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Sewer system performance assessment – an indicators based methodology

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The mind is like a parachute.
It works best when open
A. Einstein

ABSTRACT
The results of this dissertation are presented in the 7 papers included in the Annex.

A critical literature review of the most important regulations in the field of urban drainage led to the consideration that there are no clearly defined parameters (also called performance indicators) that can quantify the sewer system performance. The different regulations use different indicators to define the requirements. Emission based design criteria for combined sewer overflows (CSO) are widely used in regulations all over the world. The most common emission design criteria are either based on rain indicators (e.g. the critical rain – at which sufficient dilution is given) or on sewer system performance indicators (e.g. overflow frequency per year). The goal of the European Water Framework Directive, namely to achieve the 'good status' for all water bodies, makes it necessary to consider also the impacts on the receiving waters, **Paper I**.

This dissertation presents the development of a sewer system performance assessment methodology, which has been tested, by means of simulation, for various boundary conditions, including different rain series and sewer systems. See also **Papers VI, VII** in the annex.

Nowadays, in Europe, the highest impacts on the receiving waters, from the urban drainage side, are caused by the combined sewer overflow or direct discharges of stormwater from polluted catchments. In order to identify critical situations caused by specific CSO structures, continuous measurements in the receiving waters would be optimal, but are not affordable, due to the intermittent working of the CSO devices. In terms of an operational decision support tool for the identification of potential problems, easily obtainable indicators are needed that can describe the ecological impacts with sufficient accuracy. The indicators need to be easily calculable and based on parameters easy to measure, in order to assure the applicability of the method.

Regarding the efficiency of the sewer system, the rain variability, temporal and spatial, should also be considered. The variability can lead to high uncertainty in the simulation of the sewer system performance, because the rain is the main input. The problems related to the temporal variability and an attempt to assess climate change effects on the basis of historical data are evaluated in **Papers II** and **III**. The problems related to the spatial variability or more precisely, the best indicators in order to avoid such problems, are presented in **Papers IV** and **V**.

KURZFASSUNG

Die Ergebnisse dieser Dissertation werden in den 7 Artikeln im Annex, dargestellt.

Eine kritische Literaturecherche über die wichtigsten Regelblätter im Gebiet der Siedlungsentwässerung führte zu der Konsideration, dass keine genau definierte Parameter (genannt auch Performance Indikatoren) existieren, die die Effizienz des Kanalsystems quantifizieren können. Die unterschiedlichen Richtlinien benützen unteschiedliche Indikatoren, um die Anforderungen zu definieren. Emissionsbasierte Bemessungskriterien für Regenüberläufe sind weltweit in Richtlinien verbreitet. Die häufigsten emissionsbasierten Bemessungskriterien verwenden Regenindikatoren (z.B. die kritische Regenspende – bei der, ausreichende Verdünnung gewährleistet ist) oder Indikatoren für die Effizienz des Kanalsystems (z.B. die Häufigkeit von Regenüberläufe pro Jahr). Das Ziel von der Europäischen Wasserrahmenrichtlinie, nämlich das Erreichen „des guten Zustandes" für alle Wasserkörper, erfordert auch die Berücksichtigung der Einflüsse auf die Vorflutern, **Paper I**.

Diese Dissertation präsentiert die Etwicklung einer Methodologie, um die Leistung des Kanalsystems zu beurteilen. Diese Methodologie wurde auf der Basis von Simulationen, für unterschiedliche Rahmenbedingungen getestet und berücsichtigt unterschiedliche Regenserien und Kanalsysteme. Siehe auch **Papers VI, VII** im Annex.

Die stärksten Belastungen von Vorflutern von der Seite der Siedlungsentwaesserung, werden heutzutage in Europa, von Regenüberläufen, oder von Entlastungen von Regenwasser (im Trennsystem) aus belasteten Einzugsgebieten hervorgerufen. Um kritische Zustände zu identifizieren, die von bestimmten Regenüberläufen verursacht werden, wären kontinuirliche Messungen in den Vorflutern optimal, die aber nicht wirtschaftlich sind, aufgrund der intermittierenden Arbeitsweise der Regenüberläufe. Man braucht Indikatoren, die die ökologische Beeinträchtichungen der Gewässer mit genügender Präzision beschreiben können, um ein entscheidungsunterstützendes System zu konzipieren, für die Identifizierung von potenziellen Problemen verursacht durch solche Überläufe. Die Indikatoren sollten einfach zu berechnen sein, auf der Basis von leicht messbaren Parametern, um die Anwendbarkeit der Methode zu sichern.

Bezüglich der Effizienz des Kanalsystems, sollte auch die zeitliche und räumliche Regenvariabilität, berücksichtigt werden. Die Variabilität kann zu einer hohen Ungenauhigkeit in der Simulation von der Leistung des Kanalsystems führen, weil der Regen der wichtigste Input Parameter ist. Die mit der zeitlichen Variabilität verbundenen Probleme und ein Versuch Klimawandel Effekte zu quantifizieren, werden in den **Papers II** und **III** untersucht, basierend auf historischen Daten. Die mit der räumlichen Variabilität verbundenen Probleme, oder genauer, die besten Indikatoren um solche Probleme zu beseitigen, werden in den **Papers IV** und **V** dargestellt.

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TABLE OF FIGURES

LIST OF THE APPENDED PAPERS

The results obtained from this PhD work are reported in different papers, which are collected in the appendix of this dissertation. The titles of these articles are listed following, accompanied by their identification numbers, which will be used in the thesis for citations.

I   *De Toffol S.,* Achleitner S., Engelhard C., und Rauch W. (2005)
       Challenges in the Implementation of the Water Framework Directive: case study of the alpine river Drau in Austria. Water Science & Technology, **52** (9), 243–250

II   Rauch W. and *De Toffol S.* (2006)
       On the issue of trend and noise in the estimation of extreme rainfall properties. Water Science & Technology, **54** (6-7), 17-24

III   *De Toffol S.* and Rauch W. (2006)
       Can climate change patterns be identified in urban hydrology? (submitted)

IV   *De Toffol S.,* De Simon Bürstrom Y. and Rauch W. (2006)
       On the effect of spatial variances in historical rainfall time series to CSO performance evaluation. Water Science & Technology, **54**, (6-7), 25-31

V   Rauch W. and *De Toffol S.* (2006)
       Der Einfluss der Regencharakteristik auf den Wirkungsgrad von Mischwasserbehandlungsanlagen. Wiener Mitteilungen 2006, **196**, G1-G23

VI   Engelhard C., *De Toffol S.,* Rauch W. (2008)
       Suitability of CSO Performance indicators for Compliance with Ambient Water Quality. Urban Water Journal, Vol. 5, No 1, March 2008, 43-49

VII   *De Toffol S.,* Engelhard C., Rauch W. (2007)
       Combined sewer system versus separate system - a comparison of ecological and economical performance indicators. Water Science and Technology, **55** (4), 255–264

1. Introduction

The sewer system is responsible for the transportation of the wastewater from the households to the wastewater treatment plant. It is a part of the integrated urban wastewater system, which is also comprised of the wastewater treatment plant and the receiving waters.

Artificial drainage systems are being developed since ancient times. Examples can be found in many ancient civilisations: the Mesopotamian, the Minoan (Crete), the Greeks (Athens) and the Romans. The 'cloaca maxima', the ancient drainage, built in the 6th century b.C., to drain the 'Forum Romanum' is still in use (Butler and Davies, 2000). The concept of modern sewer systems was born in the 19th century due to hygienic reasons. The cholera epidemic, directly connected to the inadequate sanitation in European cities, was the trigger for the construction and development of urban sewer systems (Ashley *et al.*, 1999; Harremoës, 1997).

After the resolution of the hygienic issues, by means of the construction of underground pipes for the transport of the wastewater, the core issues of the urban drainage were the protection of the population from flooding and of the receiving waters from the anthropogenic impacts (Rauch *et al.*, 2002b).

In this context, the performance assessment is no more related only to the efficiency of the sewer system, but considers also their effects on the receiving waters. The sewer system performance assessment method presented in this dissertation is based on simulation results. The efficiency of the sewer system is evaluated using appropriate parameters, derived from the simulation results, also called indicators.

The aim of this dissertation is to determine the most suitable indicators, between the numerous existing, in order to assess the sewer system performance. The main issue in this work is the selection and testing of the indicators on the basis of simulation of synthetic or real catchments.

This dissertation is based on the work done in the frame of the EU-project CD4WC (**C**ost-effective **D**evelopment of urban wastewater system **for W**ater Framework Directive **C**ompliance; www.cd4wc.org) (Benedetti *et al.*, 2004), which is part of the Citynet cluster, a network of European research projects on integrated urban water management (http://citynet.unife.it/).

1.1. Background

1.1.1. *Sewer system characterization and historical review*

The sewer system, as described previously, is considered a part of the **integrated urban drainage system**. The concept of integrated urban drainage has gained increasing importance in the last years aiming at the optimisation of the drainage system. The integrated consideration of all parts of the system simultaneously allows better optimisation possibilities.
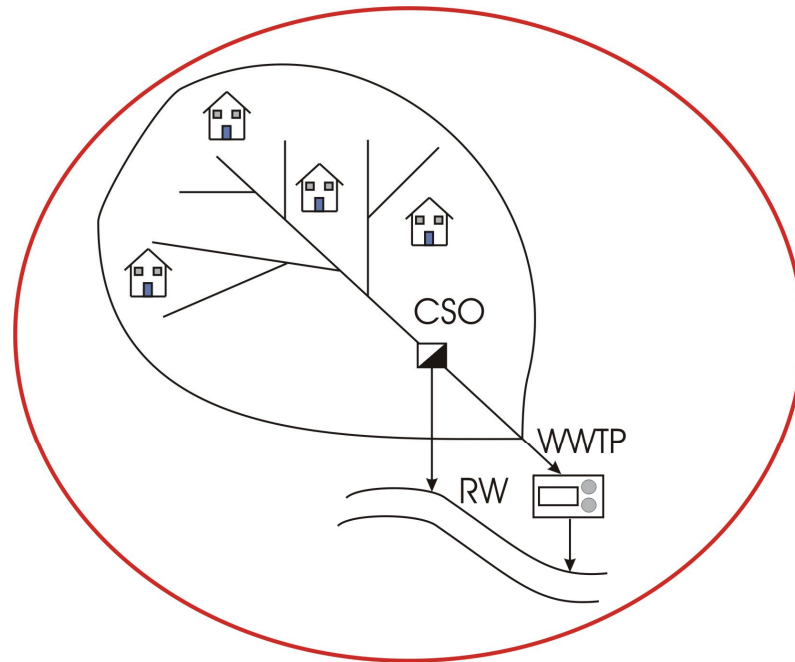
Figure 1-1. The integrated urban drainage system. RW = receiving water, WWTP = wastewater treatment plant, CSO = combined sewer system.

Generally, there are two main types of urban drainage system: the combined sewer system and the separate one. Very often there is a third one, which is a mixture between the two, in which the old part of the town is served from the combined sewer system and the new one from the separate.

Two pipelines exist in the **separate sewer system**, the storm sewer, which only carries, like its name says, the stormwater and discharges it (with or without treatment) to the receiving water, and the foul sewer, which carries only the sewage to the wastewater treatment plant. There, the wastewater is purified and discharged to the receiving water.

In the **combined sewer system,** the same pipeline carries both stormwater and sewage (also called dry weather flow) directly to the wastewater treatment plant. Due to economic reasons, it is difficult to treat a large amount of stormwater at the plant. The sewer system is therefore designed to transport only a part of the stormwater (normally 2-3 times the dry weather flow). In case of heavy rain, the stormwater in the sewer will exceed this amount; this excess water needs therefore to be discharged to a receiving water body. The structure responsible for this action is the combined sewer overflow (CSO). The following figure is a schematic presentation of the two types of sewer system.
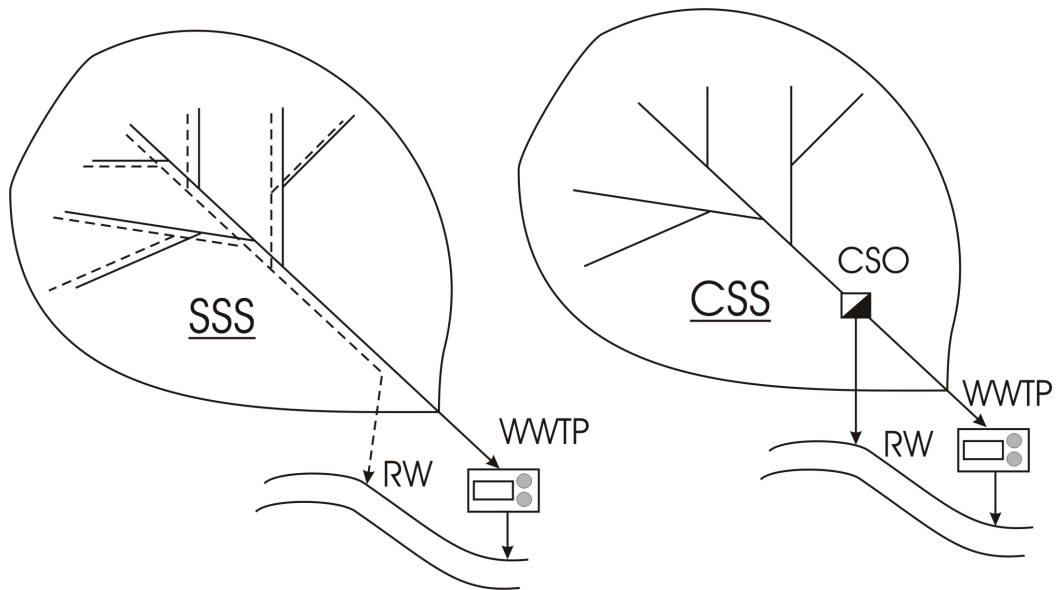
Figure 1-2. Schemes of the separate sewer system (SSS) (left) and combined sewer system (CSS) (right). RW = receiving water, WWTP = wastewater treatment plant, CSO = combined sewer system.

The question 'which system is better?' has been vigorously discussed since decades. The answer is case specific. The first modern sewer systems were constructed in the middle of the 19th century in Europe and were combined systems. Main reasons for this choice were the fact that: 1) there were no European examples of successful separate systems, 2) there existed the belief that the combined systems were cheaper to build and 3) engineers were not convinced that agricultural use of separate-sanitary wastewater was viable (Burian *et al.*, 1999). The first separate sewers were built in the USA at the end of the 19th century on the basis of the consideration that they can transport the sanitary wastes faster, preventing the formation of gases. In 1880 an American engineer, was sent to Europe in order to investigate the drainage systems. He suggested the use of combined systems in large or rapidly growing cities and separate systems for areas where rainwater did not need to be transported under the ground. This implies, that a large part of urban areas in the US, were served from combined systems. This philosophy dominated till the 1930s, when many more wastewater treatment plants were required, causing high costs. Due to this situation, American engineers started to suggest separate sewer systems (Burian *et al.*, 1999).

Starting in the 1950s, in Europe and in the USA, the increased environmental awareness led to considerations as regards the effect of the urban drainage on the receiving waters. The combined sewer overflows were considered the main cause of degradation of the receiving waters (Burian *et al.*, 1999; Butler and Davies, 2000). Due to this fact, in Europe the separate sewer started being suggested for the construction of new systems (Butler and Davies, 2000). In the USA a big CSO reducing campaign started, which suggested many different CSO reduction solutions. An example is the sewer separation, i.e. the adaptation of the old combined system into a separate one (US EPA, 1999), which is an expensive solution. In Europe the theory of sewer separation was adopted only in some regions due to the high costs related. Currently, there is a re-evaluation of the combined sewer system because it was demonstrated that the impacts on the receiving waters caused from the separate system can also be notable (Burian *et al.*, 1999; Sieker, 2003).

Suggestions on the type of system to use, can be found in **Paper VII,** on the basis of simulation of different scenarios, considering also the sensitivity of the receiving water.

Based on the two main drainage types, there are numerous cases in which the different wastewater streams are further separated, e.g. urine separation and separate treatment of stormwater. Such methods, based on the separation of the streams, are called **source control** measures, or sustainable urban drainage. Their aim is to reduce the pollutants entering the sewer from the source. A classic example, is the infiltration of stormwater. In this case, the sewer system is less hydraulically charged because of the fact that an amount of stormwater is directly diverted to the groundwater. This method is often used in case of enlargement of the urban settlement; the old sewer cannot carry all the stormwater coming from the new impervious area added and consequently the uncontaminated surface water is infiltrated.

The enlargement of the urban settlement causes indeed an improvement of the rain runoff, i.e. the overland flow. In rural conditions, the rain can infiltrate easier, the trees can catch part of the rain, the overland flow resulting is smaller and the peak is reached later. In an urban catchment, the streets, parking lots, roofs do not catch the rain but also favour the flow, so that the peaks of runoff are higher and earlier. This fact causes more unexpected peaks in river flow and introduces pollutants in the receiving waters (Butler and Davies, 2000).

1.1.2. *Pollution in the sewer system*

The pollutants, transported in the sewer system have two main sources: the human excrements (urine and faeces) and the anthropogenic environment (e.g. industry, traffic, atmospheric pollution etc.). Because of that, the pollution in the sewer system should also be divided in the two main streams, the stormwater and the foul water.

The pollutants in the stormwater are influenced by the rainfall and the catchment characteristics. Typical catchment sources are vehicle emissions, abrasion of tyres and brakes, animal faeces, street litter, de-icers (from the winter maintenance), fallen leaves, grass residues, and atmospheric pollutant wash-off, deposited on the streets. Further, a part of pollutant comes from the atmospheric wash-off, and enters the sewers directly with the rainfall. Main pollutants in the stormwater are heavy metals, but organic matter can also be found due to the street wash-off.

The main pollutant in the foul water is the organic matter, which can be quantified with the parameters BOD_5, P, N. Further pathogens and micropollutants can be contained in the wastewater, but they are not considered in this work. Other pollutants are the gross solids, which are responsible for aesthetic problems caused by combined sewer overflow and can also favour the clogging.

The main impact from the urban drainage system on the receiving water is caused by the combined sewer overflow and the stormwater discharges, like demonstrated e.g. in (Sieker, 2003). Modern wastewater treatment plants have achieved a high standard, so that their impact on the receiving water is normally negligible compared to the impacts of direct discharges in wet weather conditions. Under these conditions the rain plays a major role due to its influence on the direct discharges.

1.2. Design of the sewer system

Traditionally, the evaluation of the urban drainage system performance is based on **emission** restrictions. Emission is defined as the entrance of pollutant to the environment. This definition considers only the "end of pipe" effects (Krejci, 2004). This emission approach is from the engineering point of view, easily affordable, easy to define and calculate. The calculations are based only on parameters of the sewer system or WWTP (Waste Water Treatment Plant) and static rules like e.g. the one which prescribe that the flow to the WWTP under wet-weather conditions should be limited to a value of 2-3 times higher than the dry weather flow (Rauch *et al.*, 2005).

The introduction of the concept of integrated system implies the necessity to make use of an approach, which considers also the effect on the receiving water (**ambient water quality approach**) and not only the emissions. This methodology considers parameters and processes taking place in the receiving waters, which are more complex to describe. Considering such effects, it is necessary to make use not only of simplified methods for the calculation of the effects on the receiving water of the sewer system discharges, but also to understand the cause-effect relation between the emissions from the wastewater system and effects on the receiving water ecosystem, see e.g. **Paper I** and (Rauch *et al.*, 2002a). Such effects depend on many different factors like e.g. the initial level of water pollution of the receiving water, its self purification capacity, the sensibility of the ecosystem to ambient changes and the duration of the pressure. It is also necessary to consider not only acute impacts but also accumulation processes (Borchardt and Sperling, 1997; De Toffol *et al.*, 2004; Schilling *et al.*, 1997).

Due to the increasing importance assumed from the water quality approach the European Water Framework Directive (EU-WFD) was introduced. The main goal of the Directive is to achieve and/or maintain a good ecological and chemical status for all water bodies. In order to achieve that, it is necessary to consider not only the emissions of the urban drainage but also the effects on the receiving waters. The two approaches, emission and water quality oriented, are also used simultaneously; this methodology is called **combined approach**, see also **Paper I**.

The design of the sewer system takes into account on the one side the **CSO discharge** (e.g. the number of overflows) on the other side, the flooding frequency. The **flooding** can occur in both types of sewer system. It is caused by the surcharge of the pipeline: the wastewater flow rate grows and is discharged from the manholes. The allowed flooding frequency is defined in the (EN 752, 1997) or in the related implementations in the national guidelines and depends on the location of the manholes (city centre, residential zone, land or industrial zone).

1.3. Rain as driving force

The rain is the main input for the simulations of the sewer system. The rain causes pollution load not only from the combined sewer overflow (Sieker, 2003) but also from the outflow of the treatment plant, which can decrease among others the oxygen concentration in the receiving waters (Rauch and Harremoës, 1996a).

The **rain input** can assume many formats, from the most simple with constant intensity over a given duration (block rainfall), to the historical time-series, in which

every rain event is reported together with the dry periods. The rain input could also be a synthetic design storm, which is a single, statistically determinate event, with a given return period. This is generally derived, from the Intensity-Duration-Frequency (IDF) curves. Such curves represent the rainfall intensities corresponding to a particular storm recurrence interval for various storm durations. These curves are the results of the statistical analysis of rainfall data for a particular area.

1.4.   Assessing the sewer system performance by means of simulation

The analysis presented in this PhD work is based on **simulation's** results. Simulations are run using models, which simplify more or less the processes taking place in the reality and can be used to evaluate existing systems or to design new ones. They represent the behaviour of the sewer system. There are many kinds of models that can be used for the simulation of the sewer system and can be classified in two main types: conceptual and physical models. In the **conceptual models**, the physical laws are expressed by highly simplified concepts, e.g. the physics of flow routing in the sewer are represented from a simple tank system. The advantage is that the phenomena are easier to describe. The solving of the equations, which are ordinary differential equations, needs short computing time. **Physical models** are based on mathematical formulation in order to describe the processes (Butler and Davies, 2000). The calculation of flow routing is based on mass and energy conservation. In this case, simplifications of the problems are always necessary (see chapter 4). As regards flow routing calculation the two types of models are also called hydrological (conceptual) and hydrodynamic (physical).

The accuracy of the simulation's results depends on the input data used, as well as on the calibration. The **input data** are typically the rain and the dry weather flow. The rain is discussed in chapter1.3. The **dry weather flow** represents the pollutant and the flow of the wastewater coming from the households or from the industries in the analysed catchment, without the influence of the rain. The dry weather flow can be assumed to remain constant over the day or week or to vary according to numerous different time distributions. In the analyses reported in this work, it was always assumed constant.

The other important task of the simulation is the **calibration**. This is necessary in order to reproduce results similar to the reality and consists of the adaptation of the system variables, so that given the right input data it is possible to obtain emissions from the simulated catchment similar to the measured ones in the real catchment. The importance of the calibration increases with the simplification degree of the system. Good calibrated systems can give acceptable simulation results even with simple models (De Toffol *et al.*, 2006). In each case, it should always be considered that uncertainty is in the nature of simulation and is due to the lack of knowledge of model structure, input functions or parameter estimation. This uncertainty is higher if modelling incorporates chemical and biological phenomena (Harremoës and Madsen, 1999).

The simulation of the sewer system has a long history and can be typically classified into the simulation of quantitative and of qualitative aspects. The first computer programs for drainage design (only quantitative, i.e. flow models) and analysis were developed in the 1970s, but became a standard tool only when higher computing power was available (Butler and Davies, 2000). By the mid of the 1980s, flow

models became popular and engineers started to think about flow quality modelling. As advanced wastewater treatment became a standard and the combined sewer overflow less acceptable, in sewer processes modelling gained importance (Ashley *et al.*, 1999). The sewer is not only considered as a transporting medium, but also as a reactor. The article (Gent *et al.*, 1996) presents a review of the sewer sediment modelling in the UK. Some problems related to the sewer processes modelling are for example, the difficulty of observing the processes in-situ and the extreme spatial and temporal variability (Ashley *et al.*, 1999).

With the increasing importance of the integrated urban drainage management, the simulation of the impacts on the river water and on the whole system, became very relevant.

River water quality models describe the spatial and temporal changes of pollutants. They investigate the oxygen household, nutrients and eutrophication, toxic materials etc. The complexity varies between the simple Streeter Phelps model (used first in the year 1925), the QUAL2 and similar tools describing O, N, P processes with approximately ten state variables (Rauch *et al.*, 1998b). At the end of the 1990s an IAWQ (International Association on Water Quality) task group was assembled, in order to develop standardised and consistent river water quality models and guidelines for their implementation, analogous to the existent models for the simulation of the wastewater treatment plant, i.e. the Activated Sludge Models (Henze *et al.*, 2000). The results obtained from this working group are explained in the following three papers: (Reichert *et al.*, 2001; Shanahan *et al.*, 2001; Vanrolleghem *et al.*, 2001).

