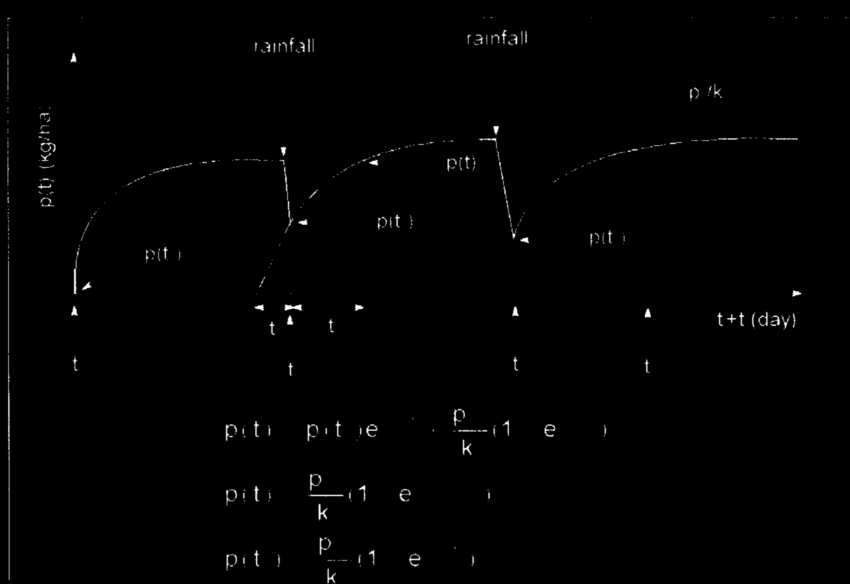
COMPUTATIONAL MODELLING OF EMISSION FROM COMBINED SEWER OVERFLOWS



Mingchuan Ruan

STELLINGEN

behorende bij het proefschrift

"Computational Modelling of Emission from Combined Sewer Overflows"

van M. Ruan

Delft, 14 september 1999

1。Stedelijke Ontwatering en Afwatering is meer kunst dan wetenschap. Daarom is "the state-of-the-art" van Stedelijke Ontwatering en Afwatering meer conceptueel dan deterministisch.
Urban Storm Drainage is more art than science. Therefore the-state-of-the-art of Urban Storm Drainage is rather conceptual than deterministic.

2。Geen enkel model is 100% foutloos vanwege de complexiteit van de werkelijkheid, maar sommige zijn wel nuttig als ze op een juiste manier toegepast worden.
All models are not 100% correct due to the complexity of the reality, but some of them are useful if applied appropriately.

3。Als een model geen redelijke antwoorden kan geven zonder dat parameters worden ingevoerd buiten het aanvaardbare gebied, dan is er iets aan de hand met het model.
If a model cannot give reasonable answers without leaving acceptable ranges for parameters then something is likely wrong with the model.

4。"巧妇难为无米之炊" - een oud Chinees gezegde.
"Zelfs een bekwame huismoeder kan bij gebrek aan rijst geen maaltijd bereiden". Dat geldt ook voor bouwers van modellen bij gebrek aan goed gereedschap.
"巧妇难为无米之炊" - a old Chinese saying.
"A skilful housewife can not prepare a dinner if rice is not available". This applies also to modellers if no suitable tools are available.

5。Neerslag vertoont een spreiding in de tijd en met de plaats. Dit is een van de belangrijkste oorzaken van de promblemen die worden ontmoet bij het kalibreren van numerieke modellen die de werking van rioolstelsels beschrijven.
Rainfall shows a variation in time and in place. This causes one of the main problems in the calibration of numerical models which describe the functioning of sewer systems.

6。Een-tijdstap vooruit voorspelling gebaseerd op tijd-reeks modellen kan op bijna elke datareeks worden toegepast. Het is echter in alle gevallen geen krachtig middel.
One-step ahead prediction using time-series models can be applied to almost every data series, but it is not a powerful tool at all.

7。Levenslange gevangenisstraf heeft niet dezelfde zwaarte bij een jonge man als bij een oude man.

Life long imprisonment does for a young man not have the same impact as for an old man.

8。"Mensen worden zo arm dat geld hun enige bezitting is geworden" - Dat is het gevolg van de tegenwoordig hoge economisch ontwikkeling in China.

"People are getting so poor to have money only" - this is the results of current high economical development in China.

9。Als jouw rijinstructeur je nadrukkelijk zegt door te rijden, moet je snel van rijstrook verwisselen.

If your driving instructor tell you emphatically to keep on driving, then you must change the traffic lane as soon as possible.

10。Sommige dingen zijn meer ingewikkeld dan ze lijken. Bij voorbeeld, 9^9^9 is een zodanig astronomisch cijfer dat niemand in staat is zich dat hoe dan ook voor te stellen.

Something is more complicated than it looks like. For example, 9^9^9 is such an astronomical figure that people cannot imagine it in any way or by any means.

11。De verbetering van afvalwatersystemen in ontwikkelingslanden is meer afhankelijk van de financiele middelen dan van de beschikbare technologie.

The improvement of wastewater systems in developing countries is more dependent on financial resources than on technology.

12。Het voltooien van dit proefschrift kan de Chinese Stedelijke Ontwatering en Afwatering helaas niet verbeteren als gevolg van het optreden van vuiluitworp vanuit de gemengde rioolstelsels tijdens de droogweerafvoer.

The main achievements of this thesis are unfortunately not applicable to the actual Chinese Urban Storm Drainage situation due to the continuous emission from combined sewer systems during dry weather.

13。De lettelijke vertaling van Ph.D in het Chinees betekent dat de drager van de titel niet alleen kennis bezit op een specifiek gebied van de wetenschap doch op een breder gebied. Dit is in overeenstemming met het beleid van TU Delft, immers door middel van het poneren van stellingen dient de promovendus te laten zien dat zijn/haar wetenschappelijke kennis een zekere breedte heeft en niet is beperkt tot het onderwerp van het proefschrift.

The literal translation of Ph.D in Chinese stands for a person having not only expertise in a specific area but also possessing a wider knowledge. This is in compliance with the policy of TU Delft, as the issued propositions should show that the scientific knowledge of a Ph.D is broadly based and not limited to the subject of the thesis.

COMPUTATIONAL MODELLING OF EMISSION FROM COMBINED SEWER OVERFLOWS

COMPUTATIONAL MODELLING OF EMISSION FROM COMBINED SEWER OVERFLOWS

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof.ir. K.F. Wakker,
in het openbaar te verdedigen ten overstaan van een commissie,
door het College voor Promoties aangewezen,

op dinsdag 14 september 1999 te 10:30 uur

door

Mingchuan RUAN

Bachelor of Science in Engineering (Tsinghua University, China)
en civiel ingenieur (Technische Universiteit Delft)

geboren te Wenzhou, Zhejiang Provincie, China

Dit proefschrift is goedgekeurd door de promotor:
Prof.ir. J.B.M. Wiggers

Samenstelling promotiecommissie:

Rector Magnificus, voorzitter	
Prof.ir. J.B.M. Wiggers	Technische Universiteit Delft, promotor
Prof.dr.ir. J. Berlamont	Katholieke Universiteit Leuven, België
Prof.ir. J. Kop	Technische Universiteit Delft
Prof.dr. R. Price	IHE, Delft
Prof.dr. A.J. Saul	The University of Sheffield, Engeland
Prof.dr. W. Schilling	Norwegian University of Science and Technology, Noorwegen

Computational Modelling of Emission from Combined Sewer Overflows
Ruan M. - Delft: Delft University of Technology,
Thesis Delft University of Technology. - with ref.-
With summary in Dutch

Subject headings:
Combined sewer system, CSO emission, conceptual modelling, time-series analysis, hydrodynamic models, continuous simulation

ISBN 90-9013023-3

Printed in the Netherlands

The search for truth is in one way hard and in another way easy.
For it is evident that no one can master it fully nor miss it wholly.
But each adds a little to our knowledge of Nature,
and from all the facts assembled there arises a certain grandeur.

Aristotle

aan mijn ouders
aan Hui en Linda

ABSTRACT

The emission from Combined Sewer Overflows (CSOs) is one of the major pollution sources to receiving waters. In the near future, CSO emission may be considered the main criterion concerning the evaluation, rehabilitation and design of combined sewer systems. No existing hydrodynamic models are able to predict CSO emission effectively, particularly for planning studies which are intended to predict the long-term impact of CSO emission due to changes in combined sewer systems.

The research presented in this thesis is to investigate the computational modelling of CSO emission. The existing modelling approach focuses on detailed, physically-based models, which are found to be too time-consuming and data-intensive, thus not cost-effective. In addition, the hydrologic and hydraulic processes involved, particularly for sewer sediments are stochastic in nature. Therefore, a parametric modelling approach, including a regression analysis of measurement data and time-series models for describing hydrographs and pollutographs, has been investigated. The models have been found to be particularly useful in real-time control of sewer systems where on-line measurement data are available. However they are rather site-specific and are unable to solve "what-if" problems concerning changes to sewer systems.

A new modelling approach has been investigated for predicting CSO emission more effectively. In particular, a conceptual CSO emission model, SewSim, has been developed, which is capable of generating detailed simulation results, such as CSO hydrographs and pollutographs using single rainfall events or multiple years of recorded rainfall. In SewSim, a sewer system is conceptualized into the following three reservoir-modules:

- surface reservoir: representing the impervious catchment surface, including surface runoff, overland routing (quantity) and sediment buildup/washoff (quality).
- sewer reservoir: representing the sewer network, including dry weather flow, pumping capacity, variable storage (quantity) and sediment deposition/erosion (quality).
- tank reservoir: representing the off-line settling tank, including flow routing (quantity) and sediment deposition/erosion in the tank (quality).

The model has been developed using the high-performance programming package MATLAB and its comprehensive toolbox SIMULINK. Only important processes have been included in the reservoir-modules to keep the model robust and efficient. Compared to detailed models, the compact modelling approach requires much less input data and simulation time for event-based or continuous simulation without reducing the model accuracy. Sensitivity analysis has shown that the four important system variables are: impervious area, sewer storage, pumping capacity and tank storage (if available); and two important quality parameters are: the initial amount and buildup rate of sediment on impervious surfaces. Particularily for planning studies, SewSim is more cost-effective than a detailed hydrodynamic model, such as HydroWorks.

SewSim has been successfully verified and applied to predict CSO frequency, volume and TSS emission using the standard rainfall record (25 year) of De Bilt. The so-called "reference sewer system" that can be ideally represented by this model has been extensively investigated. Simulation results of this model, time-series models and HydroWorks have been compared and discussed.

HET MODELLEREN VAN DE VUILUITWORP VANUIT GEMENGDE RIOOLSTELSELS

SAMENVATTING

De emissie vanuit de overstorten van een gemengd rioolstelsel is een van de belangrijkste bronnen van vervuiling van het ontvangende oppervlaktewater. In de toekomst zal dan ook deze vuiluitworp als voornaamste criterium worden beschouwd ten aanzien van de evaluatie, de verbetering en het ontwerp van gemengde rioolstelsels.

De bestaande hydrodynamische modellen zijn niet in staat de vuiluitworp effectief te voorspellen, vooral niet voor zogenaamde planningstudies, die bedoeld zijn om de lange termijn effecten van de vuiluitworp - als gevolg van de geplande veranderingen van het beschouwde rioolstelsel - te voorspellen.

Dit proefschrift is gewijd aan een nieuwe, andere wijze van modelleren van de vuiluitworp. De bestaande modellen baseren zich op gedetailleerde hydrodynamische modelleringstechnieken. Deze wijze van modelleren vergt het gebruik van veel invoergegevens en rekentijd. Daarom is hij niet kosteneffectief, vooral waar het de regenreeksberekeningen betreft. Bovendien geldt, dat er veel onduidelijkheden zijn met betrekking tot de hydrologische en hydraulische processen, en het feit dat de sedimenttransportprocessen in het rioolstelsel zich van nature in hoge mate stochastisch gedragen (in hoge mate stochastisch van aarde zijn). Daarom is de weg gevolgd van de parametrische benadering en is hierop het onderzoek gericht, te weten: regressie-analyse van meetgegevens en tijdreeksmodellen voor het genereren van hydrogrammen en vuiluitworp-grafieken. De hieruit resulterende modellering is vooral geschikt voor "real-time control" van rioolstelsels, omdat er zogenaamde "on-line" metingen beschikbaar zijn. Deze modellering is evenwel vaak aan bepaalde locaties gebonden en aldus niet te allen tijde in staat in het algemeen "wat-indien" ("what-if") problemen op te lossen.

Deswege is een verdergaande, nieuwe modelleringstechniek ontwikkeld voor het effectief voorspellen van de vuiluitworp uit gemengde rioolstelsel, met als resultaat het conceptuele vuiluitworpmodel "SewSim". Dit model kan gedetailleerde simulatieresultaten genereren in de vorm van overstorthydrogrammen en vuiluitworpgrafieken, gebaseerd op zowel enkele regenbuien als regenreeksen.

Voor de modellering is het rioolstelsel geschematiseerd tot de volgende bakmodellen:
- het oppervlakte-bakmodel, dat het verharde oppervlak vertegenwoordigt, inclusief de processen van oppervlakte-afvoer en inloop in de riolering (kwantiteitsaspecten) en de processen van sedimentaccumulatie en sedimentuitspoeling op het verharde oppervlak (kwaliteitsaspecten);
- het rioolbakmodel, dat de riolering als zodanig vertegenwoordigt, inclusief de processen van droogweerafvoer, de pomp(over)capaciteit, variabele berging (kwantiteitsaspecten) en de processen van sedimentafzetting en sedimenterosie (kwaliteitsaspecten);
- het bezinkbakmodel, dat de bezinktank benedenstrooms van de overstort vertegenwoordigt, inclusief de processen van het stromingsgedrag in de tank (kwantiteitsaspecten) en de processen van sedimentafzetting en sedimenterosie in de tank (kwaliteitsaspecten).

