sedimentation, adsorption, precipitation, filtration, volatilisation and microbial degradation, and these processes would be needed to describe mathematically in the proposed model.
7 REFERENCES


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