To avoid model complexity and allow the simulation of all parts of the integrated urban drainage system, a reconciliation of the different model approaches used is necessary. An effort in this direction is described in (Fronteau *et al.*, 1997). A good overview of the development and tasks of the modelling of integrated urban drainage systems is given in (Rauch *et al.*, 2002c). In this dissertation, only a short summary is presented. The basic principles of integrated urban drainage were presented in (Lijklema *et al.*, 1993), however the integrated modelling was still in development. The complexity of the systems introduced problems in the modelling tasks, so that a classification of the different impacts types and of the duration of the impacts was initiated (Borchardt and Sperling, 1997; Schilling *et al.*, 1997). Further, a simplification of the effects to be modelled was necessary, in order to reduce the complexity. The simplification is carried out, concentrating on the dominating effects (Rauch *et al.*, 1998a). First examples of models applied to the whole system can be found in (Rauch and Harremoës, 1996b; Schütze *et al.*, 1996; Vanrolleghem *et al.*, 1996).

At this time began also the first studies on real time control of the integrated drainage system (Rauch and Harremoës, 1996c; Schütze *et al.*, 1996). The definition of real time control can be found e.g. in (Schütze *et al.*, 2004) 'An urban wastewater system is controlled in real time if process variables are monitored in the system and, (almost) at the same time, used to operate actuators during the flow process'.

A still unsolved problem connected with the modelling of the integrated system, is the link between the biological response and the impact of the urban drainage on the

receiving waters. An approach for the solution of this problem for a particular type of river can be found in (Rauch *et al.*, 2002a).

1.5.   **Indicators**

Simulation results alone are not enough to assess the performance of the sewer system. It is necessary to define adapted **indicators**, which should provide key information needed to assess the efficiency of the system. Indicators are parameters, which are used to describe relevant properties of the system, or to compare the performance of e.g. water service provider, like described in (Ashley and Hopkinson, 2002). The introduction of the Water Framework Directive and more specifically of the combined approach, set the need for new indicators to evaluate the performance of the sewer system. In this case, it is not enough to consider only the classic indicators for the urban drainage (commonly emission based), but it is necessary to consider also parameters, which describe the impact of the urban drainage activities on the receiving waters. In order to quantify such impacts, there are numerous systems which use as indicators for example macrozoobenthos (Hering *et al.*, 2002) or fishes (Noble and Cowx, 2002). These indicators are however difficult to model.

Performance indicators are used in each country inside the different evaluating systems for the water supply and the urban drainage. Due to this fact, the indicators are often associated with benchmark analysis. However, a performance indicator may be used as a qualitative index of a particular aspect of a procedure's performance or standard of service. Based on a literature review of legal requirements (chapter 3) and on the existing databases reported in (Balkema *et al.*, 2002; Matos *et al.*, 2003), a set of adapted indicators was defined to evaluate the performance of the sewer system (chapter 4). The suitability of such indicators to describe the different behaviours of the sewer system is analysed in the papers included in the annex and also in chapter 6.

2.   Scope and structure of the dissertation

The aim of this dissertation is to identify and test a set of easily calculable indicators, in order to assess the sewer system performance. The main focus will be on the combined sewer system, because this is the most common system used in central Europe and nowadays, due to the high standards of the European wastewater treatment plants, the overflows are responsible for the main impacts on the receiving waters (Sieker, 2003).

The outcomes of this dissertation are presented in the 7 papers included in the annex, and are also summarised in chapter 6. The papers constitute the core of this work. The following chapters present an introduction to, and explanation of the concepts presented in the papers.

The knowledge of the current regulations is essential for the definition of indicators. Chapter 3 presents a short overview of many European and North American regulations on sewer planning with a focus on the CSO design. From these regulations, many indicators can be derived, applicable to ambient water quality and emission compliance. Further, a result of this overview is the assertion that there are no clear and uniform definitions of the requirements for the sewer system performance assessment. Due to this fact, there are no clearly defined indicators for the evaluation of the performance. The work conducted in this dissertation aims at the establishment of precisely defined indicators for the performance assessment of the sewer system.

The indicators are calculated by means of simulation with the software Karen (Rauch, 2005) and City Drain (Achleitner *et al.*, 2006). Both programs use similar hydrological models for the runoff generation and for the transport. The results are elaborated with ad hoc developed Matlab programs. The methodology and the procedures used in the calculation of such parameters are explained in chapter 4. This chapter begins with an overview of the hydrological background, because the rain is the principal input for the combined sewer system simulation. Furthermore, a literature review of the methodology of sewer system modelling is presented. Finally, the selected indicators are listed and the calculation procedure is described.

The 5th chapter introduces the 7 papers and presents their scientific background. The last chapter, chapter 6, summarises the results, also reported in the articles, and the outlook of this work.

The following picture illustrates the structure of this dissertation, in which the first two chapters serve as an introduction to the entire study. Chapter 3 to 5 present the methods, procedures and the background on the basis of the studies reported in the annexed papers. The last chapter, chapter 6, summarises the results of the studies and the gives an outlook on future research.
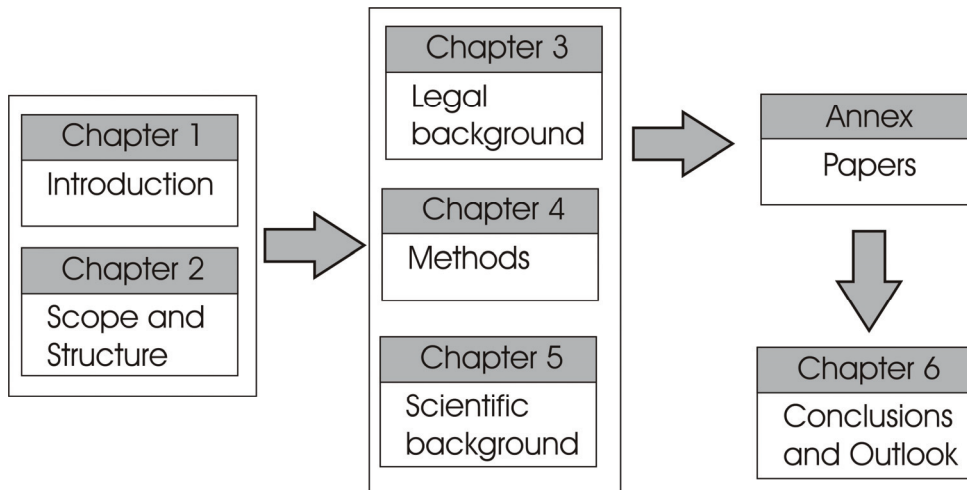
Figure 2-1. Structure of the dissertation

Figure 2-2 presents schematically the topics of the annexed papers. The main feature of all papers is the definition and testing of indicators for the assessment of the sewer system performance.

The **Paper I** deals with the challenges introduced from the European Water Framework Directive. The **Papers II** and **III** analyse the temporal variability of selected rain characteristics indicators, in order to quantify its influence on the sewer system modelling and on the performance assessment. The **Papers IV** and **V** analyse the relation between selected rain characteristics and sewer system performance indicators, in order to define the best indicators to compensate the spatial variability of the rain. The **Paper VI**, completes the previous study (**Papers IV** and **V**) analysing the relation between indicators for the sewer system performance and the receiving water quality. The **Paper VII** presents an application of the indicators defined previously in order to quantify the performance of the two most common sewer systems (combined and separate), considering sewer system performance indicators but also receiving water impacts and costs.
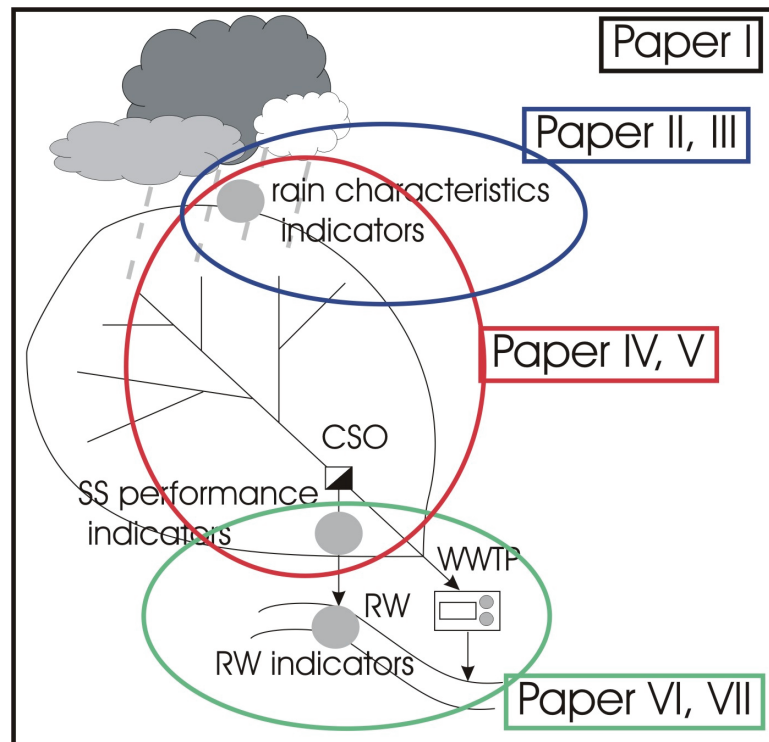
Figure 2-2. Topics of the annexed papers. SS = Sewer System, CSO = Combined Sewer Overflow, RW = receiving water, WWTP = wastewater treatment plant.

Following, the annexed papers are presented in detail.

2.1.   Paper I

An overview of the most important aspects of the EU-WFD for the identification of indicators for the urban drainage system performance is presented in this paper. Due to the shift towards an overall ecological focus, standardized classification systems are required, addressing biological conditions. During planning procedures, engineers are requested to predict biological effects in rivers. Furthermore, this work provides a closer look at the combined approach, where emission and water quality standards, have to be considered concomitantly.

2.2.   Paper II

The term, "performance of the sewer system" is often related to the different measures that can be adopted for the sewer system optimisation. However, a very important issue is the choice of the suitable rain data for the simulations. Climatic changes and random variations can cause significant temporal variations in the precipitation. Climate models predict under greenhouse conditions increases in both heavy rainfall frequency and intensity, in the high latitudes of the Northern Hemisphere.

The issue of a potential trend in the estimation of rainfall properties for 6 rain series ranging from 19 to 55 years is investigated in this paper. In contrast to recent research, which predicts a - climate induced – increase in heavy precipitation, no clear indication for such trend was found in the investigated historical rain series for

the selected indicator. Another important aspect also investigated in this paper, is the length of the rain series that is required for the estimation of extreme rainfall properties and the associated uncertainty.

2.3.   Paper III

In order to give a clear picture of the eventual presence of trends, the analysis of the temporal variation of the rain is here deepened, considering on the on side longer series (8 rain series from 53 to 75 years with 5 minutes time step) on the other side further different analyses and more indicators. Additionally, the effects on the sewer system are analysed by means of simulation of a simple catchment and of a real one.

2.4.   Paper IV

The spatial variation of the rain can also influence notably the sewer system performance. In order to account for the spatial differences, when using a regional rain series instead of the accurate local one (if the last one is not available), it is necessary to define the suitable indicators. In order to prove the suitability, the relation between chosen sewer system performance indicators and rain characteristics was analysed. The data, on which this research is based, are 37 rain series, 10 years long with a time step of 5 minutes, from different European countries (Austria (19), Switzerland (5), Italy (2), Spain (1), Norway (1), Belgium (1), France (2) and Denmark (6)).

2.5.   Paper V

This paper deepens the analysis started in **Paper IV.** While in **Paper IV** more parameters are analysed, **Paper V** concentrates on the CSO efficiency as the main indicator for the evaluation of the CSO impacts in the Austrian regulation. The analysis is based on 67 Austrian rain series. **Paper V** was also the basis for a modification of the draft version of the (ÖWAV-Regelblatt 19, Draft 11.2005). In an older version of this regulation the suggested limits for the CSO efficiency depend on the mean annual rain volume. As demonstrated in this publication, the rain volume correlates more with the overflow volume then with the CSO efficiency.

2.6.   Paper VI

This paper completes the indicators analysis started in the two previous papers with the investigation of the relation between the indicators for the sewer system performance and for the receiving water quality. Further, the aim of this article is to assess the applicability of easily obtainable emission based performance indicators for combined sewer overflows, in order to describe the impacts of the sewer system on the water quality of the receiving water.

2.7. Paper VII

The indicators presented in **Paper VI** can also be used to assess the performance of the separate sewer system. In the analysis reported in this paper, a comparison of the performance of both types of classical sewer system is undertaken. To evaluate the impacts caused from the two systems, simulations using different boundary conditions were run. The focus is here not only on the sewer system efficiency, but also on the impacts on the receiving waters and the costs, according to the philosophy of the European Water Framework Directive.

3. Legal background of sewer design

In the present chapter the core guidelines for the sewer system design, are presented. The aim of this review is to investigate the boundary conditions for the choice of the indicators. The main focus is on the CSO regulations because the combined sewer is the most common used in central Europe and the impacts caused from the overflows are the most relevant. Due to this fact, in the selection of indicators there are numerous referred to the combined sewer overflows.

At first the core issues of the EU-WFD are described. Following, the implementation of the Directive in the Austrian guideline on CSO design is reported (ÖWAV-Regelblatt 19, Draft 11.2005) and a review on CSO design guidelines in different states (Europe, USA, UK, Germany, Belgium), which are basis, together with a literature review, for the choice of the indicators selected for the evaluation of the sewer system performance in this work. To complete the frame of the guidelines for urban drainage design, the European norm on sewer design (EN 752, 1997) and related implementations, as example, in the Austrian guideline (ÖWAV-Regelblatt 11, Draft 07.2004; ÖWAV-Regelblatt 35, 2003) are described. The last part of the chapter summarises the German guideline for rain analysis (ATV - A 121, 2001), which presents the calculation procedure of the statistical rain intensity. This parameter is used as indicators for the climate change analysis in **Paper II**, **III** and **V**, also reported in the annex.

A particular case is the Austrian guideline for CSO design (ÖWAV-Regelblatt 19, Draft 11.2005), which influenced from one side the choice of the indicators and was influenced from the other side from the results of this study.

3.1. The European Water Framework Directive

3.1.1. Introduction

The European Water Framework Directive (EU-WFD) is an innovative guideline in the water policy. It introduces new objectives and planning procedures at river basin scale. The final goal of the EU-WFD is to achieve the "good status" for all water bodies. In contrast to older guidelines, this status is defined by combining ecological and chemical conditions. Further, the Directive aims at an equalisation of the water quality all over Europe, so that the good water quality is comparable in each member state.

3.1.2. Implementation process

The implementation process of the Water Framework Directive involves all EU Member States and aims at allowing a coherent and harmonic implementation of the Directive. Several Guidance Documents (http://forum.europa.eu.int) were published, addressing the resolution of the numerous implementation problems. These documents have an informal, legal not binding character. Due to the diversity within the European Union, the way to implement the EU-WFD will vary from one member state to the other. The methodologies proposed in the Guidance Documents will therefore need to be tailored to specific circumstances.

The Water Framework Directive presents deadlines for the implementation process. The first steps are summarised in (Achleitner *et al.*, 2005). The general implementation plan is reported in the following pictures.

2003	WFD implemented into National water laws. River Basin co-operation operational
2004	Analysis of pressures and impacts on the waters and economic analysis completed
2006	Monitoring programmes operational
2008	River Basin Management plans presented to the public
2009	Publishing first River Basin Management plans
2015	Final goal: water meet "good status"

Figure 3-1. Deadlines of the implementation of the Water Framework Directive (redrawn from (CIS-WG2.3, 2003))

3.1.3. *Water bodies classification*

To allow the classification of the water quality of European water bodies, each member state has to set reference and calibration sites. A reference site represents the high ecological status, whereas a calibration site represents the lower boundary of the good status. Generally, both reference and calibration sites were proposed by the national authorities on the basis of their insight knowledge in the regions. Criteria for the choice of sites beside the appropriate water quality are the accessibility (e.g. sampling of fish has to be possible) and the availability of existing monitoring devices (Engelhard *et al.*, 2004). Further, the local authorities have to designate the water bodies, of which the dimension can be defined from the member states on the basis of the specific conditions. After that, each single water body is compared with the reference and calibration sites and its status is evaluated (Achleitner *et al.*, 2005). Finally, to allow the comparability of the "good status" in the different European countries, an inter-calibration process will start between the numerous reference sites.
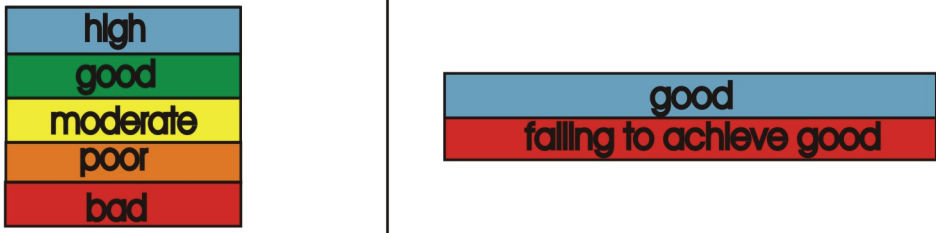
After a water body status is classified it is not possible to deteriorate such status, the only change accepted is an improvement. This means that the EU member states are concerned that all water bodies achieve the good status and after they obtain that they should make sure that this status will not decline.

The classification of surface water bodies according to the Water Framework Directive is not limited only to chemical and physico-chemical conditions but also includes hydro-morphological and biological conditions.

For the classification of the ecological status the reference conditions are used. The classification is performed using a five class system based on the degree of deviation from the reference condition. Class 1 equals the high ecological status being widely undisturbed from anthropogenic stressors (reference condition). Class 2 equals the quality objectives of the EU-WFD, the good ecological status. The definition of the ecological status is given in Annex V of the directive.

The chemical status can be defined as "good" or "Failing to achieve good".

To achieve the "good status" both, the chemical and the ecological status, have to be evaluated as "good". Figure 2-2 gives a schematic overview on the classification process and the presentation of the status of water bodies according to the WFD.

Figure 3-2. Classification process of the surface water bodies (redrawn from (CIS-WG2.3, 2003))

This classification system does not apply to heavily modified water bodies and artificial water bodies. The heavily modified water bodies are surface water bodies physically altered by human activity, where the effort to reinstate the good ecological status is not cost-effective or the restoration measures will affect the use of such water bodies (e.g. navigation, hydropower, water supply or flood defence). Artificial water bodies are surface waters created by human activity. Both types do not have to achieve the "good ecological status" but also the "good ecological potential". Guidelines on the identification and designation of such water courses are given in the common implementation strategy guideline (CIS-WG2.2, 2003).

For the engineering practice, this class definition presents some problems; the ecological status is defined on the basis of biological indicators. The reactions of the biota on different impacts cannot be modelled. This implies the difficulty in evaluation of the effect of simulated solutions on the biology. To enable the consideration of such effects, a cause-effect relation is necessary between chemical

indicators (which are easier to model) and the biological ones. This relation is nowadays still missing.

3.1.4. *Combined approach*

An innovative concept, for a guideline, introduced by the EU-WFD is the combined approach. The combined approach consists in considering contemporaneously the emission limits from the urban drainage and ambient water quality limits, not ignoring in this way the impacts derived from such emissions too.

The consideration of sewer optimisation taking into account the effects on the receiving waters is a well known concept since years, examples can be found e.g. in (Rauch *et al.*, 1998a; Schilling *et al.*, 1997; Schütze *et al.*, 1996), but for the first time it is expressed in a guideline.

The common interpretation of this concept is that the most stringent limit (grey zone in the Figure 3-3) has to be adopted (Achleitner *et al.*, 2005).
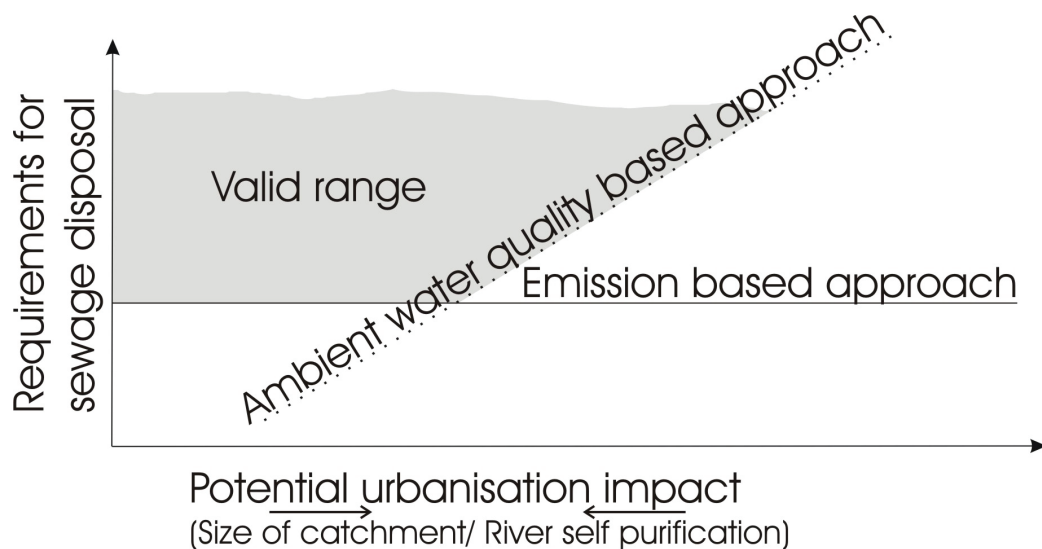
Figure 3-3. Requirements of the wastewater system by the combined approach extended from (Achleitner *et al.*, 2005)

This concept can be easily explained looking at the previous picture. Depending on the characteristics of the system (size of the urban area or capacity of self-purification of the receiving water) one of the two approaches is more stringent. While the emissions are constant, not depending on the size of the catchment, the ambient water quality limits depend on the type and the status of the river. If the capacity of self-purification of the river is lower then the requirements of the sewage disposal has to be set higher. Otherwise, if the size of the catchment is larger then the requirements of the sewage disposal has to be set higher

The word emission defines each discharge to the receiving water from the side of the urban drainage, it comprehends also the wastewater treatment plant effluent but also the combined sewer overflow. While for the first one Europe wide similar emission standards are defined, for the second the situation is not so clear.

The control of combined sewer overflows is generally based on design criteria and/or operating conditions, which do not consider the impact on the receiving waters. In the EU states, there are many different criteria for regulating the emission of CSOs,

some consider the influence on the receiving water whereas others does not (Zabel et al., 2001). The EU-WFD implies the necessity to assess the impact of CSOs on the receiving water quality and the possibility to adopt a combined control methodology that considers both ambient water quality and emission impacts. From such cosiderations arises the necessity to define new indicators to assess the performance of the urban drainage system, see also **Paper VI**. More on this issue and the application of a methodology for the identification of a new set of parameters to describe the impacts on the receiving water quality on a real case study is presented in **Paper I**, which is also included in the annex of this dissertation.

3.1.5. Economic issues

The Water Framework Directive clearly integrates economics into water management and policy making. The Directive calls for the application of economic principles (e.g. the polluter pays principle), approaches and tools (e.g. cost-effectiveness analysis) and for the consideration of economic instruments (e.g. water pricing) for achieving its environmental objectives. That is the good status for all waters in the most effective manner (CIS-WG2.6, 2002). For the water supply and the urban drainage the prices should be cost covering.

Furthermore, due to the limited financial resources dedicated to the wastewater issue and the high environmental concerns, economics increasingly play an important role in the development of sustainable wastewater management.

3.1.6. Implementation in Austria

In Austria nowadays, the water courses with more than 100 km² catchment and lakes with surface larger than 50 ha are included in the WFD implementation procedure. The whole Groundwater surface was included. 78% of the watercourses were evaluated to meet the "good chemical status".
Due to the high use of hydropower and the need of flood protection, a huge part of the Austrian rivers (44%) risk not to meet the goal of the WFD. This fact is due to morphological problems, which cannot be solved without large expenses. Therefore these watercourses are proposed as "candidates for heavily modified water bodies". In 2009 it will be decided which water courses should be considered as heavily modified (Marent *et al.*, 2005).