Het model is ontwikkeld met behulp van het softwarepakket MATLAB/SIMULINK. Alleen de belangrijke processen zijn in de bakmodellen opgenomen, teneinde het model zo robuust en zo efficiënt mogelijk te toen zijn. Dankzij de compacte modelleringsaanpak vergt het model veel minder invoergegevens en rekentijd dan de hydrodynamische modellen voor de berekeningen op basis van enkele regenbuien of regenreeksen, zonder dat de nauwkeurigheid van de modelleringsuitkomsten in het gedrang komt. De gevoeligheidanalyses hebben aangetoond, dat er vier belangrijke systeemvariabelen zijn te weten: het verharde oppervlak, de berging in het rioolstelsel, de pomp(over)capaciteit en de eventuele berging in de bezinktanks. Twee belangrijke kwaliteitsparameters zijn: de initiële hoeveelheid en de accumulatiesnelheid van het vuil (sediment) op het verharde oppervlak. Vooral voor planningstudies is het model SewSim in het algemeen kosten-effectiever dan een gedetailleerd hydrodynamisch model, zoals HydroWorks.

SewSim is met succes getoetst aan en toegepast op de standaard regenreeks (25 jaar) van De Bilt voor het voorspellen van de frequentie van overstorten, overstortingsdebieten en volumes, en de emissie van het totaal aan zwevende bestanddelen. Gebaseerd op uitgebreid onderzoek kan nu worden gesteld, dat het zogenaamde "referentie-rioolstelsel" op ideale wijze kan worden doorgerekend met behulp van SewSim. De simulatieresultaten van SewSim zijn vergeleken met die van tijdreeksmodellen en het hydrodynamische model HydroWorks, en geëvalueerd.

TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION

In the Netherlands, as in most other European countries, the majority of sewer systems are of the combined type; that is, they transport municipal sewage and infiltration water together with surface runoff away from the urban areas to prevent flooding. At the downstream end of the sewer system a waste water treatment plant (WWTP) removes the significant part of the pollutants before the effluent is discharged into receiving waters. Due to economic and geologic limitations, sewer systems are in general designed to carry only a certain magnitude of flow under wet weather conditions. During some heavy rainfalls, it is normal that the surface runoff far exceeds the amount of foul sewage and the sewer system may then be overloaded. As a result, it may cause flooding in the urban area and possible disturbances of the treatment processes in the WWTP. Therefore, combined sewer overflows (CSOs) are built in appropriate locations in the sewer system to relieve the overloading and to allow excess flows to escape directly from the system to receiving waters. Consequently this CSO emission (see **1.1**) inevitably pollutes receiving waters. Nowadays, as the removal efficiency of the WWTP has been progressively improved, the effluent from the WWTP distributes less polluting load to receiving waters. Because of that, the impact of intermittent CSO emission becomes more significant concerning the pollution of receiving waters.

In order to preserve receiving waters which may be a river, a lake or coastal waters, CSO emission should be taken into account in the design of new sewer systems and the rehabilitation of existing ones. This requires sound judgement, normally based on two sorts of information, which should both be adequate and as accurate as possible. The first, and commonly most accurate sort of information, consists of measurements, such as rainfall depth, CSO discharge and pollutants concentrations etc., which are to be used to assess CSO emission or to calibrate and validate a numerical sewer model able to predict CSO emissions. When the measurements are not sufficient for making the required judgement, a switch is made to the second sort of information, mainly consisting of the results predicted (i.e. CSO discharge/emission) by a well validated numerical sewer model.

A Dutch nationwide research programme of urban storm drainage (NWRW, 1989) was carried out with the aim of extending the knowledge of the design, construction and maintenance of sewer systems and of the negative effects of sewer emission on the quality of receiving waters. The NWRW database of measurements is important for this research. However, such specific measurements are in general expensive, time consuming, and site specific, which implies that numerical sewer models are an essential complement to measurements for predicting CSO emission for a wide scale of applications.

During the last decades, the development of numerical models for predicting CSO emission has been one of the major topics in urban storm drainage. There are three categories of numerical models. Some well known deterministic sewer models are SWMM (Huber and Barnwell, 1992), MOUSE (Lindberg *et al.* 1990; Nielsen *et al.*, 1987) and HydroWorks (Price and Wixcey, 1994; Assel *et al.*, 1997). These models have not been extensively applied for predicting CSO emission in practice, due to the fact that the use of these models is very data-intensive and time-consuming, and moreover, the described phenomena are too complex to be modelled physically. The second sort of numerical models are stochastic sewer models which may give accurate prediction results that are quite useful for practical purposes, like real time control of sewer systems. However, they need a large amount of qualified input-output measurements which are not easily available in practice. Moreover stochastic models are not able to solve "what-if" problems which engineers are just facing to solve. The third sort of numerical models are of the conceptual type; that is, they are based on well known hydrologic and hydraulic relationships related to water flow and sediment movement within the sewer system rather than detailed physically-based processes. They tend to use simple mass-balance relationships with numerical coefficients instead of complicated mathematical equations describing the detailed physics. Hence they are simpler and much more efficient than deterministic models when applied in practice. In the Netherlands, no conceptual sewer models exist which are able to predict CSO emission effectively using time-series data of recorded rainfall, such as those measured in De Bilt (see Appendix B). Conceptual sewer models developed in other countries like SIMPOL (Dempsey *et al.*, 1996), FLUPOL (Blanc *et al.*, 1995) and HYPOCRAS (Bertrand-Krajewski, 1992) are not suitable for use in the Netherlands, because of the quite different local geographical situations. This research has been carried out mainly to solve this problem by developing a comprehensive conceptual sewer model to predict effectively CSO emission in the Netherlands.

1.1 CSO emission

In this thesis CSO emission is defined as the intermittent discharges of sewage through the CSO during wet weather. Figure 1.1 shows the various processes going on within a sewer system before pollutants move from the urban catchment surface and sewer network to receiving waters (Ruan, 1995). During dry weather period (DWP), sediments are accumulated on the urban surface and sanitary solids are deposited in the sewer network. During wet weather period (WWP), the accumulated surface sediments are washed into the sewer network via gully pots and mixed with in-sewer sediments that are re-eroded. The overflowing mass will discharge into a basin or directly into receiving waters.

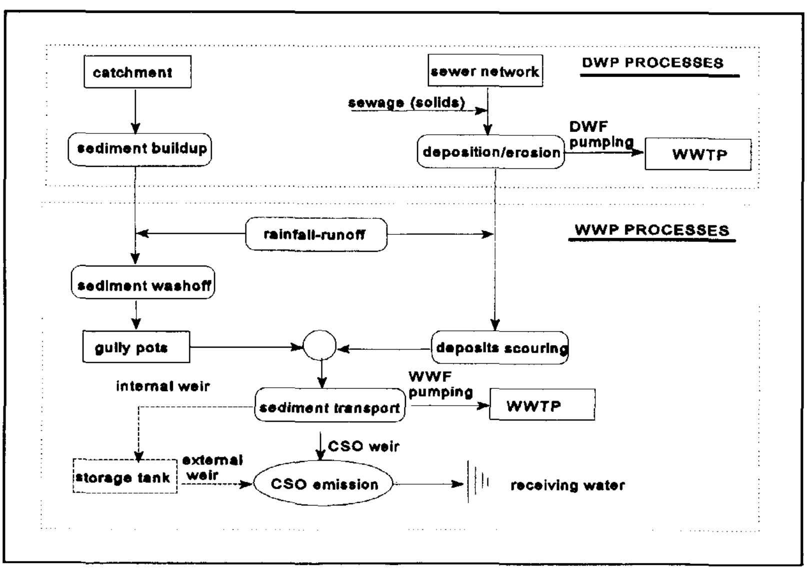


Figure 1.1 Sediment movement during dry and wet weather periods

Thus, CSO emission consists of a mixture of municipal sewage, stormwater, surface and in-sewer sediments. Samples of this mixture can be analysed in terms of TSS, BOD, COD, Kj-N, heavy metals, etc.. Generally, various pollutants are attached to sewer sediments and can be estimated as fractions (i.e. potency factors) of their mass. Indeed, the analysis of NWRW data has shown that BOD and COD concentrations of CSO are correlated to TSS concentrations. Therefore, CSO emission can be quantified in terms of sediment load of CSOs. However, as Xanthopoulos and Augustin (1992) have stated that sediments have various sizes with median grain size from less than 6 μm to more than 1000 μm. Pollutants such as heavy metals and organic mater are generally associated with the finest size (<6 μm) fractions of particulate solids accumulating on urban surfaces. These highly polluting and non-settleable solids are normally transported as wash load. Sediments with the size between 6 μm and 600 μm are also highly polluting and are normally transported in suspension. These two fractions of sediments are mostly responsible for the detrimental effects of CSOs. Coarse sediments are transported by bed load and are only responsible for the reduction of hydraulic capacity of sewers and not directly for CSO emission. Due to the complexity of sediment movement within the sewer system, most sewer quality models take only one fraction of sediment into account. This is also due to the fact that CSO load is normally not measured in terms of different fractions of sediments; for example, the NWRW database contains no specific CSO load of different fractions of sediments. Therefore this study concentrates on the total sediment load discharged by the CSO and does not distinguish between the sediment sizes [1].

1.2 Dutch sewerage practice

In the Netherlands, about 75-85% of the sewer systems are of the combined type. Due to the flat nature of the urban catchments and high groundwater levels, most sewers have a minimum slope and a large storage capacity. The velocity of dry weather flow in such sewers is low and sanitary solids carried by this flow tend to deposit in the sewer network. During wet weather, surface runoff can wash the solids that are accumulated on the urban (impervious) surface during dry weather into the sewer system. The velocity of wet weather flow in the sewer network increases and sediments deposited in sewers are re-eroded, transported and washed out to receiving waters. In the meantime, surface solids that are washed into the sewer network may be deposited when the flow is receding normally near the end of a rainfall event. Over a period of time more solids may be deposited than washed out, which implies that sewers will need to be cleaned regularly to preserve the hydraulic capacity. Thus, sewer sediments may cause two main problems: they increase the pollution strength of CSO emission and they reduce the hydraulic capacity of the sewer system.

To evaluate combined sewer systems in terms of their emission into receiving waters, the average CSO frequency per year has been widely used in Dutch sewerage practice. In the past, CSO frequency was determined merely from the sewer storage capacity and the excess pumping capacity (i.e. the pumping capacity minus the dry weather flow) using the so-called Kuipers' graphical method (see **6.2**). However, the estimated result was not necessarily the actual CSO frequency due to the simplifications that are built in this method. At present, it is usual to use complicated hydrodynamic models to calculate the CSO frequency (and volume) based on time

[1] The total sediment load here includes suspended and wash loads but no bed load.

series data of recorded rainfall. However, the method is extremely time-consuming and data-intensive, and is therefore not cost-effective. Moreover, according to research carried out in the framework of NWRW (1989), CSO frequency and volume actually do not give reliable information on the negative environmental effect of CSO emission on receiving waters, since the pollutant concentrations of each CSO emission vary considerably. Thus CSO emission cannot be simply quantified by CSO frequency, CSO volume or both. It is widely recognised that CSO load, defined as the product of CSO discharge and its corresponding concentration of pollutants, is much more relevant to quantify CSO emission and its negative effects on receiving waters. However, due to the complexity of the sewer sediment behaviour, there are no methods currently available to predict CSO emission effectively.

This concern was the major motive for studying sewer sediments problems within the NWRW research programme and laboratory experiments (Kleijwegt, 1993). These research works showed that a deterministic approach to sewer sediment movement was difficult if not impossible, and not cost-effective. Corresponding to the state-of-the-art of Dutch sewerage practice, it is more suitable to choose a conceptual and/or stochastic approach to predict CSO emission.

1.3 Research objective

Globally three emission sources pollute receiving waters. They are the emission from agriculture, the emission from a WWTP and the emission from CSOs. In urban areas, however, CSO emission will be the main criterion concerning the protection of receiving waters and the evaluation, rehabilitation and design of combined sewer systems. None of the existing hydrodynamic models are currently able to predict CSO emission effectively with sufficient accuracy which is needed for planning studies. The objective of planning studies is to determine the long-term impact of CSO emission on receiving waters due to changes to the catchment and the sewer system, such as the impervious area, sewer storage, pumping capacity and storage tank etc..

The objective of this research is to develop alternatives to the currently used hydrodynamic models. They are parametric modelling and conceptual modelling, which are able to predict CSO emission more effectively, particularly for planning studies. It implies that taking into account the required computing facilities, data availability, model calibration and verification, the simulation accuracy and duration, and the processing and implementation of model outputs, it is less labour-intensive and thus more cost-effective to use new approaches than hydrodynamic models.

Due to the lack of sufficient measurement data, one of the highly accepted hydrodynamic models, HydroWorks has been used in this research, in order to verify the parametric and conceptual models that have been built.

1.4 Outline of the thesis

Chapter 1 gives an introduction to the present sewerage practice concerning CSO emission to receiving waters. The problems encountered in the present modelling approaches are analysed. Further, it formulates the research objective and presents the outline of the thesis.

In Chapter 2 the present modelling approaches to sewer systems in urban area are discussed. In particular, physically-based hydrodynamic models are reviewed. These consist of hydrologic and hydraulic, and quality modelling. Sensitivity analysis of CSO volume and emission are also carried out.