3.2. Austrian guideline on CSO design, "Regelblatt 19"

Based on the concepts introduced from the Water Framework Directive, the Austrian water wastewater association (ÖWAV) will enact soon the new guideline on combined sewer overflow design (ÖWAV-Regelblatt 19, Draft 11.2005). It represents an innovative guideline, which deviates from the rigid old version in which a specific volume was suggested and introduces the concept of CSO efficiency that can be achieved not only by increasing the retention volume but also through real time control, infiltration etc. The effectiveness of the new measures has to be proven through dynamic simulation of the sewer system. The minimum requirements for the combined sewer overflows are here subdivided in two groups: the requirements regarding the emission and the ones regarding the ambient water quality target.

3.2.1. *Requirement for combined sewer overflows for the emission approach*

The parameter used for the emission approach, as indicator for the impacts of CSO, is the CSO efficiency defined as the part of rain runoff treated at the wastewater treatment plant and expressed in percentage. The formula for the calculation of the efficiency is:

$$\eta = \frac{(VQ_c - VQ_d) \cdot c_c - VQO \cdot c_o}{(VQ_c - VQ_d) \cdot c_c} \cdot 100 = \frac{VQR \cdot c_c - VQO \cdot c_o}{VQR \cdot c_c} \cdot 100$$

where (see also the following picture):

η	CSO efficiency	[%]
VQ_c	Total volume of the combined sewage in one year	[m³/a]
VQ_d	Total volume of the dry weather flow in one year	[m³/a]
VQR	Total volume of the runoff in one year	[m³/a]
VQO	Total volume the overflow discharge in one year	[m³/a]
c_c	Concentration in the combined sewage	[mg/l]
c_o	Concentration in the overflow discharge	[mg/l]

The total volume is calculate as sum of the volumes in each subcatchments. On the method for the calculation of the efficiency see e.g. (Fenz and Rauch, 2003)
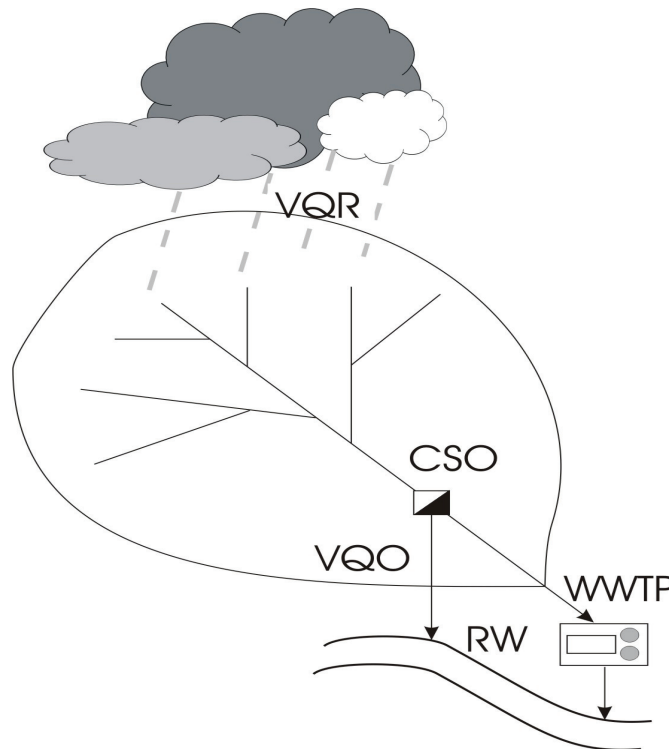
Figure 3-4. Schematic representation of an urban drainage catchment. VQR = runoff volume, VQO = overflow volume, CSO = Combined Sewer Overflow, WWTP = Wastewater Treatment Plant, RW = receiving water.

The percentage of runoff that should be treated is suggested in this guideline and depends on the dimension of the wastewater treatment plant and the rain characteristics of the investigated catchment. The rain characteristic used in a previous version of this guideline was the mean annual rain volume, but in analyses also reported in this dissertation, **Paper IV,** it was demonstrated that this is not the best parameter to use. Further analysis was also undertaken in order to define another indicator for the rain characteristic easy to calculate and of high availability. It was

found, that the statistical rain intensity (see chapter 3) with a duration of 12 hours and return period once per year, **Paper V**, meets these expectations and is the one, between the analysed parameters, that better correlate with the CSO efficiency. The calculation of the efficiency should be done using long-term simulation (at least 10 years) and a temporal resolution of the rain data of 10 Minutes or higher.

Furthermore, the removal of the sediments is required. The efficiency in this case is calculated as follows:

$$\eta_{sed} = \frac{c_{c,CSO} - c_o}{c_{c,CSO}} \cdot 100$$

η_{sed}	Sedimentation efficiency	[%]
$c_{c,CSO}$	Concentration in the CSO basin	[mg/l]
c_o	Concentration in the overflow discharge	[mg/l]

Table 3-1. Sedimentation efficiency for solids depending on the specific volume of the measures used (for values not mentioned in the table interpolation should be used)

Specific volume [m³/ha$_{Aimp}$]			Efficiency η_{sed} [%]
Hydrodynamic separator	Basin	In pipe storage with overflow downstream	
0	0	0	0
3	5	10	20
7	10	20	35
> 10	> 15	> 30	50

This simplified procedure is based on the assumption of constant wastewater concentrations in time and along the sewer network. The sedimentation efficiencies to be used for different treatment devices are reported in table 3-1.

The overall efficiency for solids (η_{TSS}) is calculated as the sum of the sedimentation efficiency for all the overflows and the rain related CSO efficiency (η) for the whole catchment calculated as cited above.

$$\eta_{TSS} = \eta + \frac{\sum_j VQO_{cso,j} \cdot \eta_{sed,j}}{VQR}$$

For overflows without retention basin or other sediment treatment device the overall efficiency for solids results equal to the rain related efficiency ($\eta_{TSS}=\eta$), if sediment treatment devices are present the overall efficiency for solids results higher then the rain related efficiency ($\eta_{TSS}>\eta$).

The use of this simplified method for the calculation of the sedimentation efficiency can lead to imprecision in the calculation. Furthermore, this approach does not consider the sedimentation capacity of the sewers, which in case of large and flat pipes can play a major role.

Furthermore, it should be considered that at each overflow the mixing's ratio between the throttle flow (Q_{thr}) and the mean dry weather flow (Q_{dwf24}) should be at larger than 8.

$$Q_{thr} > 8 \cdot Q_{dwf24}$$

The limits for the CSO efficiency and for the solids removal efficiency are reported in the following table. Such values are mentioned in the version of November 2005, the regulation is still not emended, changes can occur, but it seems interesting to have an example of the ranges of validity. Both limits, for the CSO efficiency and for the efficiency for solids removal, are valid contemporaneously.

Table 3-2. Minimum values of the CSO efficiency and the efficiency for solids removal depending from the statistical intensity over 12 hours ($r_{720,1}$) and the dimension of the wastewater treatment plant. For value not defined in the following table interpolation should be used

		Dimension of the WWTP [PE]	
		$\leqslant 5\ 000$	$\geqslant 50\ 000$
$r_{720,1} \leqslant 30$ mm/12h	η (NH$_4$-N, Ntot, Ptot, COD, BOD$_5$) [%]	50	60
	η_{TSS} [%]	65	75
$r_{720,1} \geqslant 50$ mm/12h	η (NH$_4$-N, Ntot, Ptot, COD, BOD$_5$) [%]	40	50
	η_{TSS} [%]	55	65

3.2.2. Requirement for combined sewer overflows for the ambient water quality approach

In this case, contrarily to the above mentioned, the impact observed is related to each overflow separately. The ambient water quality approach comprehends six kinds of impacts: hydraulic impact, acute ammonia toxicity, oxygen concentration, solids, hygenic and aestetic impact.

3.2.2.1. Hydraulic impact

The hydraulic impact should not have relevant effects on the biocoenosis. This requirement is defined using as indicator the maximum sewer overflow discharge with a return period of one year. This parameter should be smaller than 10 – 50% of the maximum water discharge in the river with return period once per year (HQ$_1$).

$$Q_1 \geq 0.1 \text{to} 0.5 \cdot HQ_1$$

Q_1 Maximum sewer overflow discharge with return period one year   [l/s]
HQ_1 Maximum water discharge in the river with return period once per year   [l/s]

The lower value has to be applied to more sensible watercourses, the higher, to rivers with more stable bed and higher re-colonisation potential.

3.2.2.2. Acute ammonia toxicity

The guideline subdivides the water courses in cyprinid and salmonid. For the first, the ammonia concentration due to the combined sewer overflow calculated for one hour should not be higher than 5 mg/l, for the second 2.5 mg/l.

The ammonia concentration in the river can be calculated using the following formula:

$$c_{r,d} = \frac{Q_{r,u} \cdot c_{r,u} + Q_d \cdot c_d \cdot \dfrac{Q_o}{(Q_t + Q_o)} + (Q_t + Q_o - Q_d) \cdot c_r \cdot \dfrac{Q_o}{(Q_t + Q_o)}}{Q_{r,u} + Q_o}$$

$Q_{r,u}$	Discharge in the river (MNQ or Q_{95}[1]) upstream the overflow	[l/s]
Q_o	Overflow discharge	[l/s]
Q_t	Throttle flow	[l/s]
Q_d	Dry weather flow	[l/s]
$c_{r,d}$	NH_4-N concentration in the river downstream the overflow	[mg/l]
$c_{r,u}$	NH_4-N concentration in the river upstream the overflow	[mg/l]
c_d	Total N concentration in the dry weather flow	[mg/l]
c_r	NH_4-N concentration in the runoff	[mg/l]

3.2.2.3. Oxygen concentration

The oxygen concentration in the watercourse after the CSO discharge should not be lower than 5 mg/l. The oxygen depletion can be calculated according to the oxygen sag curve equation presented first by Streeter and Phelps in the year 1925.

$$\frac{dD}{dt} = (K_1 \cdot S + R) - (K_2 \cdot D + P)$$

$$Dc = \frac{k_1}{k_2} \cdot c_G \cdot e^{(-k_1 \cdot t_c)}$$

D	Oxygen depletion	[g/m³]
K_1	Degradation rate	[l/d]
S	Content of degradable substance	[g/m³]
R	Oxygen consumption of the water plants, algae and river bed living micro organism	[g/(m³·d)]
K_2	Re-aeration rate	[l/d]
P	Oxygen input due to photosynthesis	[g/(m³·d)]

3.2.2.4. Solids

For the solids in the watercourses, due to sewer discharge, the suggested limit is 50 mg/l.

3.2.2.5. Hygienic impact

The frequency of limit's excess for overflows in bathing water should be avoided, or, for smaller watercourses, reduced at minimum possible.

3.2.2.6. Aesthetics

At watercourses, which are sensible to aesthetic impacts, filters and racks should be added at the combined sewer overflows.

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[1] *MNQ is the mean low water flow in the river, Q_{95} is the discharge, which is exceeded at 347 days per year (95% of the days), both are indicators commonly used in the German hydraulic specific literature.*

3.3.   Other national guidelines on CSO design

There is only a limited number of approaches for emission standards for CSOs and even less for ambient water quality standards. A commonly used approach is a minimum CSO setting depending on the mean dry weather flow as applied in many European countries. In the USA, the percentage of wastewater that has to be treated is defined. Another possibility is the limitation of the number of overflows per year, sometimes dependent on the receiving water (e.g. Belgium, Denmark or Netherlands) (Zabel et al., 2001). The volume of the CSO storage basin can be prescribed depending on the impervious area connected to the CSO, by a critical rain or a certain dilution (ATV - A 128, 1992; ÖNORM EN 752, 1997). The table below gives an overview on the requirements in different EU member states.

Table 3-3. Overview on the requirements for CSOs in European member states and USA elaborated from (Fenz, 2002; Gamerith, 2006; Krejci, 2004; UNEP, 2002; Zabel *et al.*, 2001). % CSS is the percentage of combined sewer system in each country; treatment rate is the percentage of wastewater that should be treated at the treatment plant.

Country	Guideline	% CSS	Q_{wwtp}	Q_t (CSO)	Required storage volume	Treatment Rate considered	Effects on RW considered
Austria	(ÖWAV-Regelblatt 19, 1987)	75-80	$2\,Q_{DWFp}$	<15 l/(s·ha$_{Ared}$)	15-25 m³/ha$_{Aimp}$	no	no
Austria new	(ÖWAV-Regelblatt 19, Draft 11.2005)		$2\,Q_{DWFp}$			50% rain runoff (tab 2-2)	yes
Belgium (Flanders)		70	$3\text{-}5\,Q_{DWFm}$	5-10 Q_{DWFm} NO=7/a	Remaining spilling vol. with T = 1/7 year	no	yes
Denmark		45-50	$2\,Q_{DWFp}$	$5\,Q_{DWFp}$ NO=2-10/a		no	yes
Finland		10-15	$2\,Q_{DWFp}$	6-7 Q_{DWFm}		no	
France	(CERTU, 2003)	70-80	$2\text{-}3\,Q_{DWFm}$	$3\,Q_{DWFp}$	Interception of rainfall with T = 3-6 months	no	sometime
Germany	(ATV - A 128, 1992; BWK, 2001)	67	$2\,Q_{DWFp}$	7.5-15 l/(s·ha$_{Aimp}$)	10-40m³/ha$_{Aimp}$	90% of COD load	yes
Greece		20	$2\,Q_{DWFm}$	3-6 Q_{DWFm}		no	sometime
Ireland		60-80	$3\,Q_{DWFm}$	6-9 Q_{DWFm}		no	sometime
Italy	Local e.g. (Regione Toscana, 2006)	60-70	$2\,Q_{DWFm}$	3-5 Q_{DWFm}		no	sometime
Luxembourg	(ATV - A 128, 1992)	80-90	$2\text{-}3\,Q_{DWFm}$	7.5-15 l/(s·ha$_{Aimp}$)	10-40m³/ha$_{Aimp}$	no	
Netherlands		74	$3\,Q_{DWFp}$	$5\,Q_{DWFm}$ NO = 3-10/a	ca. 70 m³/ha Aimp	no	sometime
Portugal		40-50	$2\,Q_{DWFm}$	$6\,Q_{DWFm}$		yes	sometime
Spain		70	$2\,Q_{DWFm}$	$5\,Q_{DWFm}$		no	no
Sweden		25-40	$3\text{-}4\,Q_{DWFm}$	5-20 Q_{DWFm}		no	
Switzerland	(AfU, 1977; GSchG, 1991; GSchV, 1998)		$2\,Q_{DWFp}$			no	yes
UK	(FWR, 1998)	70	$3\,Q_{DWFm}$	6-9 Q_{DWFm}	t_D= 2h at 3 Q_{DWF}	no	yes
USA	(CWA, 1997; US EPA, 1995)			NO=4-6 /a		85% combined wastewater	yes

Where:

Q_{wwtp}	Wastewater flow rate to wastewater treatment plant allowed	[l/s]
Q_t	Throttle discharge at CSOs	[l/s]
Q_{DWFm}	Mean dry weather flow	[l/s]
Q_{DWFp}	Dry weather flow (daily peak)	[l/s]
T	Return period	[year]
NO	Number of overflow per year	[l/a]
t_D	Detention time	[h]
A_{imp}	Impervious area connected to the combined sewer system	[ha]

Note, that all the below mentioned standards are not laws. They represent only design procedures, in German speaking countries they represent the 'state of the art' accepted in legal procedures. Other design procedure could be used, however it should be demonstrate that they give comparable or better results then the procedure presented in the guideline. In many other countries the procedure is more flexible with additional diverging requirements given by governmental bodies. Note that in the UK, Denmark, USA and to a lesser extent in Switzerland, Germany and Austria ambient water quality standards also apply.

Following, a more detailed description of selected guidelines is presented.

3.3.1. *The approach for CSO design of the European Norm EN 752-4, "Drain and sewer systems outside buildings. Hydraulic design and environmental considerations"*

The European norm EN 752-4 proposes standards for the CSO emission. The main goal in dimensioning an overflow structure, is the protection of the receiving water without causing hydraulic overload of the sewer system or diminished purification capacity of the wastewater treatment plant. Two approaches are presented in this norm. The first one considers the fact that the overflow structure allows the discharge only after achieving a determinate critical specific flow. This is defined depending on the sensitivity of the receiving water between 10 and 30 l/(s ha), depending on the dimension of the impervious area drained. The second alternative approach considers the self-purification capacity of the receiving water. It proposes that the overflow water should be at least the 5-8 times dilution of the dry weather flow. By dimensioning the overflow structures a reduction of the floatables discharged in the receiving water should be considered (ÖNORM EN 752, 1997).

3.3.2. *Legislation and Technical Guidance on CSO in Germany*

Germany is characterised, due to the federal structure, by a great diversity of laws and ordinances. Water laws are a matter of the individual German states, whereas the framework law, the Federal Water Act (WHG), of the Federal Government lays down basic provisions. The organisation and implementation of the wastewater disposal are duties of the municipalities, in accordance with state water laws. The intention of the Federal Water Act is to prevent the pollution of waters and to enforce a precautionary approach to water protection.
In Germany, the technical guideline (ATV - A 128, 1992) deals with the design and construction of stormwater facilities in combined sewers. The main goal is the best possible reduction of total emissions discharged from CSOs and WWTPs. The dimensioning of stormwater treatment facilities consists of determining the critical flow, the water surface and the throttle flow of retention basins. This emission based

dimensioning of CSO structures manages to improve the receiving water quality in many cases. In some cases, the receiving water quality remains unsatisfactory. New ambient water quality based guidelines (ATV-M 153, 2000; BWK, 2001) have been developed, which are receiving water target oriented.

3.3.3. Legislation and Technical Guidance on CSO in Flanders (Belgium)

The presented regulation is only for Flanders, in Wallonia and Brussels other regulations apply. In Flanders the 'vulnerability' of the receiving water is important, ranging from 'extremely vulnerable' to 'not vulnerable'. The vulnerability determines the overflow frequency that is allowed. For extremely vulnerable receiving waters, no overflows are permitted. For other receiving waters, the basic rule is that a CSO basin has to retain an event that occurs seven times per year. The number of overflows per year is to be calculated using simulations.

There exist until now no real guidelines or legally binding design criteria on CSOs. There are some rules of common 'good practice' like: (1) the throttle device after the CSO is supposed to work on $6Q_{14}$. This means, that throttle flows are limited to six times the (peak) dry weather flow (Q_{14}), where Q_{14} equals 1.7 times the dry weather flow (normally used 150l/d.PE); (2) the overflow layer should not exceed 20 cm, according to which the length of the CSO can be altered (ATV-M 153, 2000). The crest level is designed according to the local situation and is therefore site dependent, attention should be paid not to cause basement or surface flooding. The code of good practise is currently under revision and a new guidance document on CSOs will be published (CD4WC D2.1, 2005).

3.3.4. Legislation and Technical Guidance on CSO in the USA

Key source of this chapter is the paper presented on the World Water and Environmental Resources Congress 2005, in Anchorage, Alaska (Zukovs, 2005).
In the US, the federal government (represented by US EPA, Environmental Protection Agency) has defined national CSO control requirement. The Clean Water Act is the US legislation for federal and state CSO programs. This document presents the "fishable, swimmable" goal. The CSOs are point pollutant sources, thus are subjected to the regulations associated with the National Pollutant Discharge Elimination System Program, which is the basis for permitting CSO. In 1994 the CSO control policy was promulgated. The Policy sets expectations for all parties. They include:
  ➢ Immediate implementation of the technology based requirements called the Nine Minimum Controls (NMC);
  ➢ Priority for CSO abatement for sensitive areas;
  ➢ Preparation of a long term control plan;
  ➢ Review of the State water quality standards, and
  ➢ Consideration of the community's financial capabilities.

3.3.4.1. Nine Minimum Controls

The implementation of these controls together with the characterisation of the integrated system behaviour is the first step for the CSO municipalities. The required measures are:
  1. Proper operation and maintenance program for sewer system and CSO devices;

2. Maximum use of the collection system for storage;
3. Review and modification of pre-treatment programs;
4. Maximisation of the flow to the wastewater treatment plant;
5. Prohibition of CSO discharges during dry weather;
6. Control of the solid and floatable materials in CSO discharges;
7. Pollution prevention programs that focus on containment reduction activities;
8. Public notification in order to ensure adequate information on CSO occurrence and CSO impacts, and;
9. Monitoring CSO controls to effectively characterise their impacts and efficiency.

3.3.4.2. Preparation of CSO Long Term Control Plan

The policy requires that the communities develop a CSO abatement program that will meet at the end the water quality standards in all waters receiving CSO discharge. In the evaluation of CSO control alternatives, either a presumption or a evaluation approach are allowed. The presumption approach considers CSO control objectives defined by end-of-pipe measures such as frequency overflow (4-6 overflows per year), percentage volumetric control (85% of the wastewater in wet weather calculated as mean over long term) or percentage loading control (should not be smaller than the load calculated with 85% flow reduction). By meeting these end-of-pipe objectives it is presumed that the water quality standards are met too. The demonstration approach, on the other side, is water quality based and evaluates the ability of CSO control measures to meet the standards cited in the Clean Water Act.

3.3.4.3. Long Term Control Plan and sensitive areas

For areas classified as sensitive particular precautions are prescribed:
➢ No new or increased overflows are allowed;
➢ Elimination and relocation of overflow is suggested;
➢ Where elimination or relocation is not possible, the CSO should be treated; and,
➢ In those locations where elimination or relocation is not possible reassessment should be performed.

3.3.4.4. Long Term Control Plan and water quality standards review

An important principle of the CSO Control Policy is the review and revision of water quality standards and their implementation procedure when developing CSO Control Plans. Where existing standards cannot be met, CSO communities, state and the US EPA can modify existing standards.

3.3.4.5. Long Term Control Plan and affordability

The CSO Policy stipulates that the Long Term Control Plan implementation may be based on the importance of the impacts and on the financial capability of the community. The financial capability is assessed using three indicators:
➢ The total annual wastewater and CSO control cost as a percentage of the household median income;
➢ The bond ratings; and
➢ The overall net debt as a percent of full market property value.

3.3.4.6. Long Term Control Plan and level of treatment

CSO abatement technologies include the application of on-site measures, at the CSO devices, and at the wastewater treatment plant. For the on-site measures the presumption approach requires an equivalent treatment to primary clarification, for removal of flotables and settable and disinfection, where necessary. Particular rules are prescribed for the wastewater treatment plant to allow bypassing. A bypass is defined as a diversion of flows including secondary treatments.

3.3.5. *Legislation and Technical Guidance on CSO in Great Britain*

The foundation for Water Research of the United Kingdom published a guiding manual, called Urban Pollution Management (UPM) manual, based on earlier Danish regulations, for the planning of measures controlling the wet weather wastewater discharge into a watercourse considering the whole system in an integrated analysis. The aim of this manual is to achieve environmental targets with cost effective solutions. The manual provides background information and explains in detail the approach developed.

A key characteristic of the UPM procedure is the introduction of intermittent standards, which are limits for the protection of river aquatic life during short-term pollution events, expressed in terms of concentration/duration thresholds for DO and un-ionised ammonia for a range of return periods. This means that not only the concentration allowed, but also the duration of exceeding the suggested standards and the return period of the exceeding, are considered. Further, the impact can have different effects depending on the kind of the receiving water. The UPM procedure contemplates this fact considering different limits for the two defined river types: salmonid and cyprinid. Salmonid rivers have usually lower nutrients; a discharge of polluted wastewater will have higher impact on the aquatic environment. In table 3-4 the standards for un-ionised ammonia are reported as example of this procedure. Similar standards are given for the dissolved oxygen.

Table 3-4. Fundamental Intermittent standards for un-ionised ammonia - concentration/duration thresholds not to be breached more frequently than shown

a) Ecosystem suitable for sustainable salmonid fishery

Return period	Un-ionised ammonia concentrations [mg NH3-N/l]		
	1 hour	6 hours	24 hours
1 month	0.065	0.025	0.018
3 months	0.095	0.035	0.025
1 year	0.105	0.040	0.030

b) Ecosystem suitable for sustainable cyprinid fishery

Return period	Un-ionised ammonia concentrations [mg NH3-N/l]		
	1 hour	6 hours	24 hours
1 month	0.150	0.075	0.030
3 months	0.225	0.125	0.050
1 year	0.250	0.150	0.065

c) Marginal cyprinid fishery ecosystem

Return period	Un-ionised ammonia concentrations [mg NH3-N/l]		
	1 hour	6 hours	24 hours
1 month	0.175	0.100	0.050
3 months	0.250	0.150	0.080
1 year	0.300	0.200	0.140

Notes:
1. These limits apply when the concurrent dissolved oxygen concentration is above 5 mg/l. At lower concurrent dissolved oxygen concentrations the following correction factor applies: <5 mg/l DO, multiplicative correction factor = 0.0126 (mg DO/l)2.72
2. The standards also assume that the concurrent pH is greater than 7 and temperature is greater than 5°C. For lower pH and temperatures the following correction factors apply: pH <7, multiplicative correction factor = 0.0003(pH)4.17 Temperature <5°C, multiplicative correction factor = 0.5

Due to the definition of intermittent standards (see table 3-4), the planned measures should be modelled in temporal dynamic conditions, in order to prove their effectiveness.

3.4. Guidelines on sewer design

Many guidelines on sewer design have been updated in the last years including more information on modelling and calibrating issues. The European guideline EN-752 and its national implementation in Austria are presented in the following pages.

3.4.1. *European guideline "Drain and sewer systems outside buildings. Hydraulic design and environmental considerations", EN-752*

The European guideline EN-752 has been implemented in the national guidelines in the member states. This norm represents a basis for the dimensioning of urban drainage systems. A key concept is the relation between the probability of damage due to pluvial flooding and the protection necessity of the drained catchment (expressed in form of urbanisation categories). The EN-752 defines flooding as a 'condition where waste water and/or surface water escapes from or cannot enter a drain or sewer system and either remains on the surface or enters buildings'. Here the

term flooding is connected with occurrence of damage. The probability of damage occurrence is difficult to simulate. To allow a prediction of the damage produced from the flooding is necessary a deep knowledge of the local conditions of the catchment simulated (Pohl and Fuchs, 1998). Information like e.g. elevation of the cellars windows or of the walking pats is crucial. Additionally, the overflowed water can flow more in one direction than in the other, depending on the inclination of the street, in which the manholes are situated. The recommended design frequencies, suggested in the EN-752, are reported together with the Austrian standards in table 3-5.

3.4.2. *Austrian guideline on sewer design "ÖWAV Regelblatt 11"*

The main issue of the (ÖWAV-Regelblatt 11, Draft 07.2004) is the hydraulic calculation of foul water, storm water and combined wastewater sewers drained in open channel flow conditions. This guideline is the Austrian national implementation of the EN 752 (ÖNORM EN 752, 1997).

An innovation of this guideline is the differentiation between simple and complex systems. For the simple systems it is sufficient to use simple calculations methods like the time-area method (see chapter 3). For more complex systems the utilisation of simulation, based on hydrological or hydrodynamic models, is suggested.

Further, the "Regelblatt 11" presents a review on the different kinds of rain input that can be used for the calculations, more on this topic in chapter 4.1.3.

This guideline requires, in contrary to the EN 752, the surcharge frequency proof instead of flooding proof. The surcharge happens when the wastewater reaches the soil level, thus when the water starts flowing out of the sewer system. This approach is easier to model and is also used in the German implementation of the EN (ATV - A 118, 1999). Of course the surcharge happens more often than the flooding, therefore the allowed return periods are smaller.

Table 3-5. Suggested design frequency in EN 752, Regelblatt 11 and ATV118. For design storm no pipe surcharge shall occur.

Urbanisation categories	Design storm frequency EN 752 (1 in *n* years)	Design flooding frequency EN 752 (1 in *n* years)	Design surcharge frequency Regelblatt 11 ATV 118 (1 in *n* years)
Rural areas	1	10	2
Residential areas	2	20	3
City centres, industrial/commercial areas	5	30	5 (less then*)
Underground railway/ underpass	10	50	10 (less then*)

* the ATV 118 presents return period for the last two categories as less then 1 in 5 or in 10 respectively.

The design storm has a smaller return period then the surcharge return period. The given design storm's return period is the one used for dimensioning the sewer system with the time-area method. In sewer systems dimensioned with these design storms are surcharge events less frequent, due to the tendency of over-dimensioning often caused by the use of design storms (Verworn, 2002). On the problems related with the calculation of the frequency of flooding more information can be found in (Schmitt and Thomas, 2000; Stecker and Reimers, 1997; Verworn, 2002).

Additional to this guideline in the field of sewer system design, the new version of the (ÖWAV-Regelblatt 9, Draft 04.2006), the Austrian guideline for the utilisation of the drainage system, will be emended in short time. This guideline gives information on the implementation problems of the different drainage systems and is so a valuable asset in the choice of the more suitable one. Similar suggestions can be found in the German guideline (ATV - A 105, 1997).

3.4.3. *Austrian guideline on stormwater treatment "Regelblatt 35"*

The (ÖWAV-Regelblatt 35, 2003), on treatment of stormwater, gives recommendations on the treatment of stormwater in separate systems.

This guideline suggests discharging the stormwater on-site before it achieves the sewer system, if it is not contaminated. To allow that, infiltration should be preferred; a reduction of impervious area, using e.g. porous pavements on parking lots, or infiltration using infiltrating devices can deal to high stormwater runoff diminution. When the infiltration is not possible, the direct discharge to the next receiving water should be preferred.

Furthermore, this guideline gives information on the quality of stormwater suggesting mean possible pollutant concentrations depending on the origin (roofs, streets, farms, working places, airports).

According to the presentation of the possible pollution sources, the areas producing runoff are subdivided in 5 categories and to each category a treatment level necessary for the infiltration and for the discharge to the receiving waters is assigned. The effects of the discharge on the receiving waters are described, in this regulation, in detail.

At last, measures for the treatment of stormwater are suggested: infiltration, sedimentation basins, filter facilities and rain retention basins. Instruction on the design of the devices is not given, here the guidelines, giving technical information on the design, e.g. (ATV - A 138, 2002), are only mentioned.

3.5. German guideline on rain analysis ATV 121

This guideline applies to the evaluation of rain data (ATV - A 121, 2001). The procedure described here for the analysis of rain data depending on return period and duration gives IDF (Intensity Duration Frequency) curves, described more in detail in chapter 4.1.3.4. The statistical analysis is effectuated in 2-steps. The first step consists of the calculation of the statistical intensity depending on the return period for, at a time, a duration (e.g. 15 minutes intensity, also called $r_{15,1}$, or 1 hour etc.), like explained in more detail in the chapter 4.1.3.3. In a second step, the dependence of the rain intensity on the duration is adjusted using interpolating equations.

This adjustment for different duration is necessary because the intensity over all the analysed durations (5min to 6 days) does not always give a homogenous picture. It may occur that the rain depth with increasing duration and return period decreases, which is physically not possible. To avoid such inconvenience it is necessary to act an adjustment for the equation's parameters, see chapter 4.1.3.3. The analysed durations are divided in three intervals. Separating points between such intervals are 3 hours and 48 hours. Inside each interval a regression with simple or double logarithm is suggested. To avoid jumps between the boarders of two intervals, a second interpolation is necessary.

Based on this guideline in Germany IDF curves for 4500 rain gauges in the whole country, for duration between 5 minutes and 72 hours and return period from 0.5 years till 100 years where calculated, the results are reported in the database called KOSTRA-DWD-2000 (DWD, 2005), based on rain data from the year 1951 to 2000. In this case the boarders of the intervals for the adjustment where chosen to be 60 minutes and 12 hours, where 15 and 60 minutes are basis points for the interpolation. For values smaller than 15 minutes a separate interpolation was demonstrated necessary. Separately is the interpolation for the other two longer (60min-12h and 12h- 72h) intervals described. Further the KOSTRA statistic considers the seasonality and the spatial distribution.

In analogy with this approach but adapted to the Austrian conditions was created the OWUNDA analysis system (Hammer, 1993; Skoda, 1993). In this case the optimisation procedure is based on the choice between 11 interpolation functions. It is chosen the interpolation function with smallest error and monotonic grown of the rain depth. The IDF curves calculated in this way will be reported soon in the database ÖKOSTRA (Krall, 2005).

3.6.   Summary

This chapter presents a critical review of numerous guidelines in the field of urban drainage. This review serves as basis for the work presented in this dissertation. The drawn conclusions are not clear, there are no uniform definitions of requirements in the different states and the choice between the two approaches, emission or ambient water quality based, differs from country to country. Generally, the presented guidelines on CSO design are emission based, an exception is the approach of the UK guideline UPM, which is ambient water quality based. The Austrian guideline is emission based but in case of problems it also considers ambient water quality impacts. From this review it is not possible to define an indicators set for the assessment of the sewer system performance. There are numerous different indicators that need to be tested.

In this context, it is necessary to define indicators, that can be used in order to evaluate the sewer system performance, a task which was the main issue of this dissertation.

4. Methods and Procedures

Chapter 4 presents a literature review of the hydrological and flow routing processes, which are essential for the sewer system modelling. Further, the indicators used for the performance assessment and their calculation methods are described.

This is an introduction to methods and procedures used in the analyses presented in the papers of the annex. It presents no new scientific findings.

4.1. Hydrological background

Hydrology is the study of atmospheric water, of surface water and ground water. This chapter deals only with the rainfall and the resulting surface runoff in the urban area, which generates the flow in the sewer system. This part of hydrology is also called urban hydrology.

The rain data used for engineering praxis can be statistical derivates (synthetic storms) or original series, with wet and also dry periods. The resolution for urban drainage purposes should be at least 5-10 minutes. The length of the rain series depends on the problem investigated: for analysis of flooding and of CSO impacts it should be at least 10 years (ÖWAV-Regelblatt 19, Draft 11.2005).

Regarding design issues, the spatial variability of the rain should always be taken into consideration. The rain varies strongly, depending on local conditions. Many factors can influence this behaviour the most important being micro climatic conditions and orography (Germann and Joss, 2000; Mikkelsen *et al.*, 1997). This fact will be further explained in chapter 5.

The usual representation of the rainfall intensity is the plot against time, i.e. hyetograph.
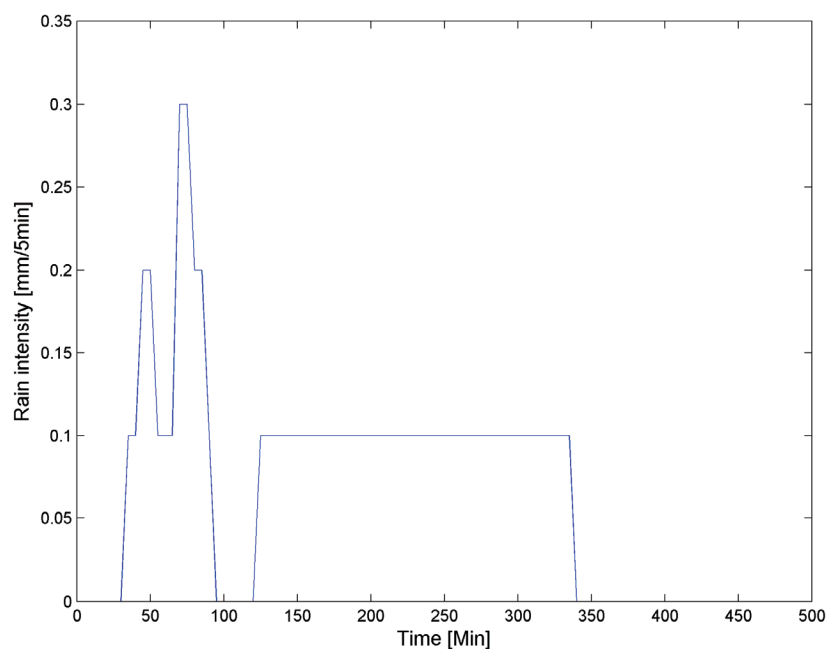
Figure 4-1. Example of a hyetograph for a single rain event.

4.1.1. *Rain measurement*

The most common rain measurement device is the rain gauge. A standard non-recording gauge collects the rain falling on a defined area over a determinate period of time. In a non-recording gauge the volume is measured manually and converted into intensity by dividing by the collection area. Collection periods range from 6 hours to one month, however one day is typical. Since a relevant time step for the urban drainage is in the range of minutes, such devices are not used often in the urban hydrology.

In order to avoid this problem, the rain gauges are connected with a recording device. Recording gauges are able to provide continuous record of the rainfall. The tipping-bucket rain gauge collects rainfall over a short period of time in a small basin subdivided in two compartments. The tipping buckets are, nowadays, the most used rain measurement system (Einfalt *et al.*, 2002a). The water starts to enter the second compartment while the first empties. The gauge produces a series of tips with changing frequency, depending on the rainfall intensity. The data is stored in a data logger and will be converted to convenient formats depending on the demand. The range of rainfall depth resolution is 0.1 to 0.5 mm/tip. The choice of the position of the gauge plays an important role. The gauge should be placed at a convenient distance from obstacles, like roofs, trees etc. On the importance of correct measurement and the possible error sources many studies can be found, among others (Einfalt *et al.*, 2002b; Jorgensen *et al.*, 1998)

Another method for the measurement of rain data is based on the weighting of the fallen rain. The rain falls on a scale and is weighted in constant intervals, e.g. each minute. The weight is then converted into rain depth.

An emerging technique for the rainfall measurement is the ground-based radar. The radar provides a picture of the rainfall in the atmosphere. The methods consist in directing a radar beam at the falling raindrops, collecting and measuring the intensity of the reflected radiation and relating this to the rainfall intensity (Butler and Davies, 2000; Einfalt *et al.*, 2002a).

4.1.2. *Return period*

The return period is the interval in which a specific event – from a statistical point of view - could take place again. The frequency is the inverse of the return period and is often used instead. The return period is on the basis of sewer system planning. For example, in Austria a pluvial flooding in residential areas is allowed only one time each 3 years (return period 3 years). Based on this limit the diameter of the pipes is chosen so that the flooding events do not happen more frequently. It could be possible to use pipes of larger diameter so that the flooding happens only each 10 years but this would implies higher expenses with are not justified. In the description of the indicators (chapter 4.3) the concept of return period is often used.

Plotting position formulas are used very often in hydrology for the calculation of the return period. Following, two of the most used formulas are presented: the California (left) and the Weibull (right) plotting formula.

$$T = \frac{i}{k} \quad \text{and} \quad T = \frac{i}{k+1}$$

where *i* is the rank of the values ordered descending and *k* is the length of the analysed series in years (Chow *et al.*, 1988).

4.1.3. *Rain data format*

The rain data are the basis for the urban drainage modelling. They can be transformed in different formats depending on the utilisation and the detail needed. Following, the most often used rain input types are reported, more on that issue can be found in (Rauch and De Toffol, 2005).

4.1.3.1. Historical time-series

The historical time-series consists of all the available rain data, including the dry periods, normally corrected from measurement errors. The row data, namely, often contain record or measurement errors.

The historical time-series give the most reliable simulation results, but the calculation time is much longer than with other formats, especially when using a hydrodynamic simulation (De Toffol *et al.*, 2006).
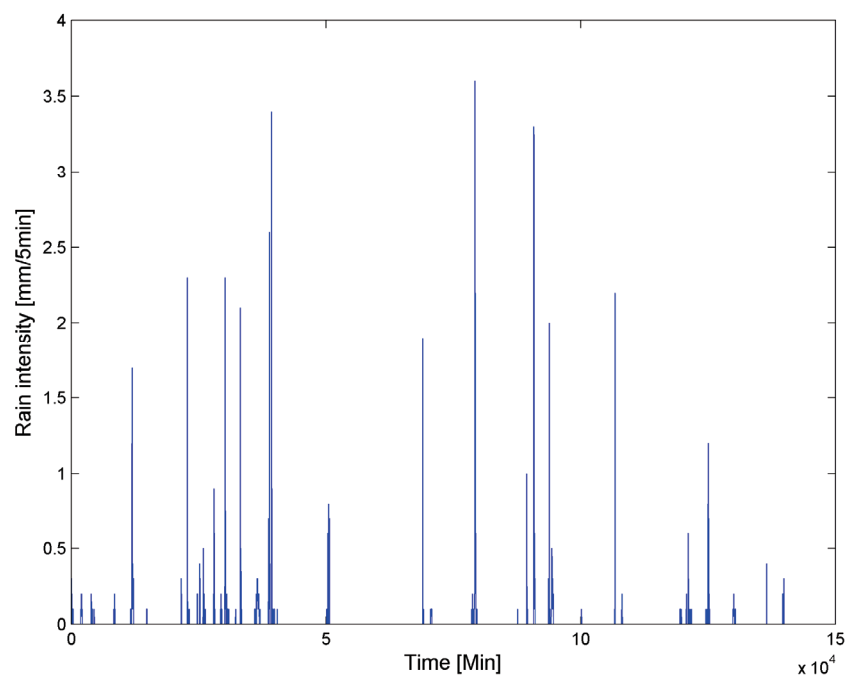
Figure 4-2. Extract from a historical time series

4.1.3.2. Selected rainfall series

The selected rainfall series is a selection of the intense events in the historical time-series. Due to the absence of dry weather periods, the simulation time is notably shorter, namely, only the relevant rain events are simulated. It is supposed that the flow produced in the sewer system, in the simulation, from such rain input has the same return period as the selected events, an assumption that is not necessarily true.

In order to build such series, it is first necessary to define the criterion to identify the single rain event by choosing the length of the rainless period, which divide two events from each other. Such a period should have the same length as the time of concentration in the sewer, which is for a city of average dimension between 1 and 2

hours. After that, a minimum value for the rain events can be chosen, which should be at least 0.1mm/5min, which is approximately the volume of the initial losses. Then all the rain events are divided in intervals for the different duration with a method like the one used for the statistical rain intensity (next chapter) and ordered descending. The number (n) of rain events for each duration is maximum 2.71 times the length of the series in years (M) divided by the smallest return period analysed (T) (**n = 2.71 M/T**). With the plotting formula presented in the chapter 4.1.3.3, the return period for the intensity for each duration can be easily calculated (Sieker, 1997).

4.1.3.3. Statistical rain intensity

The statistical rain intensity is calculated according to the German guideline (ATV - A 121, 2001). The procedure for the calculation is explained as follows.

At the beginning, it is necessary to define the base interval, which is for the calculation of the intensity in the order of minutes (until 1 hour), 5 minutes interval. For the calculation of the intensity in the order of hours the basis interval should be one hour. The durations for the intensities analysed are multiple of the base interval. The guideline reports typical durations relevant for the urban hydrology: 5 minutes, 10, 15, 20, 30, 45, 60, 90, 2 hours, 3, 4, 6, 9, 12, 18, 1 day, 2, 3, 4, 5, 6. However the durations longer then 12 hours were not used in this dissertation.

Further a series of rain intensities for the different durations analysed has to be build, making sure that each interval is contained only one time in each of the chosen values. For the example of the intensity for the duration 15 minutes it is necessary to sum 3 base intervals (each five minutes). The following picture will help the comprehension of the methodology.
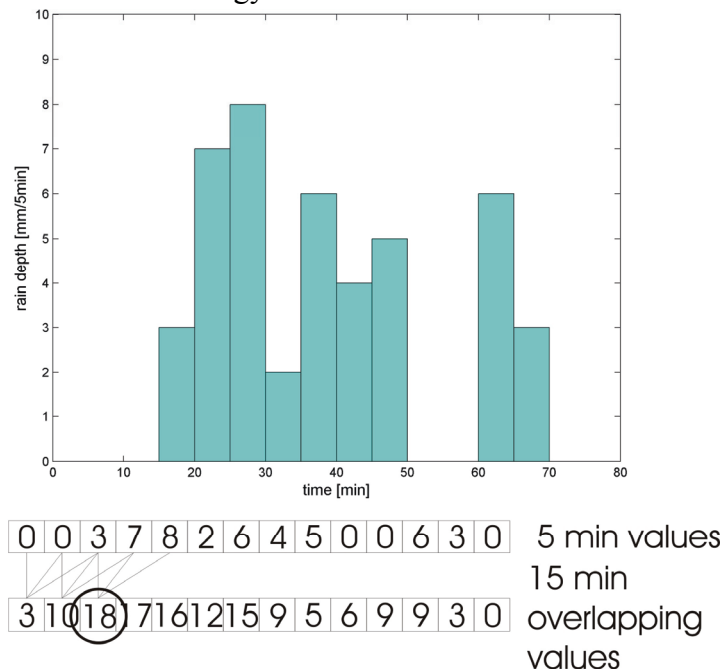
Figure 4-3. Explanation of the procedure to choose the rain depths over 15 minutes (redrawn from (ATV - A 121, 2001))

As shown in figure 4-3, the only one value of the series that can be chosen is the value 18 mm/15min, formed adding the base intervals with rain intensity 3,7 and 8 mm/5min. The two values, before and after (3,10 and 17, 16), contain the same base intervals (with rain intensity 3,7, and 8 mm/5min) and have to be excluded from the series. To assure the independence of the chosen value it is not allowed to have more than 1 value per day.

The series of rain intensities obtained from the previous points can be further elaborated using the "yearly series" or the "partial series" method. The first method chooses for each year the absolute maximum; in the partial series there are chosen the values of the intensities over a particular threshold. In the first case, the number of values in the series resembles the number of years in the rain data, in the second case it should be 2-3 times the number of years of the rain series, usually the numbers over the threshold are much more and the series has to be cut in order to complain this length. Because of the fact that the yearly series should be used only if the rain series length is larger than 20 years, (which is normally much more than the available length), it was decided to use the partial series method, which is also the one, most commonly used in urban drainage.

When using equal intervals in the forming rain intensity series, a systematic error occurs which is inverse proportional to the number of base interval used to build the series. To avoid this fact, correction factors should be used. These values are empiric and each rain intensity of the series should be multiply by that. The choice of the factor to be used depends on the number of base intervals used for the calculation of the rain intensity series (e.g. with 5 minutes basic interval for the duration 15 minutes there are 15/5=3 intervals).

Table 4-1. Correction factors (**C**) depending on the number of intervals (**i**).

i	1	2	3	4	5	6
C	1.14	1.07	1.04	1.03	1.03	1.02

The values of the series should then be interpolated using the statistical exponential distribution in order to find the value for the investigated return periods.

$$h_N(T_n) = u_p + w_p \cdot \ln T_n$$

where:

h_N	Rain depth	[mm]
T_n	Return period	[a]
u_p, w_p	Parameters of the distribution function	[-]

The distribution represents - in the semi-logarithmic sheet with h_N on the ordinate and $\ln T_n$ on the abscissa - a line in which u_p is the intersection with the y-axis and w_p the inclination.
To enable the calculation of the parameters u_p and w_p for the descending ordered series, the return periods are calculated using the following plotting formula.

$$T_{n_k} = \frac{L + 0.2}{k - 0.4} \cdot \frac{M}{L}$$

Where:

M	Length of the rain series in years	[a]
L	Number of values in the series	[-]
k	Index of the ordered series	[-]
	k=1 is the biggest	
	k=L the smallest	

$$w_p = \frac{\sum_{k=1}^{L}(h_{N_k} \cdot \ln T_{n_k}) - L \cdot \overline{h_N} \cdot \overline{\ln T_n}}{\sum_{k=1}^{L}(\ln T_{n_k})^2 - L \cdot \overline{\ln T_n}^2}$$

$$u_p = \overline{h_N} - w_p \cdot \overline{\ln T_n}$$

$\overline{h_N}$ and $\overline{\ln T_n}$ are the mean values of the rain depth and of the logarithm of the return period respectively, according to the formulas:

$$\overline{h_N} = \frac{1}{L} \cdot \sum_{k=1}^{L} h_{N_k}$$

$$\overline{\ln T_n} = \frac{1}{L} \cdot \sum_{k=1}^{L} (\ln T_{n_k})$$
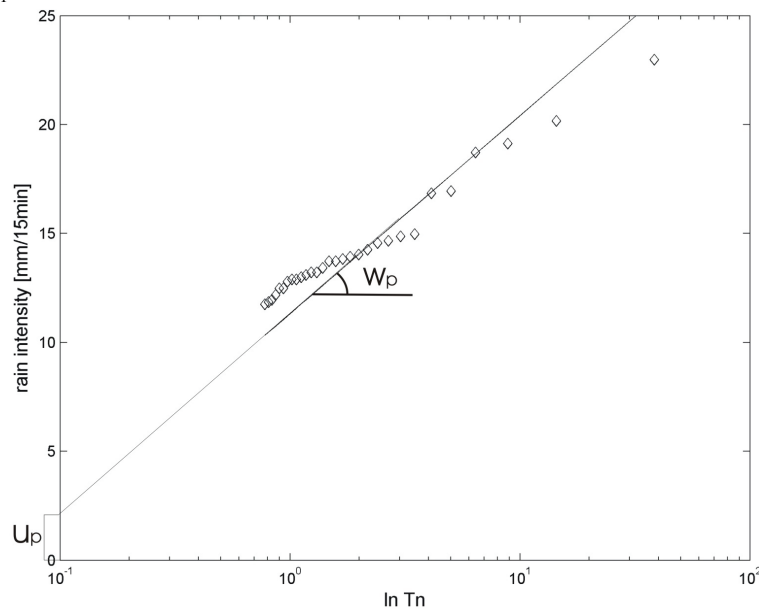
Figure 4-4. Example of calculation of the statistical rain intensity over 15 minutes, the diamonds are the points of the depth series, the line represents the interpolation with statistical exponential distribution

4.1.3.4. Intensity-Duration-Frequency curves

The Intensity-Duration-Frequency (IDF) curves represent the rainfall intensities, corresponding to a particular storm recurrence interval for various storm durations. These curves are the results of the statistical analysis of rainfall data for a particular area. Such curves can be calculated from the historical time-series, by extracting the maximum value and associating it to a return period using the plotting formula. The data set is then interpolated using a statistical distribution (e.g. log-normal, Gumbel)

with methods based on the moments of the data, least squares, or the maximum likelihood data (Butler and Davies, 2000). An example of such methodology is applied in the databases KOSTRA-DWD and ÖKOSTRA, presented in chapter 2.