Chapter 3 deals with the parametric modelling approach. Two methods can be distinguished: regression analysis of the NWRW data and time-series modelling of CSO discharge, water level and CSO emission. The limitations of parametric modelling approach are outlined.

In Chapter 4, a conceptual CSO emission model called SewSim is developed. It is suitable for event-based simulation using single rainfall events, but especially for continuous simulation using a long rainfall record.

The CSO emission model SewSim is verified in Chapter 5. The model may be verified using measurement data or simulation results of a hydrodynamic model. Both event-based and continuous simulations are involved.

Chapter 6 presents some application cases of SewSim. The model may be used for predicting CSO frequency instead of Kuipers' graphical method. The so-called "reference sewer system" [2] is investigated in detail using SewSim as well as the sewer system of Apeldoorn-West.

Finally, Chapter 7 gives important conclusions obtained from this research and recommendations for further research in the future.

---

[2] A hypothetical sewer system which has an in-sewer storage of 7 mm, an excess pumping capacity of 0.7 mm/h and 2 mm extra storage of a settling tank behind each CSO weir (see also **6.3**).

CHAPTER 2 PRESENT MODELLING APPROACHES

2.1. Introduction

Nowadays as computer and information technology are developing rapidly, modelling becomes an essential method to predict behaviours of various water systems. A model is defined as a representation of a system in some form other than the system itself (Shannon, 1975). The system in this research is the urban catchment and its sewer network. A numerical model uses mathematical relationships to represent, or to simulate the behaviour of the system. Numerical models help people study systems in ways that would not be practical, or even possible only through measurements and observations. At present, most numerical models are computerised. A computer model can be a useful tool to predict the behaviours of a system under a variety of conditions. The essential value of a computer model is that it serves as an electronic laboratory. A well-designed model can be used to conduct "simulation experiments" and address any number of "what-if" questions in an efficient manner (Nix, 1994).

This chapter deals with the present modelling approaches to the phenomena involved in the sewer system. Section **2.2** describes various types of numerical models. Section **2.3** depicts the conceptualised sewer system. Section **2.4** outlines the basic principles of hydrology and hydraulics needed for modelling. Section **2.5** deals with present modelling approaches to sediment movement on impervious surfaces, in sewer networks and storage tanks. Some limitations and a sensitivity analysis of hydrodynamic models can be found in section **2.6**.

2.2 Types of numerical models

Numerical models can be classified in terms of mechanism, spatial variability and time frame. According to the mechanisms used in the models, numerical sewer models can be classified into deterministic, stochastic and conceptual models.

<u>Deterministic models</u>

These use physical approaches to study the physical phenomena found in a system. Strictly speaking, a deterministic model is a perfect reflection of the physical world it is trying to simulate. This approach is also referred to as a basic, pure, causal, dynamic, white-box, or theoretical approach. The main advantages of this approach are that the model may lead to new knowledge about the system to be modelled and the model can be applied to other situations different from the one under which the proposed model is developed. Such models will always produce the same correct answer every time it encounted the same set of inputs, because everything is accurately depicted (Nix, 1994). For example, in the view of classic Physics, the famous Newton's model of gravity is a deterministic model. Singh (1988) stated that a physical approach to determine output from a given system would normally require specification of **(a)** system input, **(b)** system structure (geometry), and **(c)** physical laws, together with initial and boundary conditions. Due to the geometric complexity of the catchment and sewer network, it is evident that in fact no sewer models can ever be considered deterministic. However some complex and large hydrodynamic models, such as SWMM, MOUSE and HydroWorks are traditionally called deterministic models.

Hydrodynamic models may also be classified by the way in which spatial differences are handled. For example, catchment characteristics change from one point to another. Models that account for spatial variability as a function of the position in the catchment are known as distributed models. Models that assume that all characteristics are constant over the catchment are known as lumped models. A lumped model can be used to create a "pseudo-distributed"model if the catchment is divided into a number of homogeneous sub-catchments. It means that some measure of spatial variability is created when these sub-catchments are grouped to form the entire catchment. All existing hydrodynamic models are such "pseudo-distributed" models, in that they are at same level of lumping of properties e.g. sub-catchments.

Hydrodynamic models are also classified in terms of the time frame to which they are applied. Single-event models are only suitable for event-based simulation of the behaviour of sewer systems over single rainfall events. Continuous models are desinged for continuous simulation using time-sereis data of recorded rainfall. Such models must be able to simulate the hydrologic and hydraulic changes that occur between rainfall events.

Stochastic models

These use a systems approach to study the non-causal input-output relationship of a system. This is also referred to as an operational, applied, empirical, black-box, or parametric approach. The main advantages of this approach are that the model can be established without deeper insight into the process to be modelled and such models are also, in general, relatively efficient in use (Nielsen and Harremoës, 1996). Thus they can be applied to those physical processes which are as yet unknown and which are too complicated to model in detail. The stochastic modelling approach is concerned with the system operation, not the nature of the system itself (its components, their connection with one another etc.) or the physical laws governing its operation (Singh, 1988). A stochastic model will produce different sets of output from the same input (actually the distribution of inputs), though the output will have fairly consistent statistical properties.

Regression analysis can be considered one of the simple tools for stochastic modelling, because the inputs to the model are usually in stochastic nature. Based on (post-processed) measurement data or simulation results, regression analysis is useful for preliminary studies of urban storm drainage practices. Time-series analysis is normally used for investigating the stochastic properties of dynamic systems (e.g. sewer systems) based on regular time-series data. In Chapter 3 which presents the parametric modelling approach, some regression equations and time-series models will be established based on the NWRW database (1989).

Conceptual models

As described above, determinstic models generally use the physical approach to investigate the phenomena and processes involved in a system. However, usually sewer models developed in such a way are not efficient (time-consuming and data-intensive) for practical applications. In addition, they are not able to describe some stochastic processes (e.g. rainfall-runoff) involved in the sewer system. On the other hand, stochastic models use systems analysis to investigate the input-output relationship found in a dynamic system. However stochastic models have their limitations in application: they are site-specific and are not able to solve "what-if" problems concerning changes to sewer systems.

A new modelling technique to simulate the processes involved in urban storm drainage is "conceptual" or "grey-box" modelling which is actually located between the modelling scope of the deterministic and stochastic approaches. A conceptual sewer model can be described as a "pseudo-deterministic", "pseudo-distributed" single-event or continuous model. Such a model combines simple and well established hydrologic and hydraulic principles with systems analysis to describe the phenomena found in a sewer system. This approach complies with the state-of-the-art of urban storm drainage, because,

1) due to the complex geometric conditions of the catchment, sewer systems have to be conceptualised and simplified no matter which approach is to be used (see **2.3**).
2) most processes in hydrology and hydraulics are conceputal rather than deterministic (see **2.4**).
3) processes related to sediment behaviour in particular are stochastic in nature as well (see **2.5**).

In fact, "conceptual modelling" has two meanings: first, the sewer system has to be conceptualised and simplified, which has also to be done even using the full hydrodynamic models. However with conceptual models, the sewer system is much more simplified than with hydrodynamic models, for example, it can be conceptualised as a series of reservoirs. Second, the hydrologic, hydraulic and (some unknown) quality processes involved have to be simplified in order to use systems analysis and hydrologic/hydraulic principles, mass balance relationships etc. to ensure the efficiency of model simulation.

Like hydrodynamic models, conceputal sewer models may also be classified into single-event models and continuous models in terms of the time frame. This classification corresponds to the description of event-based and continuous simulation (see **5.2**).

2.3 Conceptualised sewer systems

Even using a hydrodynamic model, a sewer system has to be conceptualised in terms of the geometry data of the sewer system (i.e. the catchment, sewer network and ancillary structures) so that the model can use these data to represent the real sewer system. In general these data can be indentified in three categories: node data, conduit data and ancillary data.

Node data consist of coordinates of each node (manhole, outfall, pond, etc.), ground level and slope, storage volume and contributing surfaces and areas. Contributing surfaces are usually classified into pervious surfaces and impervious surfaces (steep, normal, flat). Impervious surfaces have three types: closed (like roads), open (like lakes) and roof. Hence, there are in total 12 types contributing surfaces connected to a sewer system. However, due to the fact that most Dutch catchments are flat, only impervious surfaces are usually considered important for urban storm drainage. A manhole is schematised as a reservoir where turbulence occurs resulting in energy loss of the flow. If the water level rises above the ground level, surface flooding occurs.

A conduit is represented by a conceptual link in the network, of defined length, between two nodes. Conduit data consist of the length, shape and size of conduits; the upstream and downstream invert levels of conduits; roughness coefficients for the Colebrook-White equation or the Manning formula to calculate hydraulic roughness. The gradient of a conduit is defined by the invert levels at each end of the link. The governing conduit model equation is the Saint-Venant Equation: a pair of conservation equations for mass and momentum in open channel flow (see

2.4.3). The solution of the Saint-Venant Equation may be retained in pressurised flow by introducing a suitably narrow slot, the Preissmann Slot, into the pipe soffit. A smooth transition between free surface and surcharged conditions is thus enabled.

The main ancillary structures are overflows, pumping stations and storage tanks. Like any ancillary structure, an overflow is simply modelled as a continuation link of zero length between two nodes. It is common to specify a discharge control at the continuation link as an orifice, weir or other control link. If one of the two nodes is an internal node, the overflow is called an internal overflow; if one if the two nodes is an outfall, then the overflow is called external overflow. For modlling an overflow, the data of the width and the crest level of the weir are required.

A pumping station is represented by a storage volume at a node with one or more pump control links discharging into other nodes (internal nodes or outfalls). A pump control link is controlled using the switch-on and switch-off levels for the water level in the upstream node (the wet well). The pump will start operating when the water level in the upstream node rises above the switch-on level, and will continue running until the water level falls below the switch-off level. There are several types of pump characteristics, such as for fixed discharge pump, rotodynamic pump and archimedean screws etc.. The fixed discharge pump is commonly used in modelling urban storm drainage.

Storage tanks have two forms: on-line and off-line. On-line storage tanks can be modelled as a large manhole chamber, with a small manhole shaft. The flow control on the outlet is commonly represented by a weir. Off-line storage tanks can be represented in a similar manner but connected to the on-line node by a weir and a flap-valve to prevent flow back into the off-line tank and to release the water from the off-line tank to its downstream node when the storms stop. In the Netherlands, storage tanks are generally connected off-line to the sewer system. Usually the tanks have an internal weir which ensures that the water fills the tank only during heavy storms.

2.4 Hydrology and hydraulics

In an urban catchment excess rainfalls may lead to flooding of streets and the generation of CSOs which may pollute receiving waters. In order to predict the frequency and the size of the negative effect, the physical processes of urban storm drainage have long been studied. Nowadays as computer and information technology are developing rapidly, numerical models have become a powerful tool in urban storm drainage. Since a model is only a representation of reality, the physical processes involved are crucial for any modelling approaches. In this section some important processes of hydrology and hydraulics will be briefly outlined.

The hydrological processes concern those occurring on urban catchment surfaces, such as, rainfall, interception, evaporation, infiltration, and overland flow. These processes are related to sediment buildup and washoff on impervious surfaces. The hydraulic processes deal with water transport within a sewer system (sewer network and ancillary structures). These processes are related to in-sewer sediment deposition/scouring and transport.

2.4.1 Rainfall

Rainfall varies in space as well as in time. The two effects interact. Small rain cells typically produce short duration storms with a significant spatial variation of rainfall intensity. In contrast, large rainfall cells tend to produce longer duration storms with less spatial variation of intensity.

The spatial distribution of rainfall data can be captured by allocating a dense network of raingauges. Three methods can be adopted for processing the rainfall data obtained from the network - Theissen polygon method, rainfall intensity map or contour method and radar method (HydroWorks on-line document, 1998). Troutman (1982) and Mutzner (1991) concluded that spatial variability of rainfall data may result in poor prediction of runoff distribution and volume; thus it may not be used to calibrate numerical sewer models. Research carried out by Niemczynowicz (1990) suggested a one-one rule about the spatial and temporal resolution of rainfall data. This is to say one rain gauge per km^2 (100 ha) and one minute per record. The spatial resolution of 1 km^2 is easy to reach while the temporal resolution of one minute is actually far beyond usual availibility.

Rainfall data is by far the most important input variable for modelling urban storm drainage. All available numerical sewer models use rainfall intensity as a major input variable for simulating processes in the sewer system. Rainfall intensity is a continuous variable that varies highly in time and space. When rainfall data are recorded, they are measured at discrete time intervals. Therefore, rainfall intensity is actually a variable derived from the measurements, normally, the cumulative rainfall depth and the time intervals, using the following equation,

$$i(t_{21}) = \frac{R(t_2) - R(t_1)}{t_2 - t_1} \tag{2.1}$$

where $i(t_{21})$ = average rainfall intensity during $t_{21} = t_2 - t_1$, mm/h
R = cumulative rainfall depth, mm
t_2, t_1 = record time of rainfall depth, h

The temporal resolution of rainfall intensity refers to the time interval used to discretise the continuous rainfall. The time interval of recorded rainfall data varies usually from one minute to a half hour. This implies that some parts of the rainfall data have a high time resolution while other parts have a low one. Many applications of urban storm drainage require a high time resolution of rainfall events, for example a time resolution of five minutes. If the rainfall data of a lower time resolution (e.g. 15 minutes) are used to calibrate a hydrodynamic model which requires rainfall data of a higher resolution (e.g. 5 minutes), the results are not expected to be accurate. In such cases the rainfall data may be first disaggregated to e.g. 5 minutes (Einfalt *et al.*, 1998).

The spatial resolution of rainfall data varies considerably. In the Netherlands, however, due to its overall flat landscape, the spatial distribution of rainfall is considered rather uniform. A standard rainfall record with a time resolution of 15 minutes measured in De Bilt from 1955 to 1979 has been appointed for the general use of continuous simulation in urban storm drainage (RIONED, 1995; Appendix B).