In absence of local data generalised IDF curves can be used. These were very useful in the past, when the data availability was not so high. Usually, a specific formula for the IDF curves was used in every country. The (relative low) number of constants change, depending on the location (inside the country). In Switzerland the Hörler/Rhein curves are used, in Germany the Reinhold's rain curves.

A typical set of IDF curves is presented in picture 4-5. The form suggests, that when the duration increases, the intensity is reduced, which seems to be logic. Heavy storms are normally of short duration and drizzle can last long. There are many mathematical formulations for IDF curves, the simplest form expresses the average rain intensity **i** depending on the duration **D** for a fixed return period and has the form

$$i = \frac{a}{D+b}$$

where **a** and **b** are constants depending on the formula used and the location (Butler and Davies, 2000).

Example of IDF curves calculation formulas are reported following

$$i = \frac{a}{D+b} = G \cdot \frac{15+B}{t_N + B} \cdot (1 + C \cdot \log z)$$ 	Hörler Rhein (Switzerland) (Rauch *et al.*, 2002b)

where **z** is the number of years in which **i** is achieved statistically at least once, or is exceeded; tN is the rain period and **G**,**B**,**C** are constants depending on the location.

$$r = r_{15(1)} \cdot \frac{38}{T+9} \cdot \left[\frac{1}{\sqrt[4]{n}} - 0.369 \right]$$ Reinhold's rain (Germany) (ITWH, 2002)

where **T** is the duration, **n** the return frequency and $r_{15,1}$ the statistical rain intensity calculated as explained above.
The application range of this equation is for n = 0,05 to n = 4 and for T < 150 min and is obtained from 40 years observation of German rainfall.
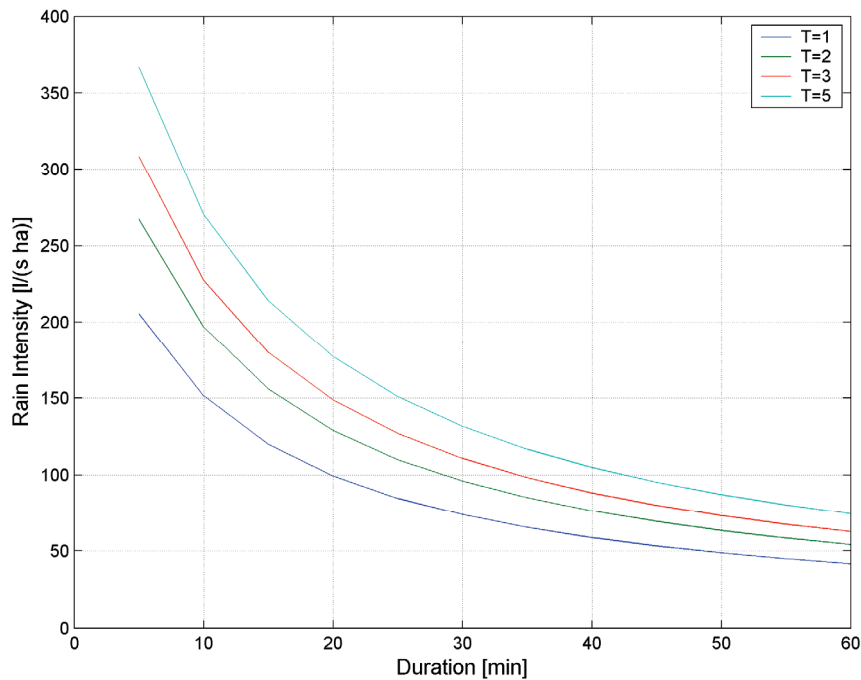
Figure 4-5. Example of IDF curves calculated with the Reinhold's rain

4.1.3.5. Synthetic design storm

The synthetic design storm is not built directly from the original data, but it is derived from a statistical analysis of them, which implies that a statistically-based return period is attached to the design storm.

It is supposed that the return period of the rain event is the same as the one of the obtained flow in the sewer system. Simulations with design storm give similar results to ones with the selected rainfall series, however they can not be used for particular analyses of the sewer system behaviour, like e.g. for the investigation of the effects of real time control measures, or retention effects.

The design storm can be derived directly from the IDF curves. The simplest form of design storm is the block rainfall. It consists of a constant rain intensity over a period, based on the statistical analysis of the historical time-series. Such a rain format should be used only for a quick first check of the system. It is not adapted to investigate the sewer system behaviour.
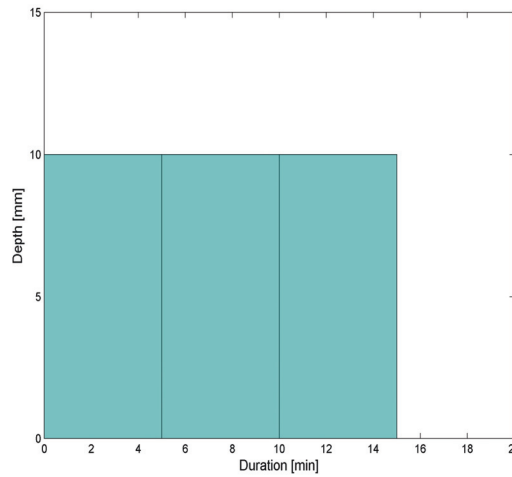
Figure 4-6. Example of block rainfall

In order to enable more accurate design solutions, other kind of profiles have been created. In the German literature the Euler rain Typ II is widely applied, which is explained as follows.

Starting from a graph, representing the rain depth in the time (e.g. Reinhold's rain), the rain depth for each interval (usually 5 minutes) is calculated. This procedure permits the derivation of the design storm Euler type I. The form of such design storm does not appear realistic, because the highest intensity is obtained in the first interval. Based on the consideration that the rain events start normally with lower intensity, in the design storm Euler type II, the first 0.3 of the design storm duration (approximated to multiple of 5minutes) is inverted: if the design storm is 60 minutes long, the maximum intensity will be after 20 minutes (ATV - A 118, 1999; Rauch and De Toffol, 2005).

D	h_N	Euler I	Euler II
5	6.17	6.17	1.12
10	9.09	2.92	1.70
15	10.79	1.70	2.92
20	11.91	1.12	6.17
25	12.69	0.79	0.79
30	13.28	0.59	0.59
35	13.73	0.45	0.45
40	14.09	0.36	0.36
45	14.39	0.29	0.29
50	14.63	0.24	0.24
55	14.84	0.21	0.21
60	15.01	0.18	0.18
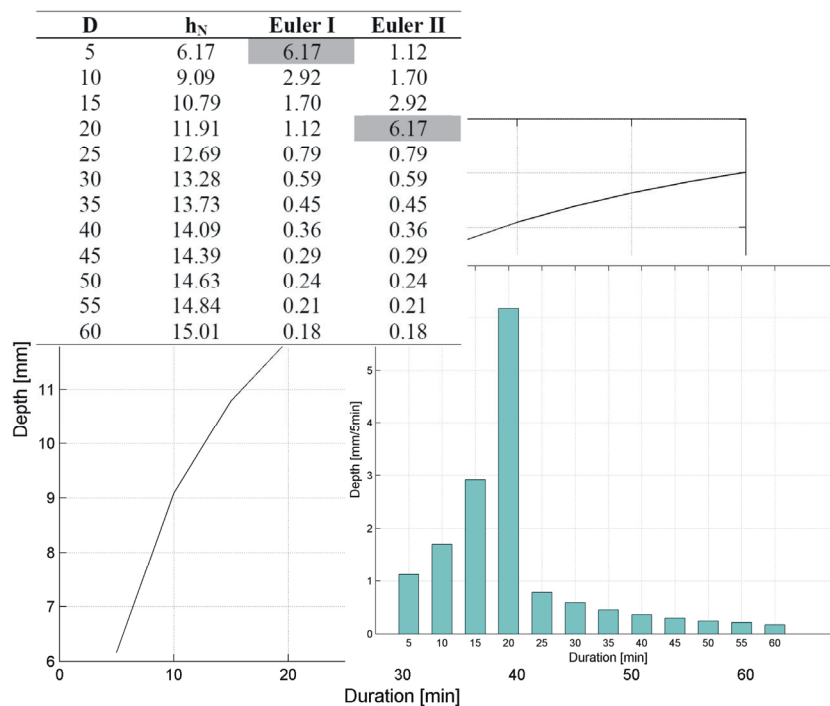
Figure 4-7. Explanation of the procedure to calculate the synthetic design storm Euler type II. D is the duration and h_N is the rain depth of a synthetic rain.

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4.1.3.6. Single events

Historical single rain events are chosen from the rain series because of their particular characteristics. The simulation of single events only is used to understand the behaviour of the system. Depending on the reaction investigated, events with different characteristics can be chosen.

4.1.4. *Runoff generation*

Not the whole rainfall contributes to the stormwater flow in the sewer system. A part, also called initial losses, is intercepted from vegetation and depression storage and contributes to the wetting process. Another part, the continuous losses, is the result of many effects like infiltration, evapo-transpiration, wind drift etc. The infiltration is flowing of stormwater through the ground surface, which happens only in pervious areas and until the soil is saturated. After saturation such areas also contribute to the runoff. The evapo-transpiration is the vaporisation of water from plants and surface waters. The runoff is the part of rainfall, which generates the flow in the sewer system, also called effective rainfall. The following picture presents a frequently applied runoff generation model.
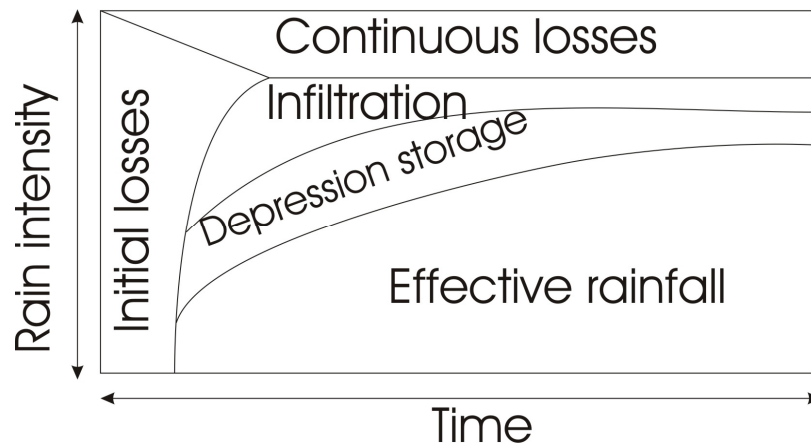
Figure 4-8. Qualitative representation of the runoff generation (Rauch *et al.*, 2002b)

4.1.5. *Surface routing*

In the modelling of surface routing, the runoff has to be transformed to obtain the surface runoff, also called overland flow. Using a transfer function, the effective rainfall hyetograph (rain intensity against time) can be transformed into a hydrograph (flow against time).
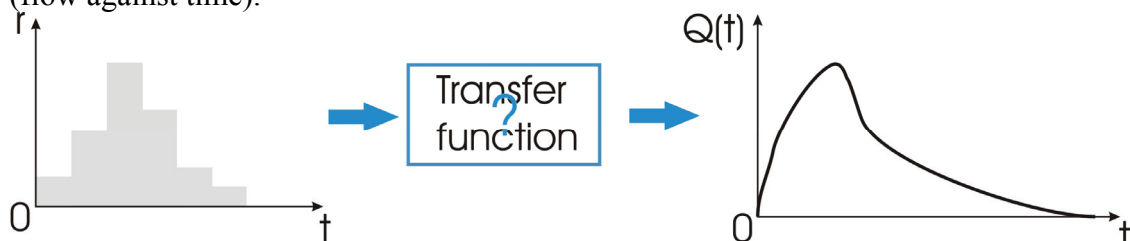
Figure 4-9. Surface routing generation, redrawn from (Rauch *et al.*, 2002b)

4.1.5.1. Transfer function

The transfer function that is widely used in linear flow models is the unit hydrograph. The unit hydrograph $g(\tau)$ describes which surface runoff is generated from 1 mm

effective rainfall, fallen in the interval Δt. In the following chapters models are presented, which describe the transfer function based on physical concepts.

4.1.5.2. Unit Hydrographs

The unit hydrograph is a widely used concept in hydrology that is applied in urban hydrology too. This is a "black-box method" for the determination of the transfer function (Rauch *et al.*, 2002b). It bases on the assumption that a unique time invariant hydrograph results from the effective rain fallen on a catchment. It represents the outflow hydrograph resulting from a unit depth (generally 1mm) of effective rain fallen uniformly and constantly in time for a unit duration.
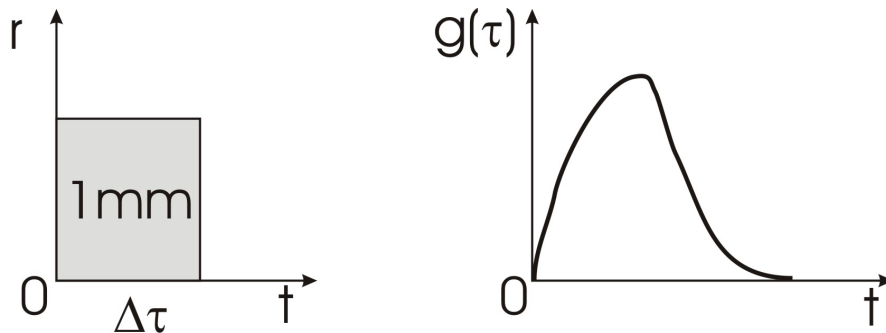
Figure 4-10. Example of unit hydrograph

The construction of the unit hydrograph is based on three principles:
- ➢ **Time invariance:** the time base of the unit hydrograph is constant, independent of the intensity of the rain
- ➢ **Proportionality:** the ordinates of the runoff hydrograph are directly proportional to the volume of the effective rain – e.g. doubling the rainfall intensity doubles the runoff flow rates
- ➢ **Superposition:** the response to successive blocks of effective rainfall is obtained by adding the individual runoff hydrograph starting at the corresponding time.

This linear approach (known as 'convolution') can be summarised in the following equation. If a rainfall event has k blocks of rainfall, of duration Δt, the runoff Q(t) at the time t is:

$$Q(t) = \sum_{i=1}^{k} (r(\Delta t_i) \cdot \Delta t \cdot g(t_{(k-i+1)}))$$

where
Q(t)	surface routing	[L³ T⁻¹]
r	block rainfall	[L T⁻¹]
Δt	Duration of the block rainfall	[T]
g(t)	Unit hydrograph	[L³ T⁻¹ L⁻¹]

4.1.5.3. Reservoir model

This approach bases on the analogy that the catchment surface acts by an effective rain like one or more reservoirs connected in series. Each reservoir receives from the one side the effective rain, multiplied by the catchment area, as input (or the outflow of the precedent reservoir) and has the flow as output.
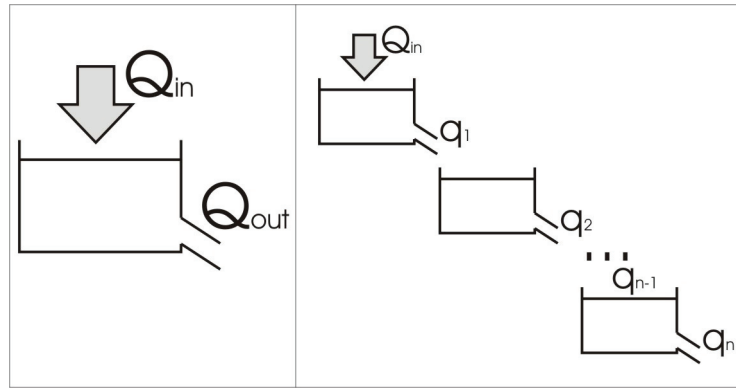
Figure 4-11. Schematic representation of the reservoir model (left) and the reservoir cascade (right)

The model is based on two equations: the continuity and the storage.

$$\frac{dV_r}{dt} = Q_{in} - Q = r_{eff}(t) \cdot A_{imp} - Q$$

$$Q(t) = \frac{1}{K_r} V_r(t)$$

from the substitution of the first formula in the second the following equation can be obtained

$$\frac{dQ}{dt} = \frac{1}{K_r}(r_{eff} \cdot A_{imp} - Q)$$

where

V_r	Reservoir volume	$[L^3]$
Q_{in}	Inflow rate	$[L^3\,T^{-1}]$
Q	Outflow rate	$[L^3\,T^{-1}]$
A_{imp}	Impervious area	$[L^2]$
r_{eff}	Effective rainfall intensity during Δt	$[L\,T^{-1}]$
Δt	Duration of the block rainfall	$[T]$
K_r	Reservoir time constant	$[T]$

The analytical solution of the transfer function for the reservoir is given in two parts: during the rainfall ($\tau \leq \Delta t$) and at the end of the rainfall ($\tau > \Delta t$).

$$g_1(\tau \leq \Delta t) = A_{imp} \cdot \left(1 - e^{-\frac{\tau}{K_r}}\right) \text{ and}$$

$$g_2(\tau > \Delta t) = A_{imp} \cdot \left(1 - e^{-\frac{t_N}{K_r}}\right) \cdot e^{-\frac{(\tau - \Delta t)}{Kr}}$$

With this two equations the behaviour of the linear reservoir can be obtained from

$$Q_1(t \leq \Delta t) = r_{eff} \cdot \Delta t \cdot g_1 \text{ and}$$
$$Q_2(t > \Delta t) = r_{eff} \cdot \Delta t \cdot g_2$$

The function $Q(g_1,g_2)$ gives for "1mm block rain" a kind of standard flow function (figure 3-12)
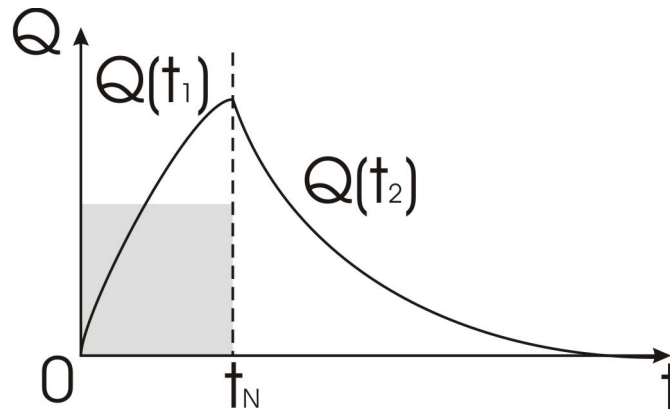
Figure 4-12. Standard flow function for 1mm block rain

The reservoir cascade (also called Nash method, see figure 3-11 right) is a sequence of reservoirs in series, therefore the formula can be expressed as follows:

$$\frac{dq_n}{dt} = \frac{1}{K_{r,n}} \cdot (q_{n-1} - q_n)$$ for the n reservoir.

Compared to the one-reservoir method this has one additional parameter for the calibration (the reservoirs number, n), which enables better results.

$$q_n(t) = \frac{1}{K_r \cdot (n-1)!} \cdot \left(\frac{t}{K_r}\right)^{n-1} e^{-\frac{t}{K_r}}$$

4.1.5.4. Time-area method

This is a special case of a unit hydrograph. The catchment should be subdivided drawing isochrones, which are lines of equal flow time. The maximum travel time represents the time of concentration of the catchment. The time area diagram is drawn by summing the areas between the isochrones and defines the response of the catchment. The time area method uses the time area diagram to produce a flow hydrograph (Butler and Davies, 2000).

$$Q(\Delta t) = \sum_{i=1}^{k} r(\Delta t_i) \cdot \frac{A_{(k-i+1)}}{A_{tot}} \cdot A_{tot} \quad \text{with} \quad g(t) = \frac{A_{(k-i+1)}}{A_{tot}}$$
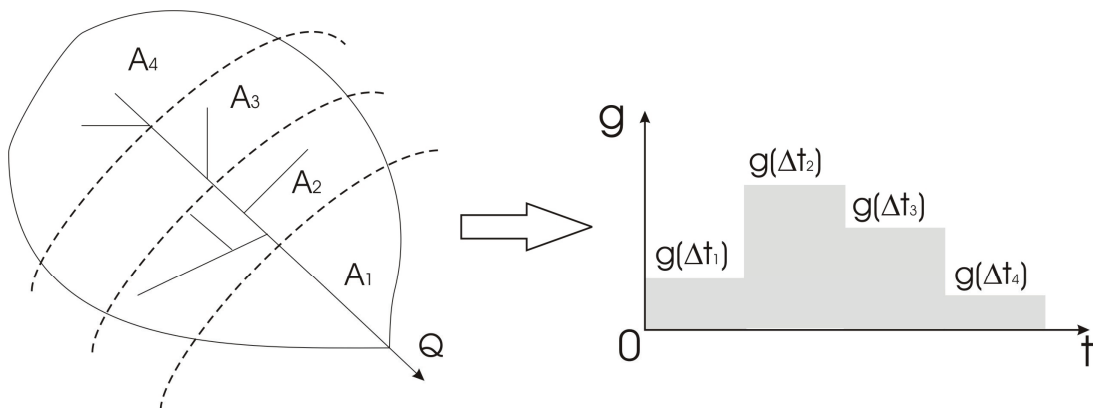
Figure 4-13. Transfer function for the time-area method, redrawn from (Rauch *et al.*, 2002b)

The area, which causes the runoff, grows during the rain event. This shows which areas (A_i) contributes to the runoff after the time interval Δt.

For a composed of 3 blocks (t_1, t_2, t_3) the discretisation is given from:

$$Q(t_1) = r(\Delta t_1) \cdot \frac{A_1}{A_{tot}}$$

$$Q(t_2) = r(\Delta t_2) \cdot \frac{A_1}{A_{tot}} + r(\Delta t_1) \cdot \frac{A_2}{A_{tot}}$$

$$Q(t_3) = r(\Delta t_3) \cdot \frac{A_1}{A_{tot}} + r(\Delta t_2) \cdot \frac{A_2}{A_{tot}} + r(\Delta t_1) \cdot \frac{A_3}{A_{tot}}$$

$$Q(t_4) = r(\Delta t_3) \cdot \frac{A_2}{A_{tot}} + r(\Delta t_2) \cdot \frac{A_3}{A_{tot}} + r(\Delta t_1) \cdot \frac{A_4}{A_{tot}}$$

...

From this formulas can be seen that at the beginning only the area A_1 (see figure 4-13) contributes to the runoff, after the end of the rain (t_4) the area nearest to the catchment outlet does not contribute more, only the more distant are still contributing (A_2-A_4)

4.2. Sewer system description

In this chapter background information is presented on the hydraulics and the processes in the sewer system. The flow in the sewer system is a mix of water, dissolved substances and gases. Depending on the position, the characteristics of the urban area (industry, land, residential area) and on the rain conditions, the composition of the wastewater and the processes in the system can vary. The key sources for the information reported in this chapter are the books (Butler and Davies, 2000; Rauch *et al.*, 2002b).

4.2.1. Processes in the sewer

The sewer systems are highly dynamic systems. There are numerous processes taking place in their inside. The inside of the sewer can be theoretically subdivided in four parts: The wastewater, the sediment, the gas and the biofilm.

The **wastewater** is composed of dissolved and suspended solids, which are transported to the wastewater treatment plant. The **sediments** are part of the suspended solids that are not transported with the wastewater, because the shear stress is not enough. They present organic and not organic parts, which vary in composition and amount depending on the specific catchment and the position inside the catchment (e.g. slope changes). The sediments in suspension are affected by the flow regime. At low flow they may deposit on the sewer bed, at high flow they can be re-eroded. The **gases** in dry weather conditions are occupying the main volume in the sewer. They are a mixture of air from the outside and gases (often toxic) produced from the biological processes in the sewer. The bio-film is a thin layer on the internal part of the sewer composed of different micro-organisms, which deprive the flowing water of substrates and nutrients.
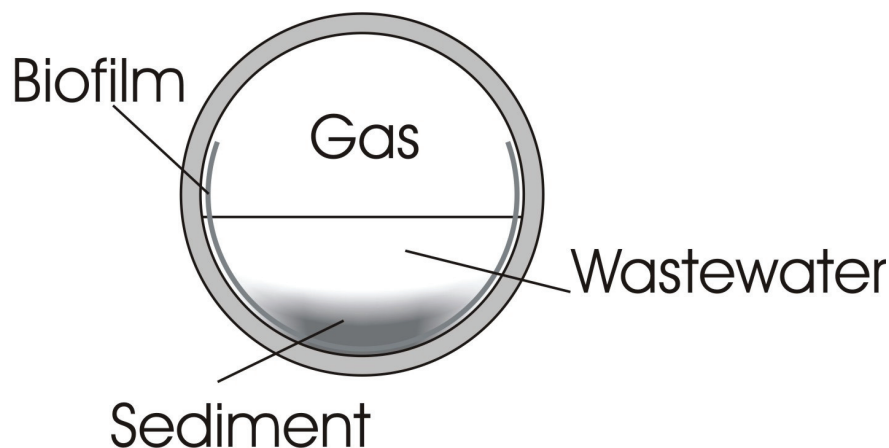
Figure 4-14. Processes in the sewer: Different parts, redrawn from (Rauch *et al.*, 2002b)

Inside the sewer, numerous transformations and interactions between the four parts listed above take place. These can be subdivided in three categories: transport processes, transformation processes and exchange processes between the parts.

The **transport processes** include the flow routing (also analysed in chapter 4.2.3), the transport of dissolved pollutants in the wastewater, the transport of suspended solids in the wastewater and the transport of gases in the airflow. The **transformation processes** may be of chemical, physical and biological nature. The organic matter is degraded and transformed in other substances. The **exchange**

processes consist of the sedimentation and re-erosion, the interaction between wastewater and gases, e.g. the re-aeration of the wastewater, between wastewater and biofilm, e.g. diffusion of ammonium from the wastewater to the biofilm.

4.2.2. Pollution sources

The pollution sources for the sewer system should be divided in the two main streams, the stormwater and the dry weather flow. In the case of combined sewer system, all pollutants are carried together in the same sewer, in the case of separate sewer system, the two streams are maintained separately. Following this consideration, this chapter is subdivided in two subchapters.

4.2.2.1. Pollutants in the stormwater

The pollutants in the stormwater are influenced by the rainfall and the catchment characteristics. Typical catchment sources are vehicle emissions, abrasion of tyres and breaks, animal faeces, street litter, de-icers (from the winter maintenance), fallen leaves, grass residues, and atmospheric pollutant wash-off, deposited on the streets. Further, a part of pollutant comes from the atmospheric wash-off, and enters the sewers directly with the rainfall. Main pollutants in the stormwater are heavy metals, but also organic matter can be found due to the street wash off.

Examples of concentrations assumed from stormwater and wastewater are contained in the German "ATV DVWK Datenpool 2001", described in (Fuchs et al., 2004) and reported here in table 4-2 and 4-3. Worldwide concentration data for different pollutants are here reported. The maximum values demonstrate high BOD, P and N, together with the expected heavy metals concentration, which can be justified with the assumption of wrong connections. Wrong connections happen when the wastewater (in this case) is connected directly to the storm sewer, instead of the foul sewer (it can happen also vice versa, the stormwater is connected to the foul sewer). This implies that polluted wastewater is not treated at the wastewater treatment plant. The larger amount of sediments enters the sewers with the stormwater.

Table 4-2. Stormwater concentrations presented in (Fuchs et al., 2004).

	BOD_5 [mgO_2/l]	COD [mgO_2/l]	P_{tot} [mgP/l]	N_{tot} [mgN/l]	Cd [µg/l]	Pb [µg/l]	Cu [µg/l]	Zn [µg/l]
Minimum	1.8	5.7	0.027	0.65	0.3	0.2	3	1
Median	13	81	0.418	2.36	2.3	118	48	275
Maximum	162.4	551	11.58	8.82	37	2745	1800	3563

4.2.2.2. Pollutants in the dry weather flow

The wastewater is composed of the black water coming from the households and the infiltrating water from the control manholes, from the pipe joints and from leakage.

The main pollutant in the wastewater is the organic matter, which can be quantified with the parameters BOD_5, P, N. Further pathogens and micropollutants can be contained in the wastewater, but they are not considered in this work. Other pollutants are the gross solids, which are responsible for aesthetic problems caused by combined sewer overflow and can favour the clogging.

Table 4-3. Dry weather flow concentrations presented in (Fuchs et al., 2004).

	BOD_5 [mgO$_2$/l]	COD [mgO$_2$/l]	P_{tot} [mgP/l]	N_{tot} [mgN/l]	Cd [µg/l]	Pb [µg/l]	Cu [µg/l]	Zn [µg/l]
Minimum	17.1	44.8	0.1	13.9	0.8	5.0	18.0	45.0
Median	178.0	403.0	4.5	34.2	2.0	32.5	58.3	231.5
Maximum	503.0	1070.4	27.0	93.8	10.0	230.0	181.0	600.0

4.2.3. *Flow routing*

The flow routing and transport of dissolved substances can be described with conceptual or physical models.
In the conceptual models, the physical laws are expressed by highly simplified concepts, e.g. the physics of sewer flow are represented from a simple tank system. The advantage is, that the phenomena are easier to describe. The solution of the equations, which are ordinary differential equations, needs short computing time.

Physical models are based on physical formulation in order to describe the processes. The calculation of flow routing is based on mass and energy conservation. In this case, simplifications of the problems are always necessary.

4.2.3.1. Hydrologic routing methods

The hydrological models for the description of the flow are the same as the ones presented in chapter 3.1.4. (e.g. reservoir model, reservoir cascade, time area method). The flow routing in the sewers is described by hydrological models.
An often used model is the **linear reservoir** (see also chapter 3.1.3.5)

A widely used method for the calculation of flow routing is also the **Muskingum-**Method. In this case, the calculation considers the translation phenomena too.

$$V = K \cdot \left[X \cdot Q_{in} + (1 - X) \cdot Q_{out} \right]$$

K is again the reservoir time constant. X is assuming values between 0 (dominated from the wave formation, linear reservoir) and 0.5 (translation dominated).

Further, the sewer system can be imagined as a sequence of linear reservoirs: i.e. the **reservoir cascade** method. In this case, the calibration parameters are the reservoir time constant K and the number of linear reservoirs.

4.2.3.2. Physical routing models

The physical description of models is based on the conservation of mass, momentum and energy. The spatial resolution differs, as it depends on the problem investigated. In case of the investigation of the flow lines in a basin or at particular points it is necessary to consider two- or three-dimensional equations. If only the flow in the sewer system is investigated, then it is enough to use a one-dimensional approach.

The basis of the description of flow for real fluids (considering also the viscosity) are the equations of Navier-Stokes. A simplification of them, for the one-dimensional approach, is the St. Venant equations system. This system is composed of two equations: the continuity and the energy equations.

$$\frac{1}{b} \cdot \frac{\partial Q}{\partial x} + \frac{\partial h}{\partial t} = 0 \text{ continuity equation}$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + g \cdot A \cdot \frac{\partial h}{\partial x} + g \cdot A \cdot (I_E - I_s) = 0 \text{ energy equation}$$

Unknown in this equation are Q(x,t) and A(x,t), with I_S being the bed slope and I_f the friction slope (i.e. slope of the energy line). Depending on the accuracy needed, the St. Venant equations can be simplified (Rauch *et al.*, 2002b).

<u>Steady solutions</u>
a. <u>Uniform flow</u>
It is the easiest form of the St. Venant equations. In this case the flow is constant over time and over the longitudinal direction, the derivate results also like 0. The equations are
0 = 0 continuity equation
g · (I_E - I_s) = 0 energy equation

From this equation, the steady uniform flow equation is derived.
I_E = I_s **steady uniform flow equation**
In this case, the soil, the water level and the energy line are parallel. The flow is not accelerated.

b. <u>Not uniform steady flow</u>
The not uniform flow is accelerated, which means that the flow velocity and water depth change along the flow direction $\left(\frac{\partial v}{\partial x} \neq 0; \frac{\partial h}{\partial x} \neq 0\right)$.

In this case, the derivates in the flow direction are not 0.
$$\frac{\partial v}{\partial x} = -\frac{v}{h} \cdot \frac{\partial h}{\partial x} \text{ continuity equation}$$
$$v \cdot \frac{\partial v}{\partial x} + g \cdot \frac{\partial h}{\partial x} + g \cdot (I_E - I_s) = 0 \text{ energy equation}$$
For a channel with rectangular section, the Froud's number results from
$$Fr = \frac{v}{\sqrt{g \cdot h}}$$
$$\frac{\partial h}{\partial x} = \frac{I_E - I_s}{1 - Fr^2} \text{ \textbf{steady not uniform flow equation}}$$

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Unsteady solutions

The unsteady solutions consider that the flow is not constant in time, which means that the water level at a defined point changes in time $\left(\dfrac{\partial h}{\partial t} \neq 0\right)$, forming also a wave.

a. cinematic wave

In the case of cinematic wave, it is supposed that the acceleration and the pressure are so small, that they can be omitted. Due to this assumption, this method is suitable only if the water depth and the velocity do not exhibit a gradient.

$$v \cdot \frac{\partial h}{\partial x} + h \cdot \frac{\partial v}{\partial x} + \frac{\partial h}{\partial t} = 0 \quad \text{continuity equation}$$

$$g \cdot (I_E - I_s) = 0 \quad \text{energy equation}$$

For a wide rectangular channel (b>>h)

$$\frac{\partial h}{\partial t} + c \cdot \frac{\partial h}{\partial x} = 0 \quad \textbf{kinematic wave equation}$$

The term c (celerity) describes the velocity of the wave in the channel

$$c = v + h \cdot \frac{\partial v}{\partial h} \quad \text{which gives for a wide channel c = 5/3 v}$$

The flow equation is the same as in the case of stationary flow. The wave moves faster than the water and the transported substances.

b. diffusive wave

In the diffusive wave approximation the pressure term $\left(g \cdot \dfrac{\partial h}{\partial x} \neq 0\right)$ of the energy equation is considered too. This term implies the attenuation of the wave due to the pressure gradient.

$$v \cdot \frac{\partial h}{\partial x} + h \cdot \frac{\partial v}{\partial x} + \frac{\partial h}{\partial t} = 0 \quad \text{continuity equation}$$

$$\frac{\partial h}{\partial x} = I_E - I_s \quad \text{energy equation}$$

from which the diffusive wave equation can be obtained

$$\frac{\partial h}{\partial t} + c \cdot \frac{\partial h}{\partial x} + D \cdot \frac{\partial^2 h}{\partial^2 x} = 0 \quad \textbf{diffusive wave equation}$$

c. dynamic wave

The dynamic wave solution considers all terms of the St. Venant equation system. The solution of this system is possible using numerical methods.

$$\frac{\partial Q}{\partial x} + B \cdot \frac{\partial h}{\partial t} = 0 \quad \text{continuity equation}$$

$$\frac{\partial v}{\partial t} + v \frac{\partial v}{\partial x} + g \cdot \frac{\partial h}{\partial x} + g \cdot (I_E - I_s) = 0 \quad \text{energy equation}$$

Table 4-4. Limitation by describing the different hydraulic conditions by the presented unsteady solutions (Rauch *et al.*, 2002b)

Hydraulic condition	Cinematic wave	Diffusion wave	Dynamic wave
Wave translation	Yes	Yes	Yes
Wave attenuation	No	Yes	Yes
Backwater	No	Yes	Yes
Flow acceleration	No	No	Yes

4.2.4. Quality models

The aim of the quality models is to simulate the variation of concentration and pollutant with time at chosen points in a sewer system. The mechanisms driving the pollutant transport are heavily dependent on hydraulic conditions, this implies that the main deterministic quality models are based on flow models.

A significant source of pollution is the first foul flush, which is the wave descending the sewer system after a dry weather period. The pollutant deposited on the sewer bottom and part of the sediment is flushed to the lower system or to the wastewater treatment plant. This phenomenon varies depending on many factors and it was not always detected.

4.2.4.1. Modelling pollutant transport

Physical advections-dispersion model
The transport of dissolved pollutant in a moving fluid can be described with advection and diffusion/dispersion consideration.
The **advection** describes the translation of a pollutant with the flow velocity v. The one dimensional flow equation is given from the following formula.

$$J_{adv} = A \cdot v \cdot C = Q \cdot C$$

where

J_{adv}	Advective pollutant flux	$[MT^{-1}]$
A	Flow section	$[L^2]$
v	Flow velocity	$[LT^{-1}]$
C	Polllutant concentration	$[ML^{-3}]$
Q	Flow rate	$[L^3T^{-1}]$

The temporal changes in concentration are given from

$$\frac{dC}{dt} = D_x \cdot \frac{\partial^2 C}{\partial x^2}$$

where D_x is the longitudinal dispersion coefficient $[L^2T^{-1}]$ and x the distance [L].
The full advection-dispersion is given from

$$\frac{\partial C}{\partial t} + v \frac{\partial C}{\partial x} = \frac{\partial}{\partial x} \left[D_x \cdot \frac{\partial C}{\partial x} \right] \text{ one dimensional transport equation}$$

Conceptual transport models

In analogy with flow routing methods, conceptual models can be used also for the pollutant transport. Here three of the most common are reported.

a. Completely mixed tank

This approach considers each pipe length as a conceptual tank in which the pollutant are fully mixed with the flow. The equation describing this model is:

$$\frac{d(V \cdot C)}{dt} = Q_{out} \cdot C_{out} - Q_{in} \cdot C + V \cdot r$$

where:

C	Pollutant concentration in the tank	[M L^{-3}]
C$_{out}$	Pollutant concentration in the outflow	[M L^{-3}]
Q$_{out}$	Flow at the outlet pipe	[L^3 T^{-1}]
Q$_{in}$	Flow at the inlet pipe	[L^3 T^{-1}]
V	Volume of liquid in the pipe length	[L^3]
r	Reaction velocity of the pollutant	[M L^{-3} T^{-1}]

b. Ideal reactors

The transport processes in the sewer can be described from the plug flow reactor. The plug flow reactor considers no longitudinal mixing, contrarly than in the previous present model. As internal process in longitudinal direction advection is assumed.

The advective transport can be described from the plug flow reactor, the advective-dispersive transport can be described from the plug flow reactor with turbulence.

Plug flow reactor

$$\frac{\partial C}{\partial t} + v \frac{\partial C}{\partial x} = 0$$

Plug flow reactor with dispersion

$$\frac{\partial C}{\partial t} + v \frac{\partial C}{\partial x} = D_{turb} \cdot \frac{\partial^2 C}{\partial x^2}$$

The plug flow reactor with turbulence gives the same transport equation like in the physical case. In this case the flow section A is constant, i.e. this model is suitable only for constant flows (Rauch *et al.*, 2002b).

4.3.   Indicators related to the sewer system design

4.3.1.   *Introduction*

Indicators are parameters, which are used to describe relevant properties of the system. The introduction of the Water Framework Directive and more specific of the combined approach set the need for new indicators to evaluate the performance of the sewer system. In this case it is not more enough to consider only the classic indicators for the urban drainage, it is necessary to consider also parameters, which describe the impact of the urban drainage activities on the receiving waters. To quantify such impacts, there are numerous systems, which use e.g. as indicators macrozoobenthos (Hering *et al.*, 2002) or fishes (Noble and Cowx, 2002), however it is difficult to implement such systems in a model. It is also necessary to find impact descriptors easy to model. Such indicators were defined in our working group and tested in the **Paper VI** of the annex.

Performance indicators are used in many countries inside the different evaluating systems for benchmark analysis. One example is the Scandinavian six cities group in which six water authorities, from the cities of Copenhagen, Oslo, Helsinki, Stockholm, Gothenburg and Malmo, worked together to identify and use performance indicators in order to facilitate comparison between the cities and allow a benchmark analysis. The group has developed performance indicators within the following areas: Customer Satisfaction, Quality, Availability, Environment, Organisation/Personnel and Economy (Helland and Adamsson, 1998).Other examples are in (Ashley and Hopkinson, 2002; Balkema *et al.*, 2002; Stone *et al.*, 2000). Furthermore the performance indicators can be used as basis for Decision Support Systems (DSS), like e.g. in the European projects Daywater (Revitt *et al.*, 2004), APUSS (APUSS 9.1, 2003), CARE-S (Matos *et al.*, 2003), the Italian MOMA FD (Artina *et al.*, 2005), the French-Brazilian AvDren (Baptista *et al.*, 2005) and other more.

Generally, a performance indicator may be used as a qualitative index for the evaluation of the efficiency of a company or of technical systems. Based on a literature review of legal requirements (chapter 2) and existing performance indicators, an adapted set of indicators was defined to evaluate the performance of the sewer system. These indicators are described in the following chapter. The ability of such indicators to describe the behaviour of the urban drainage system is analysed on the basis of simulations. These analyses are presented in the papers of the annex.

These indicators are the tools for the assessment of the sewer system performance, which is the aim of this thesis.

Most of the indicators developed and analysed here are specific for the combined sewer system, which is the most common in the central Europe and which can cause, through the CSO, the highest impacts on the receiving waters. The receiving waters considered in this thesis are always rivers, which is the most common configuration in Europe. The indicators used in this PhD work are different depending on the problems analysed and are used for a technical assessment of the sewer system. These are here subdivided in three main groups: sewer system performance indicators, receiving water impact indicators and rain characteristics indicators.
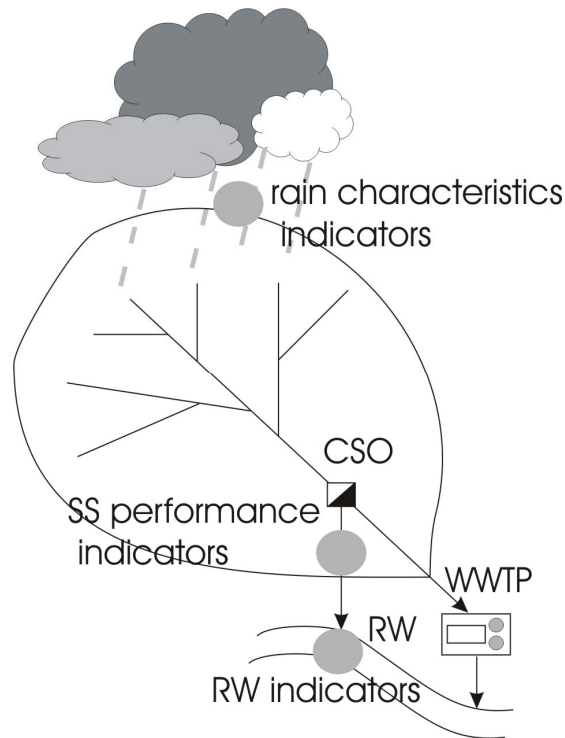
Figure 4-15. Representation of the three indicators groups used in this dissertation

Most of the indicators here presented have been used already previously in different contexts, e.g. in (Balkema *et al.*, 2002; Lau *et al.*, 2002; Matos *et al.*, 2003).

4.3.2. Sewer system performance indicators

4.3.2.1. CSO efficiency

The CSO efficiency (η) is the percentage of rain runoff treated at the treatment plant, according to the definition of the Austrian guideline (ÖWAV-Regelblatt 19, Draft 11.2005) like explained in the following formula:

$$\eta = \left(1 - \frac{VQO}{VQR} \right) \cdot 100 \quad [\%]$$

VQO represents the overflow volume of the catchment to the receiving water [mm/a]. VQR is the rain runoff, the rain minus the losses in [mm/a].

4.3.2.2. Mean annual overflow volume

The mean annual overflow volume (**VQO**) is defined as total overflowed volume per year

$$VQO = \frac{\sum VQO_i}{n} \quad [\text{mm/a}]$$

4.3.2.3. Maximum overflow discharge

The Maximum overflow discharge (**Qmax**) is the value achieved from the CSO discharge with a return period of one per year. The return period is calculated using the plotting position formula (see chapter 4.1).

4.3.2.4. Number of overflow events

The number of overflow events (**NO**) is calculated considering two events distinct if they are separated from a period, in which no overflows occur, of at least one hour.

4.3.3. *Receiving water impact indicators*

To assure a WFD conform evaluation of the sewer system impacts on the receiving waters five main impacts were identified (**Paper VI**): hydraulic impacts, oxygen depletion, eutrophication, acute toxic effects and accumulation persistent substances, see also table 4-5. For each impact one indicator was defined to allow the quantification of the effects on the receiving waters. Morphological impacts are considered by the indicator erosion frequency, acute toxic impacts by means of the un-ionised ammonia concentration, accumulating impacts by the copper load, impacts on the oxygen abundance by the oxygen deficit and eutrophication by the nitrogen load.

4.3.3.1. Erosion frequency

The erosion frequency is calculated as the number of overflow events higher than the critical discharge, calculated here for a small river with a mean low water flow Q = 2m³/s (Q_{crit_c} 3.05 m³/s). This definition bases on the comparison of the actual bottom shear stress in the river with the critical one, which is the cause of drift of the bed soil. The actual shear stress is calculated according to the Meyer-Peter formula

$$\tau_R = g \cdot \rho \cdot R_h \cdot I \left(\frac{k \cdot d_{90}^{1/6}}{26} \right)^{3/2}$$

Where:

τ_R	actual bottom shear stress	[N/m²]
g	acceleration of gravity	[m/s²]
ρ	density of the water, here given as 1000	[kg/m³]
R_h	hydraulic radius of the river stretch	[m]
I	bed slope	[-]
k	Strickler coefficient of side friction	[m$^{1/3}$/s]
d_{90}	diameter of particle such that 90% of sample is finer	[m]

The critical bottom shear stress is given from:

$$\tau_{cr} = 0.047 \cdot g \cdot (\rho_s - \rho) \cdot d_m$$

Where:

τ_{cr}	critical bottom shear stress	[N/m²]
g	acceleration of gravity	[m/s²]
ρ	density of the water, here given as 1000	[kg/m³]
ρ_s	density of the bed material, here given as 2650	[kg/m³]
d_m	mean diameter of particles	[m]

This approach is based on Swiss guidelines (Rauch *et al.*, 2002a) and applied also in various investigations (Engelhard *et al.*, 2006; Lek and Rauch, 2006).

4.3.3.2. Discharged pollutant load

The total loads are calculated as the annual mean value of all simulation years (n).

$$N_{load} = \frac{\sum N_{load\,i}}{n} \text{ [t/a] and } Cu_{load} = \frac{\sum Cu_{load\,i}}{n} \text{ [kg/a]}$$

The elements chosen for the calculation of the loads discharge are nitrogen and copper. The first one represents the discharge of eutrophicating substances to the receiving water, the second of accumulating substances, which are not significantly impacted from biological interactions.

4.3.3.3. Critical oxygen deficit

The oxygen deficit is calculated using the oxygen-sag equation, developed from Streeter and Phelps in the year 1925, which is still used to model the natural self purification capacity of streams.

$$D(t) = D_o \cdot e^{(-k_2 \cdot t)} + \frac{k_1 \cdot c_G}{k_2 - k_1} \cdot \left[e^{(-k_1 \cdot t)} - e^{(-k_2 \cdot t)} \right] \qquad \text{[mg/l]}$$

Where:
Do   Initial oxygen deficit, here $D_o = 0$ mg/l   [mg/l]
k_1 is the degradation rate   [1/h]
k_2 reaeration rate given from the following formula   [1/h]
c_G BOD concentration that is achieved for 1 hour per year continuously   [mg/l]
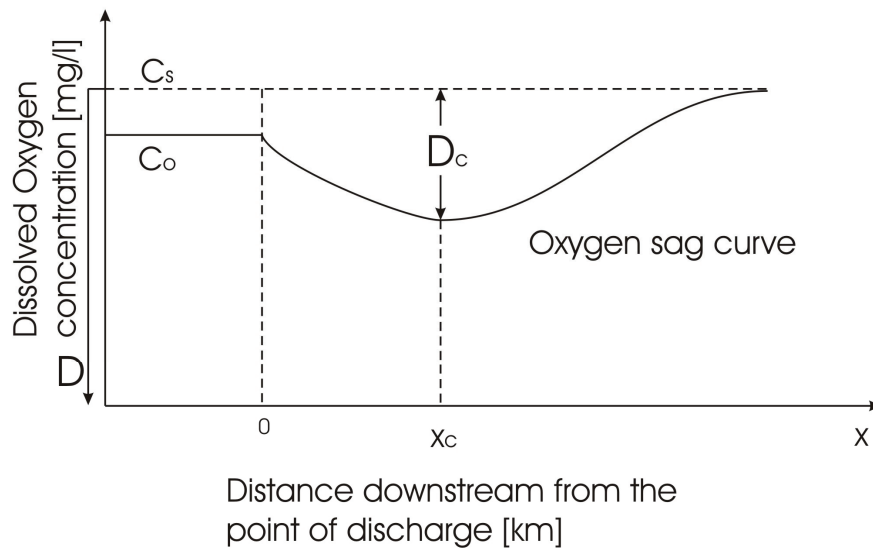
Figure 4-16. Oxygen sag curve obtained using the Streeter-Phelps equation. Cs and Co are the concentrations respectively at saturation and initial, D is the oxygen deficit which is inverse proportional with the oxygen concentration, Dc is the critical oxygen deficit obtained at distance x_c from the point of discharge redrawn from (Tchobanoglous and Schroeder, 1987).