2.4.2 Rainfall-runoff

The rainfall-runoff transformation is very important for studying urban storm drainage since rainfall is the primary generator of flow in a sewer network. For pervious and impervious surfaces, the behaviour of this transformation is rather different. For pervious surfaces, the infiltration rate is normally so high that little runoff ever appears. However, during extremely intensive rainfall, when the pervious surfaces become saturated, runoff from these surfaces may move onto the nearby impervious surface. It also follows that where there has been a recent rainfall the potential of the soil in pervious areas to absorb another rainfall may be reduced. In the Netherlands, since urban catchments are in general very flat, runoff from pervious surfaces may be negligible.

Most runoff comes from impervious surfaces such as the roads and roofs. Evaporation as well as infiltration into the impervious surfaces are negligible. The process of interception (including wetting) is represented using a depression storage which may be presented as a constant or as a time dependent variable. For example, according to the new Dutch guidelines for urban storm drainage, the initial loss at the beginning of each rainfall is defined to be between 0.5 mm and 1.5 mm for impervious surfaces. The speed of runoff depends on the slope of the surface and the length of the overland flow path to the inlet of a sewer system. In general the overland flow routing transforms the effective rainfall into an inflow hydrograph. This inflow hydrograph may be defined by linear reservoirs in a series which represent the storage available on the ground and in minor drains and the delay induced between the peak rainfall and peak runoff. In this way, a reduced peak runoff is generated with a time lag after the peak rainfall. The routing coefficient of the overland flow depends on the rainfall intensity, contributing area and slope.

In fact, overland runoff from the impervious surface can also be represented by the kinematic wave equation (Deletic *et al.*, 1997). However the direct solution of this equation in combination with the continuity equation is too time-consuming for application with a large number of contributing sub-catchments. It has been shown that simpler reservoir-based models, which are much less computationally intensive, represent the relationship of rainfall-runoff as accurately as the more complex and physically based approaches (Huber, 1986).

2.4.3 Sewer flow routing

Sewer flow routing consists of those processes like flow in conduits, flow in manholes and flow in ancillaries (overflow weir, valves, pumping stations, storage tanks, outfalls etc.). Generally the flows in the sewer network are turbulent and three dimensional, having a free surface or under pressure. The conduits will be surcharged when the discharge from upstream becomes too large or backwater occurs from downstream. In such cases surface flooding may occur via manholes when the hydraulic gradient increases above the ground level.

Flow routing in the sewer network involves complicated hydraulic processes. According to the geometry of the sewer network and boundary conditions, the flow may be unsteady, non-uniform, under pressure and with backwater effects. Commonly, the full hydrodynamic wave model, consisting of the continuity equation and the Saint-Venant equation is used for simulating flow routing in the sewer network, as represented by Equation (2.2).

$$\begin{cases} \dfrac{\partial A}{\partial t}+\dfrac{\partial Q}{\partial x}=0 \\ \dfrac{\partial Q}{\partial t}+\dfrac{\partial}{\partial x}(\dfrac{Q^2}{A})+gAcos\theta\dfrac{\partial y}{\partial x}+gAS_f-gAS_0=0 \end{cases} \tag{2.2}$$

(1) (2) (3) (4) (5)

where A = cross-sectional area, m^2
t = time, s
Q = discharge, m^3/s
x = longitudial direction, m
g = acceleration due to gravity, m/s^2
θ = angle of bed to horizontal, °
y = depth of flow, m
S_f = friction slope, = $Q|Q|/K^2$, -
S_0 = bed slope, -
K = conveyance, -

The first equation in (2.2) is the continuity equation. In the second equation, term (1) is important when the flow is changing rapidly with time (i.e. the flow is highly unsteady). Term (2) is the convective acceleration term which is important when locally the flow is changing rapidly with space (i.e. highly non-uniform flow or rapidly changing water surface). Term (3), the pressure term, is important when there is a pressure gradient caused by the changing depth of a non-uniform flow. Term (4) represents the resistance due to bed friction and term (5) is the gravity driven force due to the bed slope. This equation is only valid for flow routing under free surface. A particular difficulty with the solution of the Saint-Venant equation is the treatment of the transition between free surface and pressurised flows (Price and Wixcey, 1994). If the sewer network is surcharged, a fictitious slot called the "Preismann slot" may be introduced to simulate the pressurised flow (Cunge and Wegner, 1964).

Hydraulically, the use of the full Saint-Venant equation is not always necessary, as Yen (1994) stated in his paper "Is hydraulics over-used or under-used in storm drainage?". Depending on the practical problems needed solving, the full hydrodynamic model can be more or less simplified. For example, when the flow in sewer network is nearly uniform and steady, the first three terms of Equation (2.2) may be negligible. The simplified equation is known as the kinematic wave model. When the flow is non-uniform, particularly with a backwater effect, term (3), the pressure term, should be taken into account, which results in the diffusion wave model. If the flow is highly non-uniform or the water surface is changing rapidly, term (2), the convective acceleration term should also be included. Such a model is called a quasi-steady dynamic wave model. This model is sufficient for solving most problems in urban storm drainage, since the change of flow within the computation time step Δt is small as long as Δt is kept small enough. Therefore, term (1) may be negligible, which will be of a enormous help to reduce the long computation time, because solving the full hydrodynamic model (i.e. including term 1) is far more complicated than the quasi-steady dynamic model, for which the flow is treated as steady within Δt but varies from Δt to Δt (Yen, 1994). A new numerical scheme based on a finite volume formulation to solve the Saint-Venant equations has been recently presented by Bogaerts *et al.* (1998).

2.5 Sediment movement

2.5.1 Buildup/washoff model

The buildup of pollutants represents the complex processes that occur between storms, including deposition, wind erosion, pavement degradation, construction, etc.. The idea is simply that such processes lead to an accumulation of sediments with associated pollutants that are then "washed off" during rainfall events. In the late 1960s, a Chicago study by the American Public Association (1969) demonstrated the (assumed linear) buildup of sediments and associated pollutants on urban street surfaces. Street surface accumulation of sediments defined as anything passing through a 0.25 inch (6.35 mm) mesh screen, was measured by sweeping with brooms and vacuum cleaners. The acumulations were measured during dry weather for different land uses and curb lengths, and the data were normalised in terms of pounds of "dust and dirt" per dry day per 100 feet of curb, with the implication that the buildup was a linear function for dry days. Other studies (Sartor and Boyd's, 1972) showed that buildup can be nonlinear. Ammon (1979) summarised several studies on sediment buildup process and concluded that the buildup relationships generally fall into one of four functional forms: linear, power function, exponential or Michaelis-Menton. Most sewer quality models use this basic concept concerning the buildup of pollutants on the urban impervious surface. For example, the build-up of processes on impervious surfaces can be conceptually modelled as an exponential function,

$$\frac{dp(t)}{dt} = p_s - k \cdot p(t) \tag{2.3}$$

where p(t) = mass of sediment, kg/ha
p_s = buildup factor, kg/ha/day
k = decay factor, 1/day
t = buildup time, day

There is a limiting value (p_s/k) for accumulated mass on an impervious surface when the buildup time becomes too long. Equation (2.3) is adopted by many hydrodynamic models for modelling the accumulated mass on impervious surfaces. The two parameters - the buildup factor p_s and the decay factor k should be determined by experiments or calibration. Generally p_s = 6-35 kg/ha/day and k=0.08 /day. Butler *et al.* (1992) presented the initial results of six sites (10 meter x 2.5 meter each) studying surface deposits in terms of total dry mass, volatile component, sediment gradings etc.. The measured total solids loading on the trial sites ranged from 0.84 kg to 9.35 kg over the period studied (about 3 months). The mean solids loading at all six sites was 4.29 kg which was in agreement with 19 kg/ha/day. This can be compared with an average figure reported in the USA by Sartor and Boyd (1972) of 17.7 kg/ha/day.

Washoff processes involve erosion and solution of constituents from an urban impervious surface during wet weather or street cleaning. Actual washoff is affected primarily by the impact of raindrops. Erosion indicated by the shear stress of the overland flow has some limited effect upon the washoff processes. Some pollutant enters the dissolved phase, but most of the pollutant enters a sewer system attached to the suspended sediment. Ammon (1979) reviewed several theoretical approaches for sediment washoff processes and concluded that the sediment transport based theory was not adequate in practice because of the lack of data for parameter evaluation. Almost all modelling activities for washoff from the impervious surface have focused on improvements to the various conceptual formulations (still with some theoretical basis), which if properly calibrated, in fact usually work well and are able to approximate observed washoff phenomena (Huber, 1986). Additionally, the simpler conceptual formulations are consistent with state-of-the-art of urban storm drainage (Bertrand-Krajewski, 1992).

The following "first order" relationship has been commonly used for washoff processes,

$$\frac{dp(t)}{dt} = -w \cdot r(t)^n \cdot p(t) \tag{2.4}$$

Where p(t) = mass of sediment per surface unit, kg/ha
w = washoff coefficient, -
r(t) = runoff rate over impervious surfaces, mm/min
n = exponent for runoff rate, - (n>=1)

The two parameters *w* and *n* should be determined by calibrations or some empirical equations, such as the following equation that is used in HydroWorks to calculate the washoff coefficient,

$$w = 10^8 i(t)^{2.022} \; - \; 29\, i(t) \tag{2.5}$$

where i(t) is effective rainfall intensity in m/s (HydroWorks, 1998).

2.5.2 Gully pots transport model

During wet weather, the sediments, which are washed off by the runoff, enter the sewer system through street inlets, along curbs or in parking areas. These inlets are named gully pots when they have a storage capacity of some ten liters at their bottom. Sediments are partly retained and accumulated in these devices, which may be re-eroded and enter the sewer network due to a sufficient runoff rate. These phenomena have been studied, and it appears that they depend on runoff rate, sediment characteristics, antecedent dry weather period, season, catchment slopes and imperviousness (Fletcher and Pratt, 1981; Grottker, 1990). Gully pots are in general efficient in trapping the coarser sediments to prevent them entering the sewer network. However a gully pot acts as a settling tank for surface runoff, which implies that the waste water may become anaerobic between storms (Price and Wixcey, 1994). This can be a serious source of pollution during coming storms.

Fletcher and Pratt (1981) proposed a model to reproduce the flushing mechanism of accumulated sediments in gully pots during wet weather. This flushing is due to the stirring action of the inflow water. Their model was tested later by Wada and Miura (1988). Two phenomena can be distinguished: sediments already in suspension in the gully water, and sediments re-suspended from bottom deposited sediments.

After experimental studies, Grottker (1990) proposed a model for both dry and wet gullies, which predicts the "passed load" (i.e. the load which cannot be retained by gully pot) as a function of the two main parameters: the sediment load and the flow rate through street inlets.

2.5.3 Sewer transport model

Sediment movement (deposition, scouring and transport) in a sewer network is the most important and also most difficult phase of sediment behaviour in the sewer system to model. The theories addressing solids transport are not developed directly for sediment transport in sewers. For example, sediment transport theories developed for fluvial hydraulics are not considered to be suitable for modelling sediment transport in sewers, because the geometry of the sewer system and the characteristics of sediments are different (Bertrand-Krajewski *et al.*, 1993).

Sewer sediments can be classified into five categories (from A to E) according to their relevant physical, chemical characteristics and polluting potential (Crabtree, 1989; Ashley and Crabtree, 1992). Type C deposits, which can be easily eroded and washed off under normal shear stress, are responsible for the so-called "first foul flush", observed usually with combined sewer systems. Type A deposits, though having the largest quantity, are not significant as a polluting source due to the fact that they cannot be eroded unless under extreme shear stress. However, this type of deposit is well responsible for the reduction of hydraulic capacity of the sewers and for the large operational costs required for the maintenance programmes.

Sewer sediments are transported in a variety of modes, such as wash, suspended and bed loads (Bachoc, 1992). There is no doubt that suspended and wash loads are the most important modes, which are mainly responsible for the detrimental effects of CSOs due to their high pollution strength and the tendency of being discharged easily through CSOs. Since sewer sediments are not transported in a true bed load, it is suggested the term "fluid sediment" is used to refer to this special quasi-bed load (Ashley *et al.*, 1994).

Nalluri and Alvarez (1992) and Kleijweg (1993) stated that sewer sediments have a cohesive nature, but behave as non-cohesive sediements once they start moving. The bed shear stress is proven to be a more appropriate parameter than flow velocity for defining erosive or depositional criteria in sewers (Verbanck *et al.*, 1994). However, the cohesion of sewer sediments and the interactive effects between the particles (i.e. coagulation and flocculation, agglometration) need to be investigated further.

In-sewer sediment deposition and scouring are two main processes affecting sediment transport in sewers. However the physical and chemical principles of these processes are not properly understood. There are currently many empirical (or experimental) models of sediment transport theories, for suspended load, bed load or total load. Among many models available, Ackers-White's model is one of the most widely accepted models for the preliminary modelling of in-sewer sediment movement.

Ackers-White's model for total load was first established for sediment transport in alluvial channels. Subsequent modifications were made by Ackers (1984) in order to apply the model for predicting sediment transport in sewers.