The minimum of the sag curve represents the critical (maximum) oxygen deficit.

$$Dc = \frac{k_1}{k_2} \cdot c_G \cdot e^{(-k_1 \cdot t_c)} \quad \text{[mg/l]}$$

According to the implementation presented in (BWK, 2001) the parameter k_2 can be calculated as

$$k_2 = \frac{\left[\left(3 + \frac{40}{k_{st}} \right) \cdot \frac{v_m}{h_m} + 0.5 \right]}{h_m \cdot 24} \quad \text{[1/h]}$$

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k_{st} Manning-Strickler coefficient $[m^{1/3}/s]$
h_m mean water level calculated at MNQ (mean low water flow)   [m]
v_m mean velocity calculated at MNQ   [m/s]

Where h_m is calculated using the Manning Strickler formula.

$$v = k_{st} \cdot \sqrt{I} \cdot R_h^{2/3} \quad [m/s]$$

and the critical flow time results

$$t_c = \frac{1}{k_2 - k_1} \cdot \ln\left\{ \frac{k2}{k1}\left[1 - \frac{Do(k_2 - k_1)}{k_1 \cdot c_G} \right] \right\} \quad [h]$$

To make the calculation independent from the river size the mean low water flow in the river and the BOD concentration are assumed to be the one of the overflow water. This assumption - that essentially neglects the river base flow – is a further simplification of the Streeter-Phelps formula but makes the equation independent from the river size and thus the results more comparable.

The value Dc calculated considering the mean low water flow (MNQ in German literature) in the river and the c_G from the overflow give information on the habitat conditions of the organisms. The minimal oxygen concentration in the water body c_{min} is given from the formula:
$c_{min} = c_{saturation} - Dc \quad [mg/l]$
where for $c_{saturation}$ can be used 9.1 mg/l at 20°C.

If c_{min} is less than 5 mg/l the aquatic life can be hampered.

4.3.3.4. Ammonia indicator

The ammonia indicator is the highest load of ammonia discharged during one hour per year via the CSO to the receiving water. The load for one hour is expressed in kg.

$$NH_4 - N = max \sum^{1\,hour} NH_4 - N \quad [kg\ NH_4\text{-}N/a]$$

The list of indicators used for the description of the impacts caused on the receiving water and of the generally performance of the sewer system is reported in the following table.

Table 4-5. Summary of the used indicators with related impact types and effects.

Indicator type	Indicator name	Abbreviation	Impact type	Described effect
Sewer	CSO efficiency	η	Hydraulic/ concentration	Overall performance of sewer system
	Overflow volume	VQO	Hydraulic	morphologic impact
	Maximum overflow	Q_{max}	Hydraulic	morphologic impact + Aquatic life drifting
	Number of overflow	NO	Hydraulic	morphologic impact + Aquatic life disturbance
	Erosion Frequency	-	Hydraulic	morphologic impact
Receiving water	Nitrogen Load	N_{Load}	Load	Eutrophication
	Copper Load	Cu_{Load}	Load	Accumulation
	Ammonia concentration	NH_4-N	Acute	Toxicity for aquatic life
	Critical oxygen deficit	Dc	Acute	Oxygen depletion, i.e. life danger for aquatic life

4.3.4. *Rain characteristics indicators*

These rain characteristics indicators are used for the climate change considerations in the following chapter but also in the analysis of the best fitted rain indicators to describe sewer system behaviour.

4.3.4.1. Mean annual rain volume

The mean annual rain volume (MAR) is calculated as the sum of the rain volume divided by the number of simulation years. [mm/a]
A problem related to the use of such parameter is that often for the oldest series there are no winter months present. The number of months missing is not constant, so that a statistical analysis over the years based on this value is not reliable.

4.3.4.2. Number of events

Two events are defined independent if there is a rainless period of one hour between and if the total rain depth of a rain event is higher than 1 mm, which is assumed to be the part due to the initial losses. There are many approaches to define the single rain events, this one was chosen for the calculations in this work. The number of events (NE) is calculated counting each event and choosing the mean value over the years.

4.3.4.3. Maximum event

The maximum event (ME) is calculated as the sum of the rain volume of one single event which has return period once per year. [mm]

4.3.4.4. Statistical rain intensity

The statistical rain intensity is the intensity calculated for different durations (here 15 minutes, 1, 2 and 12 hours) with different return period (here once per year) calculated according to the procedure reported in chapter 4.1.3.3. The choice of the duration 15 minutes is connected to the consideration that this duration is important for the sewer design in German speaking countries, see IDF curves (chapter 4.1). The rain intensities for 1 and 2 hours are also influencing directly the flow in the sewers. The longer rain intensity, 12 hours, is relevant for the emptying of the retention basins.

4.4. Calculation of indicators

The indicators are calculated by means of simulation of the sewer system, using hydrological models, and elaboration of the simulation results using special tailored Matlab programs.

4.4.1. *Programs used*

The programs used are Karen (Rauch, 2005) and City Drain (Achleitner *et al.*, 2006). Both use similar models for the runoff generation and for the transport, but the first one (in the used first version) has limited configuration possibilities, the second one, which is on Matlab-Simulink basis, gives the possibility to represent numerous different configurations. Each part of the system is a block that can be combined with many others. The calculation is based on fixed discrete time steps where each subsystem uses the same time increments, generally identical to the rain data time step. The number of pollutants transported can be defined depending on the necessity. The catchment model implemented is based on a loss model followed by flow routing using the time area method. The loss model considers initial losses and permanent losses. The first are simulated with simple storage basin methodology: when the rain volume exceeds the basin volume, runoff is generated. Permanent losses are effective only during dry periods; they are responsible for the "emptying" of the theoretical basin volume. The time area method uses a stepwise translation of runoff towards the catchments outlet. The whole area is subdivided in sub areas equally distributed. The dry weather flow and the rain input are mixed together at the catchment outlet. The model for CSO is based on mass balance.
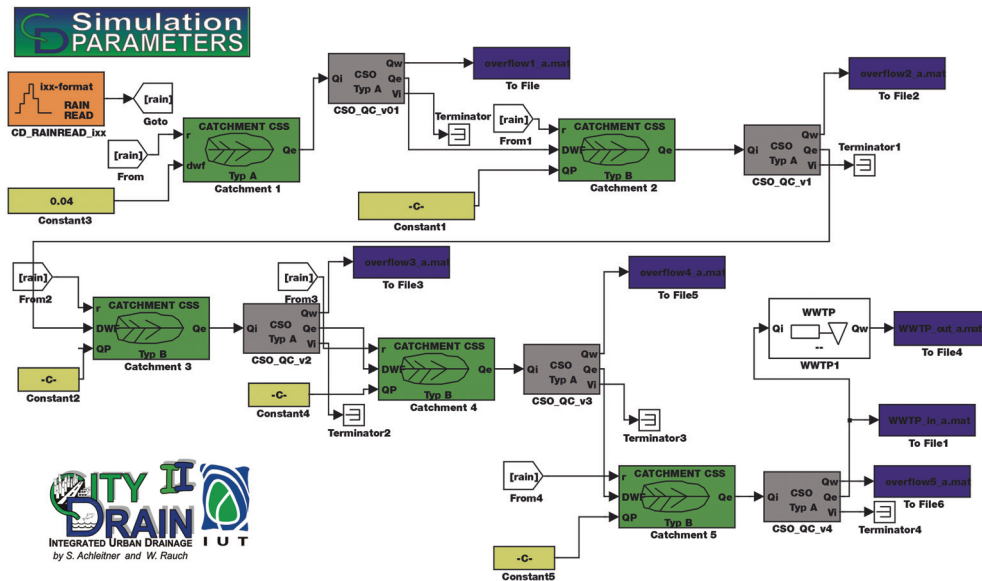
Figure 4-17. Screenshot of a complex catchment composed of five sub-catchments and drained from a combined sewer system simulated with City Drain. Configuration used for the calculation in **Paper VII**

4.4.2. *Hydrologic vs. hydrodynamic models*

The choice to use a hydrologic model instead of a hydrodynamic one is due to the necessity to run numerous long-term simulations for the indicators analysis. The first model is many times quicker than the second.

Hydrodynamic models are more complex because from the one side they represent the sewer system closer to the reality (e.g. detailed representation of pipes, manholes etc.); from the other side the sewer system processes are described more in detail. The hydrodynamic models calculate hydraulic by solving the Saint Venant differential equations. The hydrologic models calculate the processes in the catchment and in the sewer system with algebraic equations or simplified differential equation (Rauch *et al.*, 2002b). The calculation time difference for middle size linear catchment is about 100-1000 times (De Toffol *et al.*, 2006).
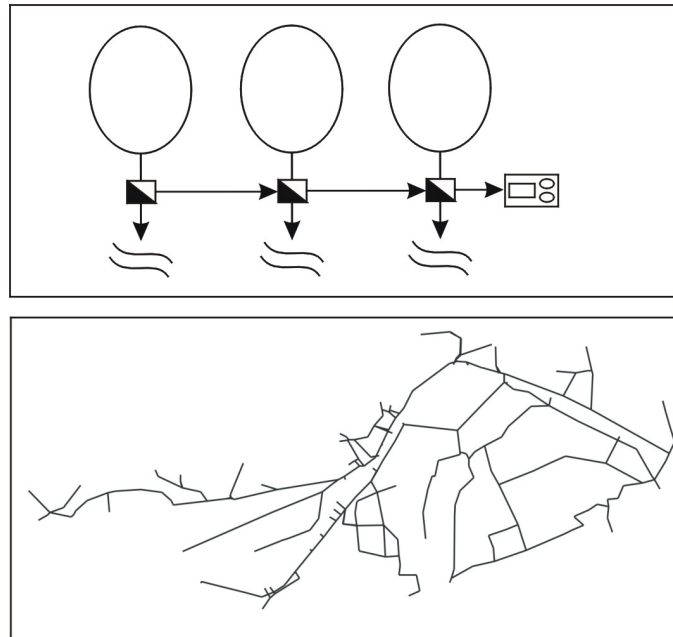
Figure 4-18. Difference in the representation between hydrologic (up) and hydrodynamic models (down)

The picture represents a real catchment simplified for the calculation, with the two different kinds of models. It is clear that whilst in the hydrodynamic model at least the main sewers are detectable, in the other one the real catchment is subdivided only in sub-catchments in which the retention function of the sewers is represented from virtual basins.

4.4.3. Basic catchment

The larger part of the simulations is effectuated using a basic catchment of 100 ha impervious area drained from a combined sewer system with one combined sewer overflow device with specific storage capacity 1.5 mm according to (ÖWAV-Regelblatt 19, 1987), population density of 70 PE/ha dry weather flow and throttle to the waste water treatment plant, calculated according to the Austrian guideline (ÖWAV-Regelblatt 11, 1982), of respectively 20 l/s and 80 l/s (considering 2 times the dry weather flow plus the parasite water).

4.4.4. Pollutants in the wastewater streams

The pollutants simulated in the analyses presented in this study are related to the indicators used. The parameters used are the classic pollutants, the priority substances proposed from the WFD are no considered. The concentrations assumed are based on the data of the German "ATV DVWK Datenpool 2001", described in (Fuchs et al., 2004). Here worldwide concentration data for different pollutants are reported (see also table 4-2 and 4-3). From this database the minimum, median and maximum values for concentration in dry weather flow and in stormwater are chosen for the simulation. The pollutant concentration is assumed constant over the day.

4.4.5. *Summary*

This chapter describes basic models and methods used in this PhD thesis, on which all analyses of the appended papers are based.

Simple models are applied to predict sewer system performance based on certain indicators. The necessity for simple models is due to the fact that the indicators calculations require long-term simulations, which will last much longer with more complicated models.

The defined indicators can be used as a tool for the evaluation of the sewer system performance. Due to this fact, the indicators need to be easy to calculate and based on parameters, which are easy to measure, in order to allow the applicability of the evaluation system.

5. Performance assessment - Scientific background

This chapter presents the 7 papers written in the frame of this dissertation and the citations of the scientific publications, which influenced this work.

5.1. Water Framework Directive and the urban drainage system, new indicators are needed

The European Water Framework Directive (EU-WFD) is an innovative guideline in the water policy. It introduces new objectives and planning procedures at river basin scale. The final goal of the EU-WFD is to achieve the "good status" for all water bodies. In contrast to older guidelines, this status is defined by combining ecological and chemical conditions. This implies new challenges for the sewer system modelling: the sewer cannot be seen anymore as a single entity, it is part of the whole integrated urban drainage system. Furthermore, a methodology should emerge, in order to quantify the impacts of the urban drainage on the receiving waters. This last issue is not so easily accomplished, due to the lack of a cause-effect relation between emissions from the sewer system and biota reactions.

An article published in this context is:

De Toffol, S., Achleitner S., Engelhard C., und Rauch W. (2005)
Challenges in the Implementation of the Water Framework Directive: case study of the alpine river Drau in Austria. Water Science & Technology, **52** (9), 243–250

This publication is also referred to in this dissertation as **Paper I**.

This paper presents an overview of the most important aspects of the EU-WFD. The focus is on the identification of the aspects, which influence the definition of indicators for the urban drainage system performance: the combined approach and the concept of integrated urban drainage system.

The combined approach considers simultaneously the emission from the urban drainage system and the ambient water quality of the receiving waters. This is encouraged from the EU-WFD, due to the importance of the water quality improvement. This concept is not new, but has gained importance in the last years. Many publications deal with this approach, among others (Achleitner *et al.*, 2005; Rauch *et al.*, 2002a; Rauch *et al.*, 1998a; Schilling *et al.*, 1997).

The concept of integrated urban drainage is also encouraged from the EU-WFD, due to possibilities offered for the optimisation of the system. The sewer system is not considered anymore as a single entity, it is a part of the whole urban drainage system. In the integrated approach the interaction between sewer, wastewater treatment plant, source control measures and receiving waters is also considered. This fact offers the opportunity to take advantage of the synergy effects and to achieve a better optimisation degree with less effort. This approach has also assumed increasing importance in the last years. In the following papers, examples of the implementation of the integrated approach in the urban drainage can be found (Achleitner *et al.*,

2006; Hauger *et al.*, 2002; Krejci, 1996; Lijklema *et al.*, 1993; Orth *et al.*, 2003; Rauch *et al.*, 2005; Rauch *et al.*, 1998a; Rauch *et al.*, 2003).

In **Paper I** basic concepts for the choice of the indicators are explained. Such parameters should consider the effects on the biology and the different reactions of the organisms, depending on different temporal and spatial scales. It is necessary to take into account not only the acute toxicity, but also the chronic effects and the accumulation processes. An example of a guideline considering this fact, is presented in (FWR, 1998).

Furthermore, the suitable indicators for the description of the impacts on a particular kind of river may not give enough information on the impacts in other receiving waters. Due to these differences, it is possible to define parameters suitable to assess the impact in various kinds of rivers. Examples of this approach can be found in the literature, e.g. (Borchardt and Sperling, 1997; Rauch *et al.*, 1998a; Schilling *et al.*, 1997).

Following, in **Paper I**, a methodology for defining the indicators for the water quality assessment is described. It complies with the EU-WFD, on the basis of a case study on alpine rivers. In this case study, the relevant parameters for water quality classification have been analysed. Due to a comparison between the historical development of the biological water classification and the concentration of the measured constituents, it was possible to derive indicators characteristic of alpine rivers. These parameters can thus be applied for the analysis and classification of other water bodies in the same type region. Major impacts in the alpine river resulted in hydraulic disturbance and morphological alterations. In this case, the simulation of standard parameters like oxygen depletion seems to be superfluous.

5.2. Temporal variation of rain data and indicators for its analysis

The expression, "performance of the sewer system" is often related to the evaluation of different parts of the system, like the combined sewer overflow. However, a very important issue is the choice of the suitable rain data for the simulations. The choice of inadequate data can influence negatively the results. New methods for digital rain data recording allow a more detailed calculation of the hydrological and hydraulic processes. Classical calculation methods based on design storm are used increasingly less often. The use of more detailed rain data leads to the consideration of the variability of the rain, which can be spatial and temporal. On temporal variation of the precipitation, analyses were conducted, that are reported in the following two papers:

Rauch W. and *De Toffol S.* (2006)
On the issue of trend and noise in the estimation of extreme rainfall properties.
Water Science and Technology, **54** (6-7), 17-24.

De Toffol S. and Rauch W. (2006)
Can climate change pattern be identified in urban hydrology? (submitted)

These publications are also referred to in this dissertation as **Paper II** and **Paper III** respectively.

The temporal variability has a notable influence on the statistical analysis of the rain data and consequently on the sewer system simulation's results. Depending on the presence of trend, the simulation of the last ten years can lead to totally different results compared with the previous years (see **Paper II**). Even if modern computer systems allow simulating sewer performance based on historical rain data over long periods, the possibility to derive design storms, with a certain occurrence frequency, is still an important tool in up-to-date sewer design guidelines. Thus, the issue of uncertainty in the estimation of such properties is very relevant, as the uncertainty will have a direct effect on the magnitude of the required measures (e.g. sewer dimensions).

Climatic changes and random variations can cause significant temporal variations in the precipitation. Climate models predict, under greenhouse conditions, increases in both heavy rainfall frequency and intensity, in the high latitudes of the Northern Hemisphere. These projections are consistent with recent measurements and predictions of heavy precipitation increase in different regions of the world (Arnbjerg-Nielsen, 2006a; Arnbjerg-Nielsen, 2006b; Brunetti *et al.*, 2000; Fowler *et al.*, 2005; Frei and Schär, 2001; Haylock and Nicholls, 2000; Mosmann *et al.*, 2004; New *et al.*, 2001). Often, the time resolution of these studies is on a daily scale. Based on that evidence, some authors came to the conclusion, that there is a necessity to adapt the sewer system design rules to this trend (Grum *et al.*, 2005; Pagliara *et al.*, 1998). The problem at this point, is the applicability of results, from simulations with so wide time scales, to the urban drainage.

Regarding this problem, the german national meteorological institute (Deutscher Wetterdienst, DWD) came to the conclusion, that the trend situation for rain intensities of 15 min and 60 min (which are relevant for the urban drainage) is not uniform (statistic carried out on data for the interval 1951-2000) (Bartels *et al.*, 2005). On the basis of this consideration, the DWD suggested to use the same design storms calculated in a previous study (Bartels *et al.*, 1997) with older data, ranging from 1951 to 1981. To similar conclusions came the literature review of this topic presented in (Schmitt *et al.*, 2006).

In the papers cited above, **Paper II** and **III**, indicators representative of the sewer system are analysed based on historical data with a high resolution, i.e. 5 minutes time step. The first research conducted in this frame considers the variation of a selected extreme rainfall property, i.e. the statistical intensity over 15 minutes with a return period of one year. The choice of this parameter is only due to the familiarity with its use in the guidelines of Germany, Switzerland and Austria. It has to be considered only as an example of an extreme rainfall property; the same consideration could be based also on other properties. In **Paper II**, 6 long-term rain series ranging from 19 to 55 years and with a time step of 5 minutes are investigated. The procedure used is a gliding mean method. For the succession of estimation intervals with an interval length of 10 years each, the corresponding property $r_{15,1}$ is plotted. Furthermore, considerations on the length of the rain series, that is required for the estimation of extreme rainfall properties and the associated uncertainty, are presented.

The **Paper III** presents the analysis of longer series: 8 long term rain series, with a length between 52 and 75 years and time step 5 minutes, were analysed. The trend is

also investigated using many different indicators for the rain characteristics and for the sewer system performance. The first analysis deals with the mean intensity (for the duration of 15 minutes, 1, 2 and 12 hours), the 100 highest values for each indicator were analysed. At first, the trend is investigated by means of the Mann-Kendall test, which is used in many studies for the analysis of environmental variables, e.g. (Birsan *et al.*, 2005; Brunetti *et al.*, 2000; Burn and Hag Elnur, 2002). Secondly, to prove if the extreme events are taking place more often than in the past, the highest 100 values of the rain intensity were subdivided in classes with different length. Then, it is calculated how many extreme intensities are contained in the different periods; this analysis was called "class analysis". Further, the difference between the value of the intensity calculated for the last then years was compared with the one calculated for the whole series except the last period (see lines in figure 5-1). This last investigation was undertaken together with the trend analysis, based on the Mann-Kendall test, for the selected indicators (for a gliding mean over 10 years): the statistical intensities calculated for the four durations used for the previous analysis. At the end, the results are validated, considering the last presented analyses for the following sewer system performance indicators: the maximum overflow event once per year and the CSO efficiency, calculated by means of simulation for a simple catchment and for a real one.

The following picture illustrates some results of the analyses. The dots present the result of the gliding mean analysis, while the horizontal lines present the values calculated for the total corresponding period. It should be considered that a decrease of the CSO efficiency is caused by an increasing rain intensity. The two cases presented are the simulation's results for the rain series of Innsbruck (negative trend for the efficiency) and Odense (positive trend). Here, it is clear that the presence of eventual trends is strongly case specific.
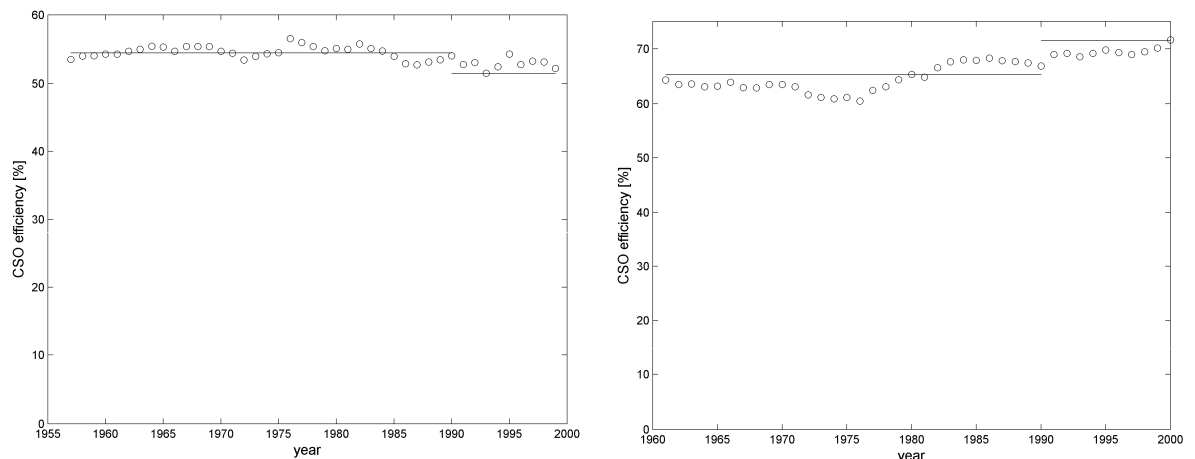
Figure 5-1. Evolvement of urban drainage performance indicators CSO efficiency (η) for two different rain series (Innsbruck, left and Odense, right). The dots represent the result of the gliding mean analysis while the horizontal lines represent the values when computed for the total corresponding period.

5.3. Spatial variation of rain data and correlation between rain characteristics and sewer system performance indicators

Furthermore, the spatial variation was considered, or more precisely, the indicators that can be used to avoid the problem related to such variation.

Regarding the issue of spatial resolution and its relevance for urban hydrology, various studies have been carried out, for example (Berne *et al.*, 2004; Mikkelsen *et al.*, 2005; Schilling, 1991). The spatial variability plays an important role in the sewer system modelling. Especially, stormy rain events can demonstrate notable differences for short distances. The rain varies strongly depending on local conditions (Einfalt *et al.*, 1998; Mikkelsen *et al.*, 1997). Many factors can influence this behaviour, the most important are micro-climatic conditions and orography (Germann and Joss, 2000). This short distance variation influences strongly the rain data measurement and the urban drainage modelling. Due to the spatial variability, it may occur, that a closer rain gauge is not the best suitable for the simulation, compared to one located further, but with similar characteristics.
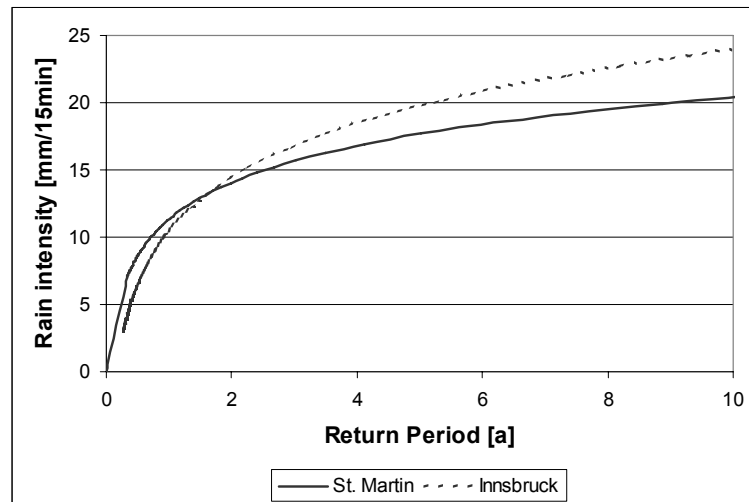
Figure 5-2. Example of spatial variability. Statistical rain intensity for the duration 15 minutes calculated from real data for different return periods for two different rain stations

The figure above presents an example of spatial variability. The two rain stations are located at a distance of 13 km, the one is in the city centre and the other is close to a mountain slope. Their behaviour differs significantly. Depending on the return period investigated, the calculated statistical rain intensity, was higher in one of the stations. This variation was also observed in the study reported in (Mikkelsen *et al.*, 1997), in which the extreme values calculated for 43 series depending on the return period vary significantly. This study proves that the spatial variability, even for rain data from closer rain gauges, can be very high.

Frequently, rain series have to be used in gauging stations at a significant distance from the catchment simulated. In order to evaluate and compensate the spatial variability, a relation between rain characteristics and CSO performance indicators would be useful. The method used to determine the best suited rain characteristics for the description of a sewer system's performance indicator, is the correlation analysis.

The results of research on this topic are reported in:

De Toffol S., Burström De Simon Y. and Rauch W. (2006).
On the effect of spatial variances of historical rainfall time series to CSO performance evaluation. Water Science and Technology, **54** (6-7), 25-31.

and

Rauch W. and *De Toffol S.* (2006).
Der Einfluss der Regencharakteristik auf den Wirkungsgrad von Mischwasserbehandlungsanlagen. Wiener Mitteilungen, 196, G1-G23 (in German)

These publications are also referred to in this dissertation as **Paper IV** and **Paper V** respectively.

The following picture presents the 3 main groups of indicators described in chapter 4. In this chapter, the focus is on the relation between two groups, the rain characteristics and the sewer system performance indicators.
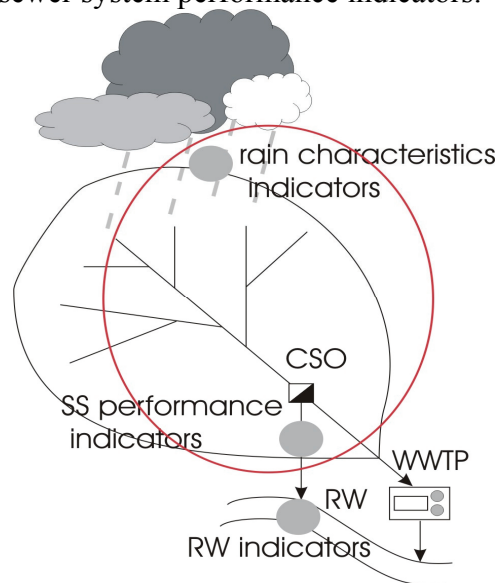
Figure 5-3. Example of the relations investigated. Focus on the relation between rain characteristics and sewer system performance indicators. SS = Sewer System, CSO = Combined Sewer Overflow, RW = receiving water, WWTP = wastewater treatment plant.

The two papers mentioned above, investigate the relation between chosen sewer system performance indicators and rain characteristics. The first paper presents 37 rain series from many different European countries (Austria, Switzerland, Italy, Spain, Norway, Belgium, France and Denmark), the second one, 67 Austrian rain series. **Paper IV** analyses more parameters, while **Paper V** one concentrates mainly on the CSO efficiency as a principal indicator for the evaluation of the CSO impacts in the Austrian regulation. This paper was also the basis for a modification of the draft version of the (ÖWAV-Regelblatt 19, Draft 11.2005). In an older version, the limits for the CSO efficiency were suggested depending on the mean annual rain volume, which correlates more with the overflow volume. In **Paper V**, it was demonstrated, that the best correlation for the CSO efficiency results for the maximum rain intensity once per year over 12 hours ($r_{720,1}$).
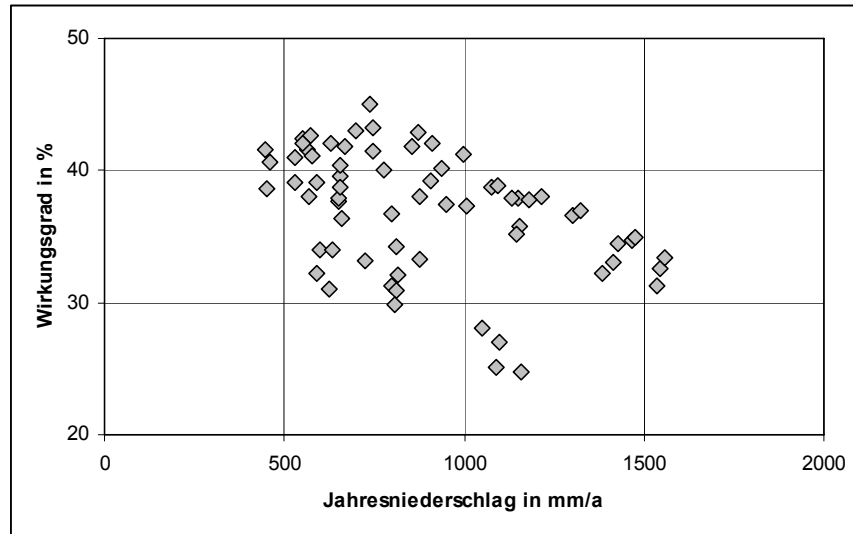
Figure 5-4. Example of the relation between the mean annual rain volume (Jahresniederschlag) and the CSO efficiency (Wirkungsgrad), see also **Paper V**

Figure 5-4 demonstrates that the correlation between the mean annual rain volume and the CSO efficiency, for the analysed rain in **Paper V**, was very low. Better results were obtained with the rain intensity over 12 hours, which is now used as indicator in the new draft of the (ÖWAV-Regelblatt 19, Draft 11.2005).

The benefit from these findings is that this relation could be used to account for the spatial differences when using a regional rain series instead of the accurate local one, if the last one is not available. Further, **Paper V**, presents a list of 16 regional rain series to be used in a specific region in absence of local rain. The regions, in which each rain is valid, are presented in the figure 14 of **Paper V**.

A similar approach was found in a Danish study. There, it was demonstrated that heavy rainfalls are more extreme in areas with high mean annual rainfall (Arnbjerg-Nielsen *et al.*, 2002; Mikkelsen *et al.*, 1998). However, the fact that the mean annual rain depth correlates with the rain intensity does not imply a correlation with the CSO efficiency too. In the Papers IV and V it was demonstrated that this is not the case.

Furthermore, the German guideline (ATV - A 128, 1992) suggests that a lower CSO efficiency can be allowed if the mean annual rain volume is higher. In **Papers IV** and **V** it was demonstrated that the mean annual rain volume is not the most suitable indicator to assess the spatial variability of sewer system performance. It is possible that the relation mentioned in the ATV was calculated on the basis of more homogeneous data. The data used in both papers present a very high variability of the analysed indicators.

5.4.   Suitability of indicators for sewer system performance

In this chapter two more papers are introduced. The first completes the indicators analysis started in the two papers described in chapter 5.3, **Papers IV** and **V**.

Engelhard C., *De Toffol S.* and Rauch W. (2008).
*Suitability of CSO Performance indicators for Compliance with Ambient Water Quality Targets.* Urban Water Journal, Vol. 5, No 1, March 2008, 43-49
This publication is also referred to in this dissertation as **Paper VI**.

The main issue in this publication is the investigation of the relation between sewer system performance and receiving water quality indicators, illustrated in figure 5-5. Furthermore, the applicability of easily obtainable emission-based performance indicators for the sewer system is assessed, in order to describe the impacts on the water quality of the receiving waters.
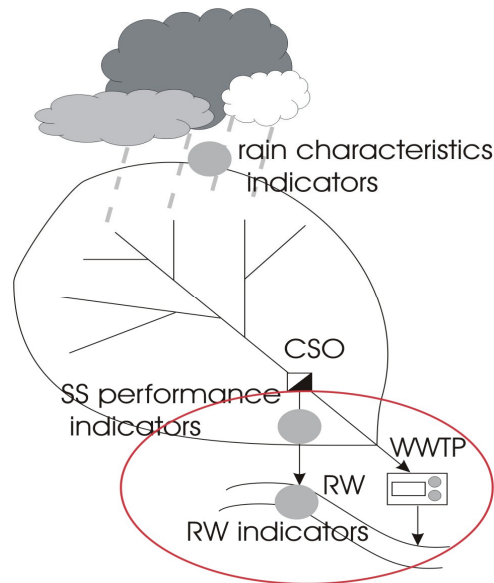
Figure 5-5. Example of the relations investigated. Focus on the relation between sewer system performance indicators and receiving water quality indicators. SS = Sewer System, CSO = Combined Sewer Overflow, RW = receiving water, WWTP = wastewater treatment plant.

The indicators are calculated by means of simulation of a simple catchment and the results are then validated with the simulation of a real catchment. The results of the analysis demonstrated, that for acute impacts (acute toxic effects of ammonia and oxygen depletion) it is not possible to demonstrate a correlation with the chosen sewer system performance indicators. For other receiving water impact types (i.e. erosion frrequency, Cu and N load), the best sewer system performance indicator is the total mean annual overflow volume. The CSO efficiency also shows an acceptable correlation for these three impact types. Therefore, the best indicator (for non acute impacts) to be monitored independently from the existing pressures on the receiving water, is the overflow volume. Furthermore, it was demonstrated in accordance with a previous study (Lau *et al.*, 2002), that the spilling frequency is not a good indicator to quantify the impacts of the urban drainage on the receiving waters.

The approach presented in **Paper VI**, based on the correlation between the two indicator groups, on the basis of simulation results, was not found in other publications. However, a similar approach is presented in (Rauch and Harremoes, 1998) and in (Lau *et al.*, 2002), and in (Mulliss *et al.*, 1996). In this last study however the correlation between similar indicators is analysed on the basis on

measurement of a real catchment. On the other side, the selection and grouping of indicators on the basis of their impact type, was used in many studies, e.g. (Lijklema *et al.*, 1993; Schilling *et al.*, 1997).

Paper VII deals with the application of the indicators described in **Paper VI**, to the assessment of the efficiency of the sewer system. A comparison of the performance of both types of the classical sewer systems, the combined and the separate one, is the main issue of this publication.

De Toffol S., Engelhard C. and Rauch W. (2007).
Combined sewer system versus separate system - a comparison of ecological and economical performance indicators. Water Science and Technology, **55** (4), 255–264

This publication is also referred to in this dissertation as **Paper VII**.

In the minds of engineers, there has been a long lasting rivalry between the two sewer system types. The first systems in Europe were combined. In the 1950s, due to the increased environmental awareness, a campaign against the CSOs started, because they were considered the main urban drainage pollution source (Burian *et al.*, 1999; Butler and Davies, 2000).

An often suggested solution (especially in the US), in order to avoid the combined sewer overflow, is the conversion of a combined system to a separate one. It is supposed that the impact on the rivers can be reduced in this way. Many studies however, demonstrated that this is not always the case, e.g. (US EPA, 1999). Stormwater runoff can be highly contaminated as demonstrated in (Fuchs *et al.*, 2004). In some German states, the treatment of stormwater before its discharge to the receiving water, is regulated by design rules (Brunner *et al.*, 1996). However, the treatment devices, for example wet ponds, should be maintained properly to assure their efficiency and it should be taken into account, that each device has a determinate lifetime of approximately 25 years (Hillenbrand and Böhm, 2003). Very often, direct discharges of stormwater without treatment can be observed, in this case the impacts on the receiving waters can be notable (Sieker, 2003). Considering all facts presented above, a comparison of both sewer systems under different boundary conditions is attempted in **Paper VII**.

Other studies also deal with this comparison, an interesting approach can be found in (Brombach *et al.*, 2005). In this case, the two systems are compared by means of constant flows. The innovative feature of the study in **Paper VII**, is that the comparison is based on the results of long-term simulation. Additionally, different catchment configurations and pollution degrees are analysed.

The following picture presents some of the results for the indicator un-ionised ammonia. The separate system is considered to discharge directly to the receiving water (without treatment), because this is nowadays the most common configuration. The letters a, b and c distinguish the pollution degrees of the simulated flows (low, medium and high respectively).

Un-ionised ammonia [mg/l]

Pollutant Concentration (a=low, b=medium, c=high)
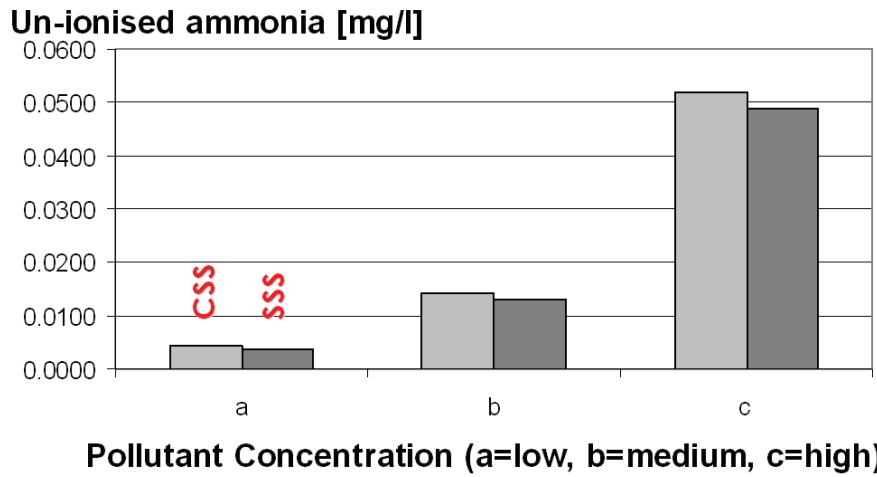
Figure 5-6. Results for the un-ionised ammonia for tree different pollution degrees, see also **Paper VII** for more results

The result of the overall evaluation is that if the pollution concentrations are low, both systems demonstrate a similar performance. With increasing pollution degree, the impact on the receiving water caused by separate systems is higher.

6.   Conclusions and Outlook

The following chapter summarises the results of the 7 papers included in the annex of this dissertation. The work presented in this dissertation can be subdivided in four main units: the EU-WFD and its implications for the urban drainage, the influence of the rain variability (temporal and spatial) on the sewer system performance and the analysis of the indicators for the assessment of the sewer system performance. Due to this arrangement, the conclusions are also subdivided in four subchapters.

6.1.   Water Framework Directive and the urban drainage system, new indicators are needed

The upcoming steps of the WFD implementation and their interactions have been presented in **Paper I**. Additionally, the strong reciprocal dependence was described between the definition of reference sites and water bodies on the one side, and the subsequent water quality classification on the other side.

Especially the size of water bodies can have a large impact on the water quality classification. The WFD demands a broad consideration of the urban drainage impacts, bearing in mind particularly the ecological conditions. As regards biological indicators, it was shown, in **Paper I**, that their monitoring requires more effort and implies larger uncertainties than dealing with chemical parameters.

In **Paper I** a methodology for defining the indicators for the water quality assessment for the EU-WFD implementation has been described. The key aspect is the identification of relevant quality assurance parameters that constitute the model state variables, the investigation of the possible cause effect relations and also temporal and spatial scales of the model.

In a case study of an alpine river, the relevant parameters for water quality classification have been analysed. Due to a comparison of the historical development of the biological water classification to concentration of the measured constituents, it was possible to derive indicators that can be considered as typical for alpine rivers. These parameters can thus be further applied for analysis and classification of other water bodies in the same type region.

6.2.   Temporal variation of rain data and indicators for its analysis

Up until today sewer design guidelines are frequently based on extreme rainfall properties. The uncertainty in the estimation of such properties is relevant, as it will have a direct effect on the magnitude of the required measures - most importantly, on the dimension of the sewers. In **Paper II**, the amount and the characteristics of the uncertainties for one example of such property (the maximum intensity over a period of 15 minutes and a return period of one year), were investigated. It can be consequently assumed, that the conclusions derived for this property, apply also to other properties.

The analysis of 6 high-resolution rain series, with durations between 19 and 55 years, gives no clear indication of a trend in the analysed extreme rainfall property. This is not in accordance with recent estimates on the increase of heavy precipitation, based

on climate model predictions. However, it has to be clear, that here historical data is investigated instead of predictions about the future precipitations.

A further analysis, in **Paper II**, indicates a significant uncertainty in the estimation of the intensity, which is based on noise in the series. An important issue in this context is the length of the estimation interval, adequate for computing the extreme rainfall property and the associated uncertainty. The analysis indicates that at least a period of 10 years should be used for the estimation. Even so, the error - expressed in terms of the 90th percentile of the possible deviation - is in the order of 5% to 10% of the 'true value' (defined as the value calculated when the complete series is used for the estimation). An increase of the duration of the estimation interval to 20 years, indicates a 2% to 5% reduction of this uncertainty. However, the longer the estimation interval is, the more possible trends, effects of non-stationariness, step changes and blunt errors will be included in the data. Therefore, it cannot be concluded that the longest possible data series should be used for the estimation of extreme rainfall properties.

The presence of trend was demonstrated to be case specific, even with the use of different indicators on the basis of longer rain series (**Paper III**). On the basis of the analysed rain series, no clear positive trend for rain specific indicators significant for the urban drainage, was found. A growing trend is present only in some series, however, a decreasing trend was also detected. The analysis of the sewer system performance, on the basis of a simple and a real catchment leads to similar results. In **Paper III**, it was demonstrated that the presence of trend in the daily intensity does not imply the presence of trend in shorter period intensities. This research demonstrated that it could be erroneous to design the sewer system considering a possible future growth of the rain intensity.

6.3. Spatial variation of rain data and correlation between rain characteristics and sewer system performance indicators

In **Paper IV** a relation was sought between parameters that characterize the rain pattern and those that describe the resulting performance of an urban drainage system with respect to CSO abatement. The benefit is that this relation could be used to account for the spatial differences when using a regional rain series instead of the accurate local one. Based on the investigation of 37 rain series representing large parts of European climatic conditions, it was found that the mean annual rain volume can explain most of the variances of the performance indicators, of the number of overflows and CSO volume. In order to explain the spatial differences in the efficiency of the CSO structures, another rain characteristic, namely the maximum event with a return period of one year could be used. A further analysis of the relation between pairs of rain characteristics and performance indicators, by means of multiple correlation analysis did not yield a relevant improvement. Finally, it was found that, for a region with homogeneous physiographic features (e.g. the alpine region), the parameter mean annual rain volume demonstrates acceptable correlation with the CSO efficiency. However, insufficient data were available to prove this assumption.

This analysis was deepened in **Paper V** considering 68 rain series from Austria. It was also demonstrated in this case, that the mean annual rain volume is not the most suitable parameter to describe the CSO efficiency. In this paper, a new indicator was

investigated, namely the statistical rain intensity over 12 hours, which proved to be the most relevant parameter, demonstrating the highest correlation. Further, this paper suggests possible regional series to be used in Austria for the simulation of sewer systems in absence of more accurate data. In the meantime, the suggestion presented in this paper found its way into the new draft guideline (ÖWAV-Regelblatt 19, Draft 11.2005). **Hence, the procedure developed herein will be the backbone of the CSO design in Austria.**

6.4. Suitability of indicators for sewer system performance

In the previous presented papers the relation between rain characteristics and sewer system performance was analysed, to help understand better the dependencies of the sewer system performance. The relation between sewer system performance and receiving water quality was also investigated, in **Paper VI**.

Continuous measurements in the receiving waters are very expensive, hence they cannot be applied to every CSO structure. Therefore, it would be useful to have easily obtainable parameters, in order to describe a particular problem caused by CSOs. This study investigated whether the impacts on the receiving water can be described by emission- based indicators, which would save money and time for the measurements. Therefore, an analysis was performed to test the correlation of different emission-based CSO indicators with receiving water indicators. The outcomes show that the four common CSO indicators investigated here (mean annual overflow volume, CSO efficiency, maximum overflow event once per year and number of overflows per year) differ in their suitability to describe an impact on the receiving water.

Main results of this study can be outlined in three points:
- ➢ The most suitable CSO performance indicator to describe the analysed receiving water quality indicators (except acute impacts), is the mean annual overflow volume. If information about mean annual overflow volume is missing, because there are no flow meters at the CSO, the indicator CSO efficiency could be used.
- ➢ Old regulations based only on the number of overflows per year should be revised with regard to the impact on water quality.
- ➢ Acute impacts, i.e. oxygen depletion and ammonia, can not be described by the emission based CSO indicators. Therefore, it is necessary to carry out a case specific analysis.

As regards acute impacts, neither system performance indicators, nor rain characteristics demonstrated relevant correlation. In this case, the impacts on the receiving water have to be analysed case specifically and with consideration of receiving water characteristics.

Based on the results of **Paper IV**, it can be concluded that the mean annual rain volume is a good indicator for the assessment of receiving water quality impacts originating from pollution loading and morphological impacts. Furthermore, a sewer system in a region with high rain volume, has a high probability to impact the receiving water.

After the investigation of the possible dependencies between the chosen indicators, an analysis was conducted using such parameters for the evaluation of specific problems: the comparison of the performance of combined and separate sewer systems.

Paper VII aims at comparing the cost-effectiveness of the two main types of urban drainage systems (i.e. the combined sewer system and the separate sewer system), based on the analysis of simulations. The evaluation of the simulation results is based on ecological and economical performance criteria. It was demonstrated that:

➢ separate sewer systems discharge considerable pollutant loads via their overflow structures into the receiving waters if no stormwater treatment is implemented. Combined systems, which are dimensioned according to current design rules (ÖWAV-Regelblatt 19, 1987) discharge lower loads via their CSO structures. The ammonia concentration in the discharged water is higher in the combined sewer overflow, leading to higher unionised ammonia concentrations in the receiving water.

➢ the magnitude of the impact caused by sewer overflows is controlled by the rain characteristics, as certain rain types can amplify the impacts on the receiving water.

➢ if the pollution concentrations are low, both sewer systems (combined and separate) have a similar performance. But, with increasing pollution concentration, the environmental impact caused by the separate system is higher compared to the combined system.

The choice of the sewer system type should therefore be made with regard to the rain characteristics, the pollutant concentration in the catchment and the sensitivity of the receiving water. Generally, it can be concluded that the separate sewer system is cheaper if the rainwater is not treated. However, many countries have implemented regulations, which enforce stormwater treatment. Depending on the type of treatment applied, the costs for separate sewer systems increase, so that the separate sewer system is generally more expensive than the combined one. The findings drawn from this investigation could help to avoid ineffective solutions in the planning phase and suggest the effects to be monitored for a proper evaluation of the system efficiency.

6.5.   Outlook

The EU Water Framework Directive introduces a legal structure for the assessment of all types of water bodies in Europe. Thereby, one main focus of future assessment systems lies in considering also the impact of the urban drainage on the receiving water quality. To quantify such impacts chemical but also biological indicators are necessary. The consideration of biological impacts introduces new needs for the sewer system modelling. The chemical indicators are still implemented in the different simulation models. The problem is that the link between emission and effects on the biology is still missing. Further studies should concentrate on the identification of indicators easy to model but also able to quantify the effects of the urban drainage system on the biology of the receiving waters. An attempt to solve this problem was made in **Paper VI**, where the receiving water quality indicators were identified considering the main problems (e.g. eutrophication, morphological problems etc.) in the water bodies.

The analysis of indicators presented in this work includes the development of a general CSO impact assessment methodology, which has been tested on the basis of virtual or real catchments, for various boundary conditions including different rain series and sewer system conditions. Further research could confirm these results on the basis of a more complex catchment and considering also the temporal variability of the dry weather flow. On the basis of the defined indicators set, a tool could be developed, to allow the screening and detection of the CSOs that are prone to demonstrate less efficiency and cause also higher receiving water impacts.

The correlation between rain characteristics and sewer system performance indicators could be further investigated considering also the influence of the spatial distribution on a regional scale. Some parameters may demonstrate higher correlation, when the rain of a single specific region is considered. An attempt in this direction was made in **Paper II** but not enough rain series were available at this time to confirm this assumption.

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