The model is able to predict both total and suspended solids concentrations in the form of a pollutograph, i.e. concentrations versus time, which may be useful in the management of applying such structures as detention basins, storage tanks and combined sewer overflows. The three main equations are as follows,

$$F_{gr}=\frac{u^{*n}}{\sqrt{gd_{35}(s-1)}}\left[\frac{U}{\sqrt{32}\log(\frac{12R}{d_{35}})}\right]^{1-n} \tag{2.6}$$

$$G_{gr}=C_{aw}\left[\frac{F_{gr}}{A_{aw}}-1\right]^{m} \tag{2.7}$$

$$q_t=G_{gr}sd_{35}\frac{1}{R}\left[\frac{U}{u^*}\right]^n\left[\frac{W_eR}{A}\right]^{1-n} \tag{2.8}$$

where:

F_{gr} = dimensionless mobility particle number, -
G_{gr} = dimentsionless solid flow number, -
q_t = total solid flow (kg particles/kg water), or concentration, kg/l
u^* = friction velocity (m/s) = $(g\ R\ S)^{½}$, S = hydraulic gradient
U = mean flow velocity, m/s
R = hydraulic radius, m
s = specific gravity of particles, g/l
d_{35} = particles diameter (35% of particles have a diameter of less than d_{35} in mass)
W_e = $10d_{35}$, effective deposited sediments width, m
A = flow section area, m^2
A_{aw}, C_{aw}, n, m = numerical coefficients, =f(D_{gr}), D_{gr}=dimensionless particle diameter

The last term of Equation (2.8), $[W_e\ R/S]^{1-n}$, is introduced to apply the equation to sewers. This modification only has an effect for coarse sediments that are generally transported as a bed load. For fine sediments that are transported generally as a suspended load, *n* is made equal to 1, so this term has no effect at all. For the calculation procedure refer to Appendix C.

Normally, this model predicts total load. However, it can also predict "pure" suspended solids concentrations by "forcing" the transition exponent (*n*) to be one.

It is not possible to calculate bed load directly using the Ackers-White model. However, it can be estimated as the difference between total load and suspended-load. An alternative is to estimate the bed load as 12% of the total load (Ashley *et al.*, 1994).

The modified Ackers-White model can be used for the preliminary modelling of in-sewer sediment concentrations of total load or suspended load during wet weather flow. For total load, d_{35}, *s*, υ, *R*, *U*, *S* and *A* must be known, whereas for suspended load, d_{35} can be calculated (see Appendix C). *R*, *U*, *S* and *A* can be calculated using a well developed hydrodynamic model. However no bed load is included in this research.

2.5.4 Tank transport model

In order to understand better the sedimentation and transport of mineral and organic sediment in combined sewer systems (including storage tanks), Michelbach and Wöhrle (1993) have investigated the settling and eroding behaviour of real sewer sediments. From a total of 350 samples of mineral sediment, slime, dry weather flow, stormwater flow and overflow, settling behaviour was determined with the aid of an apparatus developed for measuring settling velocites. The efficiency of stormwater tanks was estimated from the measured settling curves.

Due to the increasing use of settling tanks in sewer systems, more research has been performed on the optimal functioning of storage tanks. Saul and Ellis (1992) have developed a laboratory computer controlled monitoring system for the purpose of flow visualisation and for the comparative assessment of the sediment deposition and removal performance of different geometric configurations of storage tanks. The results of the work illustrate that very complex flow patterns were established within the storage tanks as flow hydrograph was discharged through the system. The majority of the sediments were deposited on the recession limb of the hydrograph while the erosion (e.g. self-cleansing operation) occurred normally during the filling of the tank. In addition to the flow pattern, the characteristics of the sediment are particularly important for the transport of sediments in tanks. For the same storage volume, long narrow tanks with a single dry weather flow channel have better self-cleansing characteristics than tanks with multiple channels. The length to breadth ratio of the tank should be as high as is practically possible and the tank width should not exceed four metres. However, in order to develop a tank module as part of a sewer flow quality model, e.g. HydroWorks QM, further work is required to assess the nature and properties of the deposits in tanks (i.e. type E, see **2.5.3**) and to relate these characteristics to the transport mechanism found in tanks.

Kluck (1997) stated that no satisfactory design methods for settling tanks - taking into account the time-varying flow pattern do exist. Presently, in the Netherlands, the design of such tanks is based merely on stationary flow conditions in full tanks, whereas in fact the tanks are filled before water flows out and the flow varies in time. A mathematical model describing the flow and settling of sediments in tanks under time varying flow conditions was set up using the CFD package PHOENICS (CHAM, 1991). The model solves equilibrium equations for mass, velocities, turbulence variables and particle concentrations in 2 or 3-dimensional grids. However, the use of the model is too complicated and time consuming for practical designs. Therefore flow simulations were performed to derive design rules to predict the removal ratio due to settling in steady state situations for rectangular tanks with a 2-dimensional flow. Furthermore, these rules were used to set up a fast model for predicting the functioning of storage tanks for time varying loadings, such as, developed by a time series of rainfall data.

2.6 Sensitivity analysis (HydroWorks)

Sensitivity analysis is commonly used to examine the accuracy of a model by determining the sensitivity of the model output with respect to perturbations of a specific parameter or system variable. Sensitivity analysis is a so-called "one-variable-at-a-time" approach.

A sewer system has many key properties, such as the structure of the network (tree-form or mesh-form), drainage area and the gradient of the catchment; the sewer storage and pumping capacity; the on-line or off-line storage tanks etc.. These key properties are represented by variables in a systematic way so that a hydrodynamic model can represent the real sewer system. Besides, some system parameters are introduced in the model merely for the modelling purpose, for example, the buildup and washoff rate of sediment on an impervious catchment surface. Sensitivity analysis is used to investigate the key sysem variables and parameters related to the demand variables, such as, the CSO frequency, volume and emission. In mathematical form,

$$DV = f(R, t, Fv, St, poc, Sc, Ss, cox, Dt, sed, \ldots) \tag{2.9}$$

where DV= demand variable
R = rainfall depth
t = rainfall duration
Fv = impervious area
St = sewer storage capacity
poc = pumping (over)capacity
Sc = slope of catchment
Ss = slope of sewers
cox = complexity of sewer structure
Dt = storage tank
sed = variables related to sediment

The last variable *sed* is only related to sewer quality modelling. For example, it can be the initial amount of sediment accumulated on the impervious catchment surface or in the sewer network; or the sediment buildup rate, solids size or settling velocity of solids. Two demand variables have been chosen for this sensitivity analysis: CSO volume and CSO emission, in that these two variables are important and mostly used for planning studies of sewer systems.

2.6.1 Introduction of HydroWorks

HydroWorks is one of the most accepted hydrodynamic models for simulating water flow and quality in sewer systems. The model's reliability for flow simulation is adequate for practical applications if the model is well calibrated by accurate and sufficient measurement data. However, the quality module is much less reliable for several reasons. First, it is much more difficult to collect accurate and sufficient quality data for model calibration. Second, the processes of sediment movement within the sewer system, i.e. from catchment to the outfalls of the sewer system, are too complicated to be modelled accurately. Also, like any hydrodynamic models, HydroWorks is a computation-, knowledge- and data-intensive software product. The required long simulation time is still a big obstacle for practical applications particularly for long-term simulation using recorded rainfall. For a large sewer system, like the one in Apeldoorn-West in the Netherlands, approximately one minute of simulation time was needed for six minutes of rainfall duration (see **6.4**). This implies that it is not feasible for HydroWorks to simulate sewer systems using the standard 25 years' rainfall record of De Bilt (see Appendix B). In addition, the accuracy of hydrodynamic models is mainly dependent on the input data which contain many uncertainties. In particular the quality processes involved in sewer systems have stochastic characteristics. Therefore hydrodynamic models should not be over-used. For some practical goals, such as planning studies of a sewer system, it is more convenient to use conceptual/simplified models, taking into account the stochastic characteristics.

To generate new ideas of modelling approaches to develop conceptual/simplified sewer models for planning studies, the present hydrodynamic modelling approach should however be studied. This is because that hydrodynamic models are commonly developed taking into account the physical phenomina found in sewer systems to be studied. It is thus useful to investigate which variables have significant influence on CSO volume and emission when using these models. One of the study methods used is sensitivity analysis of some demand variables, such as CSO volume and CSO emission v.s. several important system variables and parameters.

2.6.2 CSO volume

The sewer system of Loenen (see **5.1**) was used for systematic simulations (i.e. sensitivity analysis) carried out by HydroWorks to find the relationship between CSO volume and the following five key system variables,

1) impervious area of the catchment (A in ha),
2) storage capacity of sewers (B in mm referring to A),
3) pumping capacity (p in m^3/h),
4) roughness of pipes (k_s in Colebrook-White equation, in mm)
5) storage capacity of off-line tank (T in mm referring to A)

Eight rainfall events with different rainfall depth and intensity were selected from the rainfall record measured in De Bilt (RIONED, 1995) (see **5.5**,Table 5.3).

The first system variable investigated was in-sewer storage capacity. The diameters and inverts of all conduits were changed accordingly, keeping the sewer gradients constant. Figure 2.1 shows that when the storage capacity becomes smaller than the original value, the CSO volume changes rather irregularly. This was due to the too small pipe diameters, since the smallest pipe diameter became less than 110 mm. For such small pipes, it was possible that a greater bias would be introduced into the HydroWorks simulations. In normal cases, CSO volume decreases when the in-sewer storage capacity increases. Further the figure shows that though in general large rainfall depth will cause large CSO volume, the third rainfall (3) having the largest depth did not cause the largest CSO volume.

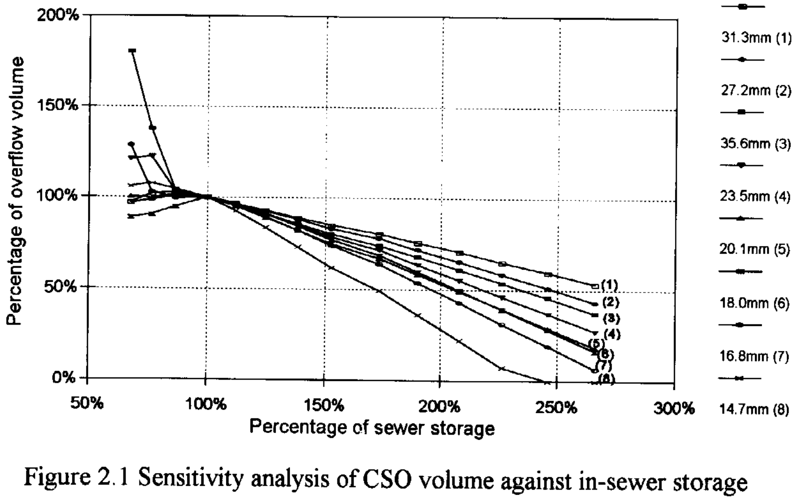


Figure 2.1 Sensitivity analysis of CSO volume against in-sewer storage

The second step was to investigate the sensitivity of CSO volume to the storage capacity of a storage tank behind the overflow weir. A storage tank with various storage capacities was added behind the overflow weir. The storage capacity of the tank was chosen such that the total storage capacity of sewer network and that of the tank corresponded to Figure 2.1 (from 100% to 300%). Figure 2.2 shows that CSO volume decreases while the storage capacity of the tank increases.

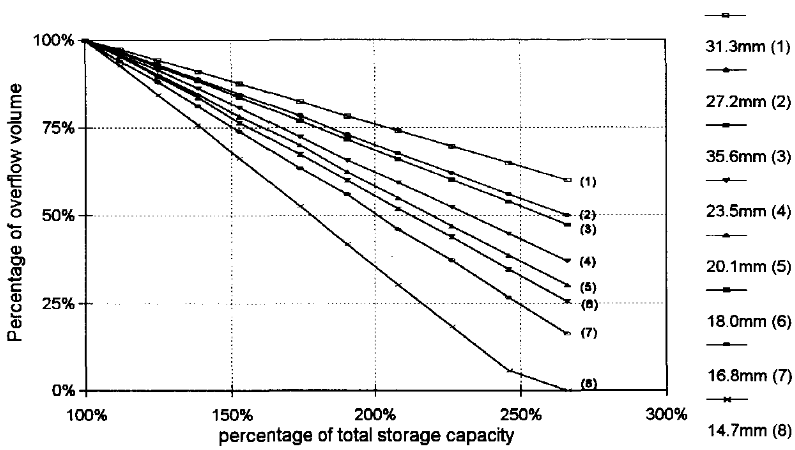


Figure 2.2 Sensitivity analysis of CSO volume against total storage
(i.e. in-sewer storage was kept constant while tank storage was increasing)

The third system variable investigated was the size of impervious surface. The original value (15.8 ha) was multiplied by a factor of between 60% and 120%. The CSO volume in mm was still related to the original value in order to compare the sensitivity with other system variables. Figure 2.3 shows that reducing the impervious area (so-called "source control") is an efficient method of reducing CSO volume.

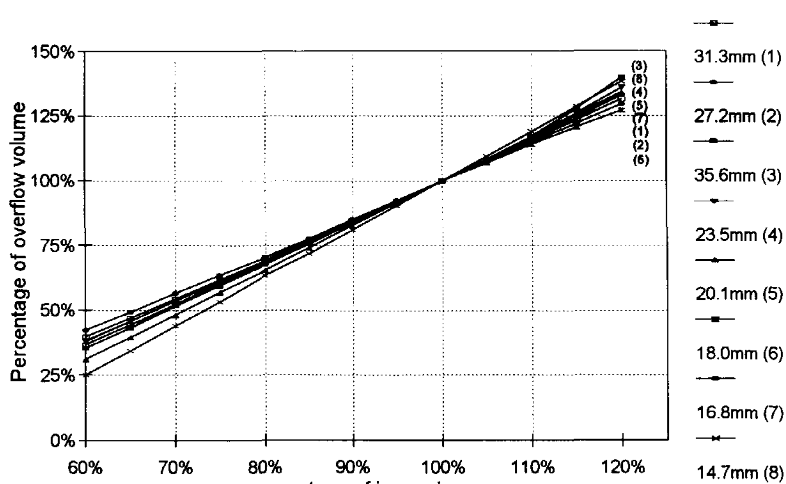


Figure 2.3 Sensitivity analysis of CSO volume against impervious area

Pumping capacity was also investigated. Figure 2.4 shows that the gradients of the eight lines obtained are rather dependent on the individual rainfall events. It is remarkable that CSO volume does not decrease significantly as the pumping capacity increases after it reaches twice of its original capacity. This is because the conduits connected with the pump were not enlarged accordingly.

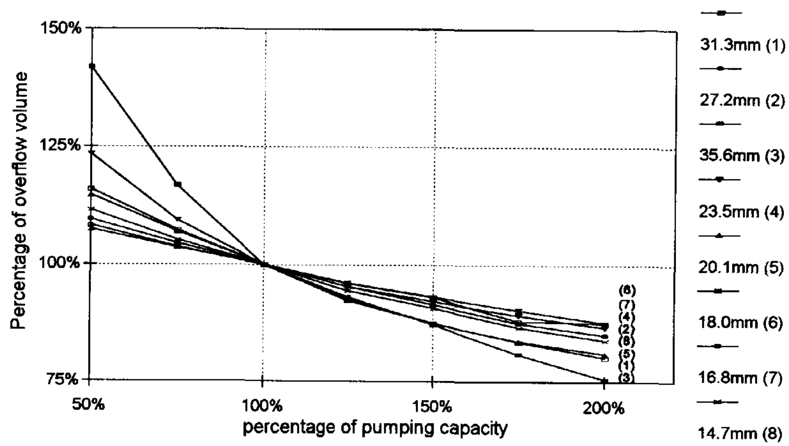


Figure 2.4 Sensitivity analysis of CSO volume against pumping capacity

Finally, hydraulic roughness of pipes was investigated. The original values of the hydraulic roughness of pipes was 2 mm (i.e. k_s in Colebrook-White equation) for the bottom one-third and 1.5 mm for the top two-thirds of a pipe section. The two original values were multiplied by a factor of between 0.5 and 3.0 and the results showed that hydraulic roughness could be negligible for CSO volume (figure not shown here).

The systematic simulations described above demonstrate that CSO volume can be analysed using the four system variables: in-sewer storage, tank storage, impervious area and pumping capacity. For the first three varables, a regression analysis has been carried out. Table 2.1 and Equation (2.10) show the results of CSO volume v.s. these three system variables.

Table 2.1 Regression coefficients of CSO volume v.s. *B*, *T* and *A* (V_{CSO} = ax + b, x = *B*, *T*, *A*)

CSO	Depth of the eight rainfall events in mm								
volume	31.3mm	27.2mm	35.6mm	23.5mm	20.1mm	18.0mm	16.8mm	14.7mm	average
vs *B*: *a*	-1.10	-1.09	-1.11	-1.10	-1.10	-1.07	-1.08	-1.10	-1.10
b	25.3	21.5	20.3	18.0	16.7	16.1	15.1	11.9	18.20
vs *T*: *a*	-0.97	-0.97	-0.95	-0.95	-0.95	-0.95	-0.96	-0.95	-0.96
b	24.7	20.8	19.6	17.2	15.9	15.3	14.2	11.8	17.46
vs *A*: *a*	1.92	1.47	1.59	1.26	1.21	0.99	0.96	0.86	1.28
b	-10.5	-7.3	-10.0	-7.3	-8.0	-5.3	-5.6	-6.3	-7.55

$$
\begin{aligned}
V_{CSO} &= -1.10B + 18.2, \\
V_{CSO} &= -0.96(B+T) + 17.5, \quad B=constant \\
V_{CSO} &= 1.28A - 7.55
\end{aligned}
\tag{2.10}
$$

where V_{CSO} = CSO volume, mm
B = in-sewer storage capacity, mm
T = storage of the off-line tank, mm
A = size of impervious surface, ha

As Table 2.1 and Equation (2.10) show, CSO volume is rather sensitive to the in-sewer storage capacity as well as the tank storage.The average CSO volume caused by the eight rainfall events was 12.7 mm. An increase of 1 mm in-sewer storage or tank storage (i.e. 20% of the original value of 5 mm) will reduce the CSO volume by 1.1 mm or 0.96 mm (i.e. 8.7% or 7.6%) respectively. CSO volume is very sensitive to the impervious area with a sensitivity of approximately 1.3 mm/ha, which means that a reduction of one hectare (i.e. 6.3% of the original value of 15.8 ha) in impervious area will cause 1.3 mm (i.e. 10.1%) less CSO volume. In practice, the impervious area is rather difficult to estimate accurately and this is probably the main uncertainty involved in applying hydrodynamic models.

Equation (2.10) is useful to estimate CSO volume from the three key variables for the sewer system of Loenen. However the regression coefficient *a* of the first two variables is more consistent than that of the third one. Thus CSO volume can be predicted more reliably using the first two variables than the third one.

2.6.3 CSO emission

CSO volume is not much representative of CSO emission, as concluded from the NWRW research programme. For example, two overflow events which have the same size of volume may have rather different size of emission, because the concentration of pollutants may vary significantly. It is one of the reasons why water quality modelling has been one of the most popular research topics on urban storm drainage. HydroWorks QM is one of the main products for water quality modelling. As stated in **2.5.1**, the two basic processes for sediment movement over the impervious surface are: sediment buildup and washoff. HydroWorks QM adopts these processes. In the sewer network, Ackers-White's model is used. Due to the many uncertainties involved in the quality modelling approach, it is necessary to investigate which variables the CSO emission is sensitive to. These results will be very useful for further study of (conceptual) quality modelling. The solution of Equation (2.3) is as follows,

$$
p = p_0 e^{-kt} + \left(\frac{p_s}{k}\right)(1 - e^{-kt}) \tag{2.11}
$$

where p = mass of sediment after dry weather period (t in hour), kg/ha
p_0 = initial mass of sediment before dry weather period, kg/ha
t = dry weather period, h
k = sediment decay factor, 1/d
p_s = surface buildup factor, kg/ha/d

Washoff processes can be conceptually represented by Equation (2.4) and (2.5), which, however, cannot be solved explicitly. The default value of the washoff coefficient calculated from Equation (2.5) was used. The four variables that were investigated concerning sediment movement on the impervious surface were p_0, t, k and p_s.

For sewer networks, the uniform sediment depth in sewers (h_s) is the only variable to be investigated. This is due to the fact that HydroWorks QM presently allows only this quality variable input for modelling sediment movement in sewer networks.

The same eight rainfall events from the last section were used for this investigation. The default values of the five variables are presented in the following table.

Table 2.2 The default values of the five variables of investigation

variable	p_0 (kg/ha)	p_s (kg/ha/d)	k (1/d)	t (hour)	h_s (mm)
value	60	6	0.08	30	40

The first variable to be investigated is the initial mass of sediment (p_0) on the impervious surface. In total, six values of p_0 were used, from 0 kg/ha to 80 kg/ha. Figure 2.5 shows that the total CSO mass per hectare is almost linearly increasing v.s. the initial mass of sediment on the impervious surface. The average gradient of the eight lines is approximately 0.49, which implies that approximately the half of the increase of mass on the impervious surface will lead to the total CSO mass. When p_0 is larger than 75 kg/ha (i.e. 125% of the original value), the total CSO emission remains constant. This is because there is a limiting value for the accumulated mass on the impervious surface in case the buildup time becomes too long. This limiting value is p_s/k = 6/0.08 = 75 kg/ha. This means that the initial mass of sediment on the impervious surface will never exceed 75 kg/ha.

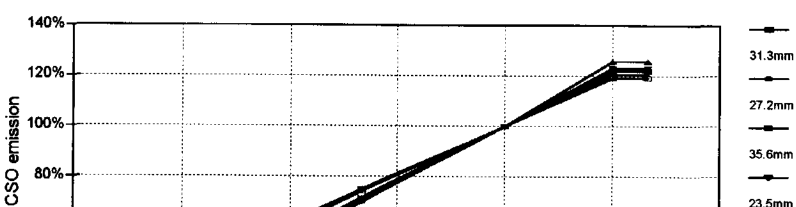


Figure 2.5 Sensitivity analysis of CSO emission against initial surface sediment

The second important variable is the surface sediment buildup rate (p_s). In total five values of p_s have been used from 6 kg/ha/day to 30 kg/ha/day. Like Figure 2.5, the total CSO emission per hectare is also almost linearly related to the surface buildup rate. The average gradient of the eight lines is approximately 0.70, which is significantly larger than that of Figure 2.5. This implies that the surface buildup rate has more influence on the total CSO mass than the initial mass of sediment. This conclusion is drawn from the results of the eight event-based simulations. In the case of continuous simulation, the surface buildup rate is even more important than the initial mass of sediment, because the former will become the determining factor for the sediment mass accumulated on the impervious surface, and the latter will be quickly "overwritten".

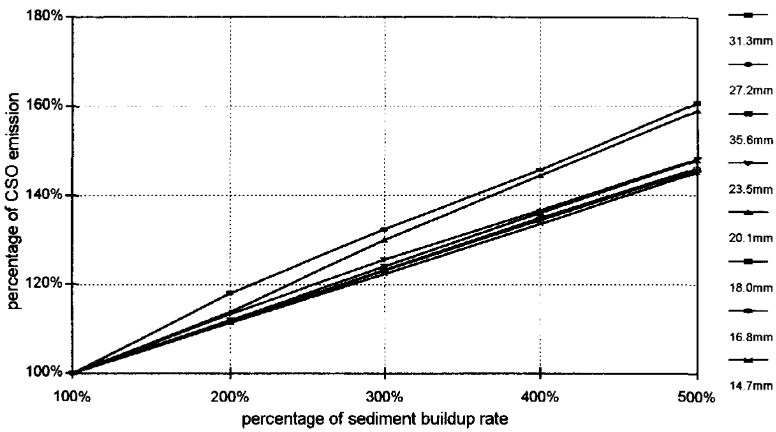


Figure 2.6 Sensitivity analysis of CSO emission against sediment buildup rate

In general, the buildup decay factor has a small influence on the total CSO emission from overflows. Figure 2.7 shows two different distributions of the lines between CSO emission and buildup decay factor. In particular, when k increases from 25% to 125% of the original value, the average CSO mass decreased only from about 108% to 98%, except for the third rainfall event which decreases from about 112%. However when k increases from 125% to 175%, the average CSO emission decreased from about 98% to 70%. Thus $k = 0.1$ /d (i.e 125% of the original value) is the key value which classifies the two different distribution domains. This can be explained as follows: the default value of the initial mass of sediment on impervious surface was $p_0 = 60$ kg/ha, the buildup rate was $p_s = 6$ kg/ha/d. The limiting factor $= p_s/k$ should be equal to or larger than p_0, thus k should not be larger than $p_s/p_0 = 0.1$ /d, which is exactly equal to the key value of k. This also implies that the second domain is not reliable for sensitivity analysis.

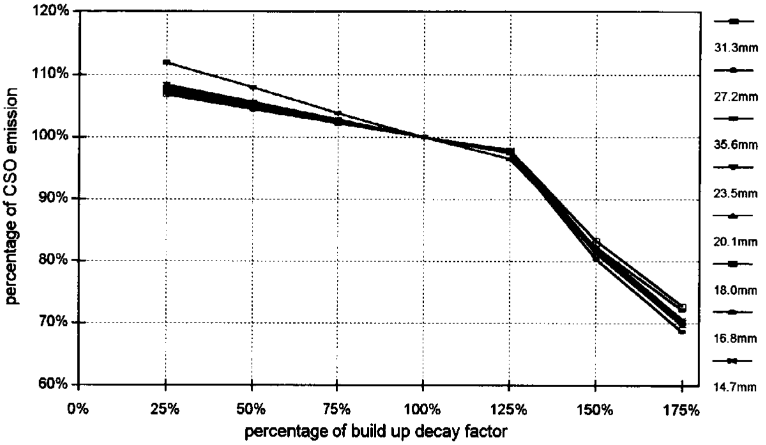


Figure 2.7 Sensitivity analysis of CSO emission against buildup decay factor

Figure 2.8 shows clearly that sediment buildup time is not very important for the total CSO emission. Of course this conclusion is based on the default value of sediment buildup rate of 6 kg/ha/d. If we use larger value of buildup rate, for example 30 kg/ha/d, the sensitivity of buildup time will be somewhat larger for the total CSO emission.

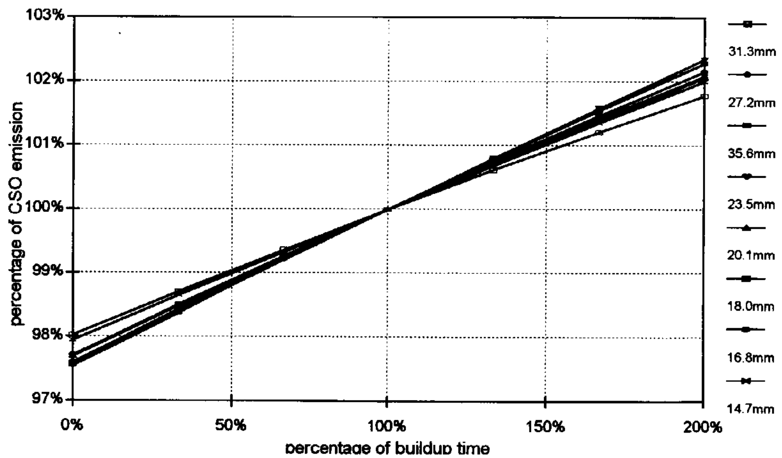


Figure 2.8 Sensitivity analysis of CSO emission against sediment buildup time

The last variable that has something to do with the total CSO emission is the sediment depth in the sewer network. As stated previously, Ackers-White's model (see **2.5.3**) is currently used in HydroWorks QM. Most variables and parameters of the model use the values from the results of quantity simulation or default values. Only one quality variable is left to the users, namely, the uniform sediment depth in sewers. This is of course not the case in practice. However no detailed quality data of sediment depth in sewers are in practice available. Therefore Figure 2.9 gives only an indication of the influence of sediment depth on the total CSO emission. The distribution of the lines is not as linear as other variables shown above. One of the rainfalls shows an abnormal distribution. This is probably related to the characteristics of this specific rainfall and the numerical solution of the software.

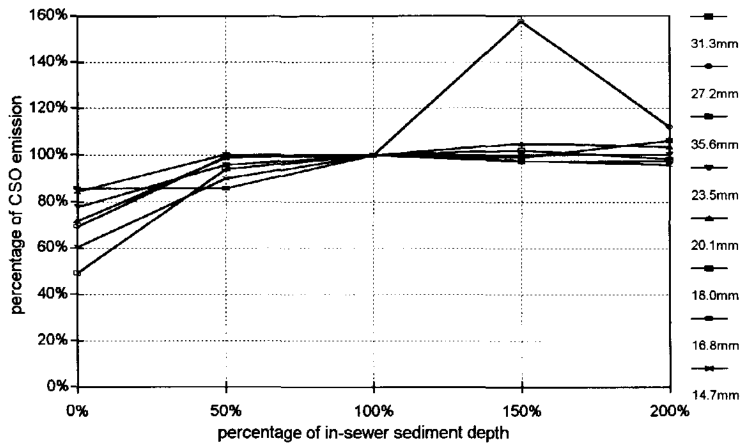


Figure 2.9 Sensitivity analysis of CSO emission against uniform depth of sediment in sewers

2.7 Summary

One of the present modelling approaches concerning CSO emission is to develop and to use physically based hydrodynamic models. The physical processes involved in the rainfall-runoff transformation and overland routing are well understood and can be described mathematically. However the uncertainty in rainfall data and the complexity of catchment surfaces cause an inaccurate input hydrograph to the sewer network. The use of Saint-Venant Equation for flow routing in the sewer network is not always necessary, in particular for sewer sysems serving a flat catchment, it is not of great importance for the overall accuracy of the system.

However the simulation time required by the present hydrodynamic models, like HydroWorks, is still too long for a complicated and large sewer system, particularly for long-term simulations. Additionally the amount of input data required is large, and may contain many uncertainties. The sensitivity analysis shows that CSO volume is rather sensitive to impervious catchment area, storage capacity of the sewer network, an off-line tank behind each overflow, and the pumping capacity. A small error in impervious area (e.g. 5-6%) will cause a significant deviation in the simulation result of CSO volume (e.g. 10%). In fact it is rather difficult to estimate the impervious catchment area accurately in practice. Hence this is the main uncertainty involved in water quantity modelling. Because most hydrodynamic models have a combination of a conceptual rainfall-runoff transformation and a physically based Saint-Venant Equation for sewer flow routing fed by a large amount of uncertain data for the complex geometry of the sewer system, they are not cost-effective, and may, hence, not be reliable at all.

The water quality aspects of combined sewer systems are much more difficult to investigate, due to the stochastic behaviour of sediment movement in the sewer system (catchment + sewer network). Various publications have shown that sewer sediments are difficult to characterise. The characteristics of sewer sediment, such as median grain size, settling velocity, cohesion, polluting strength, shear stress, transport mode and biodegradation, first foul flush are still not well known. Solids build-up and wash-off are two conceptualised processes involved in modelling the movement of solids on impervious surfaces. Ackers-White's model has been modified for predicting sediment transport in sewers.

The sensitivity analysis of one of the widely accepted water quality model, HydroWorks QM, shows that CSO emission is very sensitive to the initial mass of sediment on an impervious surface and to the sediment buildup rate. These two variables are almost impossible to measure in practice. Normally they are given a value determined by calibration. Obviously this will lead to large uncertainties in simulation results, particularly if no calibration data are available. CSO emission is not very sensitive to sediment decay factor and sediment buildup time. The sediment depth in sewers has a small but somewhat irregular influence on CSO emission. There is no doubt that water quality simulation requires even more computation time than water quantity simulation.

Due to the underdevelopment of sewer sediment transport theories, the lack of good experimental or field data and the stochastic characteristic of sediment movement, an alternative to the present event based modelling technique for predicting CSO volume and emission is parametric modelling approach, which will be discussed in the next chapter.

CHAPTER 3 PARAMETRIC MODELLING APPROACH

3.1 Introduction

In Chapter 2, the present modelling approaches to CSO emission have been discussed. In practice, hydrodynamic models, such as SWMM, MOUSE and HydroWorks are currently applied in urban storm drainage. However, comprehensive research programmes and field surveys indicated that most processes related to urban storm drainage have a stochastic nature, like the occurrence of rainfall events, rainfall-runoff and flow routing in sewer systems. Particularly, sediments found in sewers, either in suspension or in deposition, cannot be considered as having a unique description. Inhomogeneity and randomness characterise the nature of sewer sediment behaviour (Verbanck *et al.*, 1994).

The physical processes going on within urban storm drainage as outlined in Chapter 2, show at least two facts. First, some of these processes, particularly those related to sediment movement, are not yet well understood and are somewhat ambiguously described. Second, measurement data are of great importance for urban storm drainage but they are in general not complete. To capture the stochastic characteristic of processes involved and to overcome the lack of data, this chapter will investigate the potential of a new modelling approach - a parametric approach to modelling CSO problems, such as volume, water level, discharge and emission. Considering the data available, this approach consists of two parts: regression analysis of measurement data (NWRW, 1989) and time-series modelling based on these measurement data.

Time-series models have been widely applied in practice for a long time. Well-known examples are unit-hydrograph and models based on transfer functions (Singh, 1988; Zheng and Novotny, 1991; Delleur and Gyasi-Agyei, 1994). A neural network model can be categorised as a sort of time-series model in certain forms (Gong *et al.*, 1995; Mason *et al.*, 1996). Additionally, time-series models are expected to be useful in real time control of sewer systems due to their efficient predicting (forecasting) capacity. The uncertainty analysis of model parameters can be found in Lei and Schilling (1994).

3.2 NWRW database

In order to extend the knowledge of the design, construction and maintenance of sewer systems and that of the negative effect of sewer emission on the quality of receiving waters, a Dutch nationwide research programme of urban storm drainage was carried out from 1982 to 1989. The research programme covered seven locations (Amersfoort, Amsterdam, Bodegraven, Heerhugowaard, Kerkrade, Loenen and Oosterhout) in the Netherlands. These locations were chosen so that different characteristics of sewer systems were included, such as combined versus separate sewer systems, flat versus steep catchments, etc.. Each location was served by a sewer system with only one overflow weir and one pumping station. Hydraulic measurement data, such as cumulative rainfall depth and water level at the overflow weir were measured. Pollutant samples were taken and analysed only when overflow events occurred. The sampling time points of hydraulic data and the pollution data were irregular and did not correspond to each other. The processes that occurred within the sewer network, such as sediment buildup, erosion and washoff, were only partly investigated. The sewer network was assumed to be a "black box": the inputs to the "black box" were the dry weather flow and rainfall; the outputs were the pumped water to the waste water treatment plant and the overflow discharges (calculated from water level). The NWRW database consists of the original measurement data, such as cumulative rainfall depth, water level, concentration of pollutants; and the derived data that are calculated from the original measurement data, such as rainfall intensity, CSO discharge etc.. The NWRW database was the most complete database of this sort in the Netherlands. Though the entire NWRW database was built and analysed, this research used the database of one location, Loenen, more extensively than others. This is because the database of Loenen is the one that is most complete.

3.2.1 Rainfall data

The rain gauge used in the NWRW research programme was a tipping-bucket meter. The rain gauge was placed three metres above the ground level near the overflow chamber. The built-in pulse-current converter registered the cumulative rainfall depth which would be later translated into the rainfall intensity.

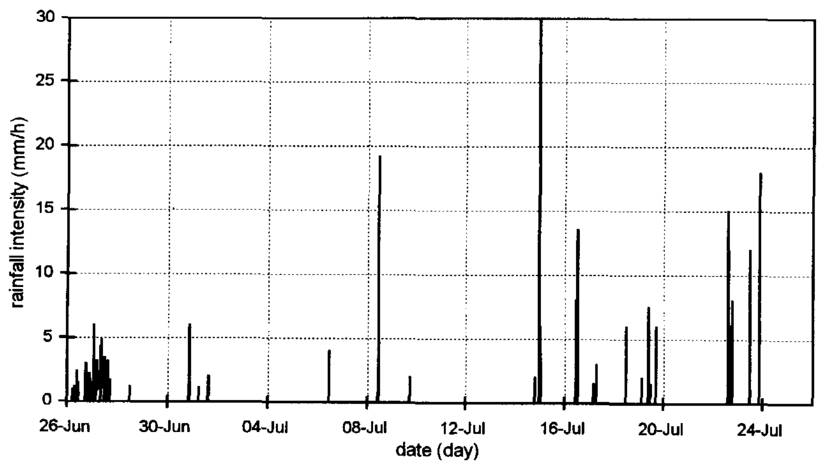


Figure 3.1 Processed rainfall data measured in Loenen (from 16 June to 26 July) in 1981

During a period of 6 minutes, if there was no rainfall, this period of wet weather was deemed to have ended; afterwards, when new rainfall occurred, the registration of the stepped lines of the next period began. For more detailed information, refer to Veldkamp (1995). Such a format of rainfall data were processed for further analysis. The time format was converted to absolute time in minutes with zero as the time at 00:00 on 1 st. January. Then the cumulative rainfall depth was converted to rainfall intensity in mm/h using Equation (2.1). Figure 3.1 shows an example of the processed data.

Based on the rainfall measurements, Veldkamp (1995) compiled a rainfall database consisting of those rainfall events that caused overflows. For example, 63 events were found to cause overflows in Loenen. The rainfall data had no constant time intervals. In order to use time-series models, these data were interpolated linearly, since no better methods were available to use irregularly measured time-series data. Two interpolation intervals were chosen: 1 minute for each rainfall event causing overflows; and 15 minutes for continuous long-term rainfall data in accordance with the standard rainfall record of De Bilt (see Appendix B). These rainfall data were used for investigating the potential of time-series models and later for developing a conceptual CSO emission model as well.

3.2.2 Water level

The water levels were measured using membrane-type pressure gauges at three points. The first gauge measured the water level below the weir crest adjacent to the overflow chamber in the sewer network. The second gauge measured the water level above the weir crest when overflows occurred. The last gauge was to measure the downstream surface water level.

The data of water levels were read from the recorder strips, depending on the presence of bends or sharp curves in the stepped lines and then stored in a similar format of the rainfall data. Water levels were also read at those moments when the rainfall data were read. Because the time registration was not constant, linear interpolation (per minute) was necessary to obtain a regular time series for water level. It was assumed that during time t_2 to t_1, the water level changes linearly from h_1 to h_2, where h_1 and h_2 are the water levels above the DWF level at time t_1 and t_2 respectively.

Since the overflow weir used in the NWRW research programme was a sharp-edged horizontal weir (Rehbock-type), the standard discharge formula of a Rehbock weir was used to calculate the overflow rate Q(t),

$$Q(t) = \frac{2}{3}\sqrt{\frac{2g}{3}}\,\mu B(H(t)-H_0)^{1.5} = 1.70\mu B(H(t)-H_0)^{1.5} \qquad (3.1)$$

where Q(t) = overflow rate, m^3/s
B = width of overflow weir, m
μ = coefficient, - (between 1.0 and 1.1)
H(t) = interpolated water levels above the weir crest, m (if $H(t)<H_0$ then $Q(t)=0$)
H_0 = level of the weir crest, m

The total overflow volume during a rainfall event can be calculated using the following formula,

$$V = \sum_i Q_i \Delta t \qquad (3.2)$$

where V = total overflow volume, m^3
Q_i = overflow rate, m^3/min (converted from m^3/s)
Δt = interpolation interval, min

The calculation results of the total overflow volume were dependent on the interpolation interval of water levels. If the interval was one minute, the calculated minimum, mean and maximum overflow volume of the 63 rainfall events observed in Loenen were 3.2 m^3 (rainfall event 14#) 1163 m^3, and 8591 m^3 (rainfall event 39#) respectively. See Appendix A for more information.

3.2.3 Pollutant concentration

Storm water samples were taken volume-proportionally, which implies that the time registration was not corresponding to that of rainfall or water level. This was because that the time interval of sampling became shorter when the overflow rate was larger. Therefore only a few samples were taken and analysed for small rainfall events. Linear interpolation was applied to the concentrations between two sampling times. This does not give a high degree of precision for concentrations. However, at present, there is no method available which is able to forecast the concentration among known concentrations. In order to avoid this problem in future research, sewage samples should be taken at a constant time interval corresponding to the constant time interval of water level. The following pollutants were analysed: Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Kjeldahl-nitrogen, Total phosphate, Suspended Solids (SS), Settleable Solids, Chloride (CL^-), Electronic Conducitivity and heavy metals.

Pollutant loads were calculated by multiplying the interpolated CSO discharge with its corresponding interpolated concentration, and the total load was obtained by adding all the loads at different time points,

$$L=\sum_i Q_i C_i \Delta t / F_v \tag{3.3}$$

where L = total load of one pollutant during one rainfall event, kg/ha
Q_i = interpolated overflow rate, m^3/min (from m^3/s)
C_i = corresponding interpolated concentration, g/m^3
Δt = interpolation interval, min
F_v = impervious catchment area, ha

Similarly, the total load of pollutants is also a derived quantity and the value is also dependent on the different interpolation intervals of water level and concentration. The measurement data from four locations (three served by combined sewer systems and one by a separate sewer system) were analysed and are summarised in Table 3.1.

Table 3.1 Mean load and concentration of CSO pollutants measured in four locations

Pollutants	COD	BOD	KJN	PTO	CL^-	TSS
mean load (kg/ha/event)						
Loenen	23.4	2.46	0.72	0.24	1.34	28.2
Oosterhout	11.5	2.74	0.60	0.19	1.00	8.60
Bodegraven	10.8	2.60	0.54	0.13	1.10	9.30
Heerhugowaard*	4.55	0.32	0.25	0.04	4.70	7.60
Mean concentration (g/m^3)						
Loenen	255	38	9.8	2.8	22	282
Oosterhout	174	45	10.6	3.2	17	124
Bodegraven	157	42	9.6	2.3	23	122
Heerhugowaard*	28	2	1.6	0.3	37	38

* separate sewer system

Tabel 3.1 shows that the separate sewer system behaves rather differently from the combined ones. Except for Chloride (CL^-), all other pollutants' load and concentration from the separate system are smaller than those from the combined ones. This means that sewer emission from this separate sewer system appears less polluting than that of CSOs. For the three combined sewer systems, the mean load and concentration of BOD have a more or less uniform distribution with the mean value of 2.60 kg/ha and 40 g/m^3. The mean TSS load from Loenen is much larger than that from Oosterhout and Bodegraven. One of the possible explanations is that Loenen is served by a relatively steep sewer system. In general, the Dutch sewer systems are flat, so it is suggested that a smaller value of TSS load, for example, 15 kg/ha per event may be chosen. For the mean concentrations of BOD and TSS, 40 g/m^3 and 150 g/m^3 may be used if no measurement data are available.

Since the objective of this research is related to CSO emission, and considering the completeness of the database, the following data processing will focus only on one typical combined sewer system, namely, that of Loenen.

3.2.4 Regression analysis

In order to predict CSO emission directly from the NWRW database, several regression equations were tried to find the relationship between CSO emission versus CSO discharge within each rainfall event. A multi-regression equation was found to fit CSO emission versus CSO discharge better than other complicated techniques of regression analysis. The equation was found to be in the following form,

$$L(t)=a_1Q(t)+a_2t+a_3 \tag{3.4}$$

where L = CSO emission, kg/min (computed from measurement data)
Q = CSO discharge, m^3/min (computed from measurement data)
t = time from the beginning of rainfall, min
a_1, a_2, a_3 = regression coefficients

Equation (3.4) is the time-dependent relation between the two variables, i.e. CSO emission and CSO discharge. In order to evaluate the predicted results, the correlation coefficient r (see Equation 3.6) was computed. Another criterion to quantify the overall goodness of fit was the percentage of the data for which the ratio $Cra = L_{cal}/L_{dat}$ was greater than 0.5 and less than 2, where L_{cal} is the computed pollutant load and L_{dat} is measured pollutant load. In total 46 rainfall events were computed using Equation (3.4). The results showed that the regression equation was able to reproduce the pollutant load for each event satisfactorily. However, the regression coefficients a_1, a_2 and a_3 were very scattered. This implies that the relationship between CSO emission and CSO discharge within one rainfall event is so "stochastic" that no common relations can ever be found using the proposed regression equation. The relationships between pollutant load and other (derived) measurement data, such as water level and rainfall intensity, were also investigated. No better results were obtained. Therefore CSO emission cannot be predicted using regression equations within a rainfall event based on the NWRW database.

Regression analysis was also applied to fit the time-independent relations among the following variables per rainfall event,

1. R: total rainfall depth, mm
2. i_{max}: maximum rainfall intensity, mm/h
3. OV_t: total overflow duration, min
4. OV_v: total overflow volume, m^3
5. Q_{max}: maximum overflow discharge, m^3/min
6. L_{tot}: total TSS load, kg
7. l_{max}: maximum TSS load, kg/min
8. C_{ave}: average TSS concentration, g/m^3
9. Ri_{max}: product of R and i_{max}, mm^2/h

Two regression equations were tried, i.e. *Linefit* and *Polyfit*,

$$\begin{aligned} &\textit{Linefit}:\ y = a_1 x \\ &\textit{Polyfit}:\ y = b_1 x^2 + b_2 x \end{aligned} \tag{3.5}$$

where $x = Ri_{max}$, R, i_{max},, Q_{max}
$y =$ OV_v, Q_{max}, L_{tot}, l_{max}, C_{ave}

The regression coefficients of *Linefit* (a_1, a_2) and *Polyfit* (b_1, b_2, b_3) are summaried in Table 3.2.

Table 3.2 Regression coefficients of *Linefit* (a_1, a_2) and *Polyfit* (b_1, b_2, b_3)

x	Ri_{max}	Ri_{max}	Ri_{max}	Ri_{max}	R	i_{max}	i_{max}	i_{max}	Q_{max}	Q_{max}	Q_{max}
y	Q_{max}	L_{tot}	l_{max}	C_{ave}	OV_v	Q_{max}	l_{max}	C_{ave}	L_{tot}	l_{max}	C_{ave}
a_1	0.053	1.164	0.0417	0.886	65.47	0.898	0.632	15.878	20.07	0.721	16.174
b_1	-.014*	1.22*	0.005*	.0123*	1.257	-.0056	0.0094	0.0343	0.228	0.0286	0.168
b_2	0.064	0.426	0.0113	0.877	31.49	1.117	0.295	14.59	11.202	-0.229	9.685

* means that this value should multiply 0.001

The correlation coefficients (r) of the regression equations can be calculated as follows,

$$r = \sqrt{1 - \frac{e^2}{\sigma^2}} = \sqrt{1 - \frac{\sum (y_i - y_i^*)^2}{\sum (y_i - y_m)^2}} \tag{3.6}$$

where y_i = an n-point data set
y_i* = fitted y_i
y_m = mean y_i
e = residual square error
σ = standard deviation (σ^2 is the variance).
Σ = sum of variable (from 1 to n)

Table 3.3 Correlation coefficients (R) of regression equations

y ↓ x→	Ri_{max} (9)	R (1)	i_{max} (2)	Q_{max} (5)
OV_v (4)	-	**0.86, 0.89**	-	-
Q_{max} (5)	**0.93, 0.93**	-	**0.87, 0.87**	-
L_{tot} (6)	**0.81, 0.84**	-	0.40, 0.41	**0.84, 0.86**
l_{max} (7)	**0.85, 0.89**	-	**0.77, 0.79**	**0.88, 0.98**
C_{ave} (8)	**0.90, 0.84**	-	**0.90, 0.90**	**0.92, 0.93**

(The first colume of values is the correlation coefficient of *Linefit* and the second one *Polyfit*)

In Table 3.3 the correlation coefficients that are around or above 0.7 are printed in **bold** letters. Table 3.3 shows that OV_v is only well correlated to R (r = 0.86 - 0.89) while the other four dependent vaiables, Q_{max}, L_{tot}, l_{max} and C_{ave} are well correlated to Ri_{max}. Furthermore, Q_{max} is also correlated to i_{max} (r = 0.87) and L_{tot} to Q_{max} (r = 0.81 - 0.84). l_{max} and C_{ave} are also well correlated to i_{max} and Q_{max}. There are therefore no good correlation between the five dependent variables and OV_t and OV_v. In practice, one can choose the appropriate independent variables, Ri_{max}, R, i_{max} or Q_{max} to predict the required dependent variables. In most cases, the independent variable Ri_{max} will be a good choice because of the following two facts,

- Ri_{max} is the product of R and i_{max} which are available without having to use any hydrodynamic models.

- Ri_{max} is well correlated to the four important dependent variables which can quantify CSO emission into receiving waters.

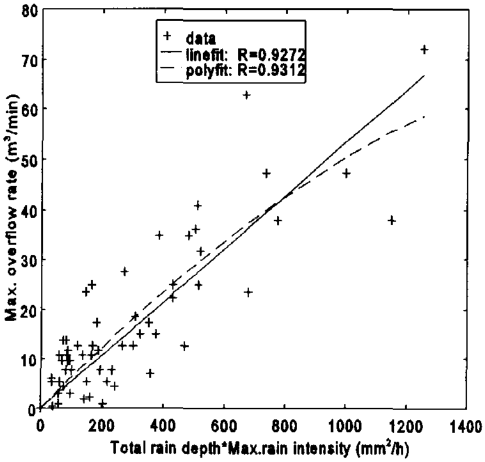
Those relationships having a correlation coefficient printed in **Bold** letter in Table 3.3 are also shown in Figure 3.2.

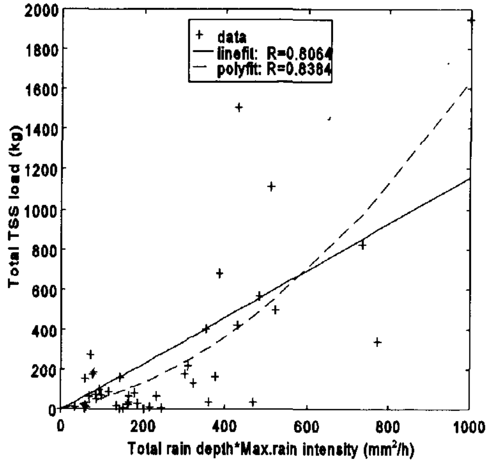
Regression analysis can be applied to the preliminary assessment studies which are intended to place an order of magnitude on CSO emission and suggest abatement strategies. For example, from Table 3.2 and 3.3, the following regression equations were established,

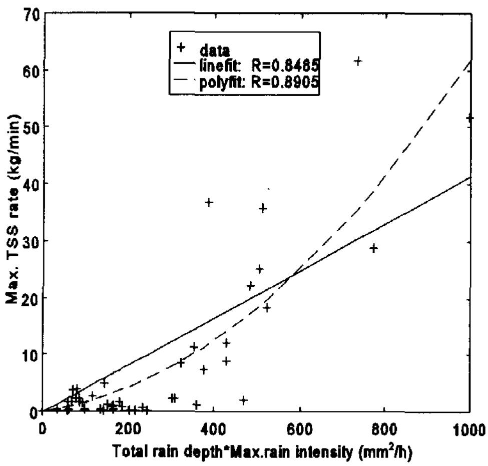
$$\begin{aligned} &\textit{Linefit}: \ L_{tot} = 1.164 Ri_{\max} \\ &\textit{Polyfit}: \ L_{tot} = 0.00122 Ri_{\max}^2 + 0.426 Ri_{\max} \end{aligned} \qquad (3.7)$$

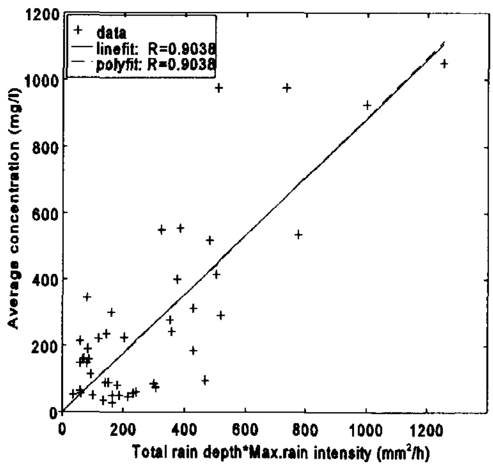
where L_{tot} = the total TSS load, kg
Ri_{max} = product of R and i_{max}, mm^2/h

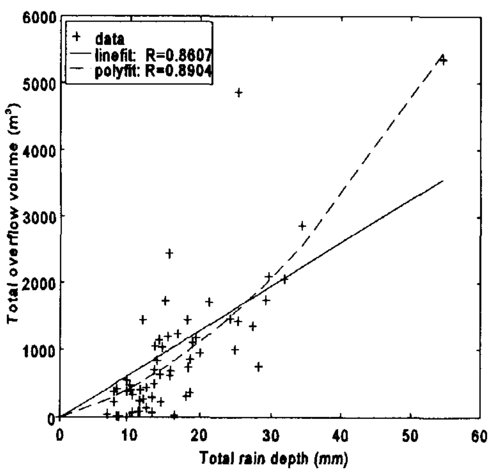
Equation (3.7) can be used for estimating CSO emisson from recorded rainfall data per event or per year. However, the equation is not able to predict the effects of adjustments to sewer systems on CSO emission, for example, enlarging diameters of the sewer network or adding a tank behind an overflow weir. Additionally, regression equations are site-specific, which implies that the equations developed under one site cannot be applied in other sites without modifications. In this sense regression equations are not useful for developing "to be" scenarios for projects of sewer systems.

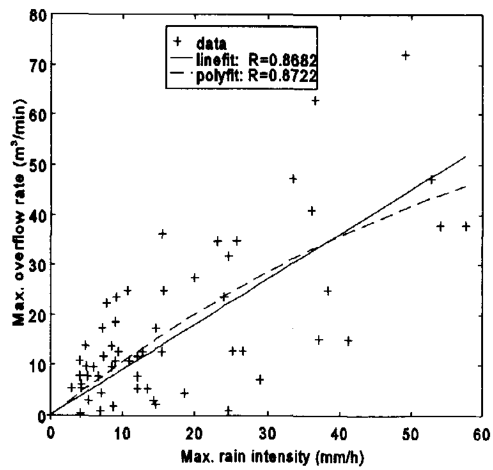

+ data
linefit: R=0.9272
polyfit: R=0.9312
Max. overflow rate (m³/min)
Total rain depth*Max.rain intensity (mm²/h)
0
10
20
30
40
50
60
70
80
200
400
600
800
1000
1200
1400

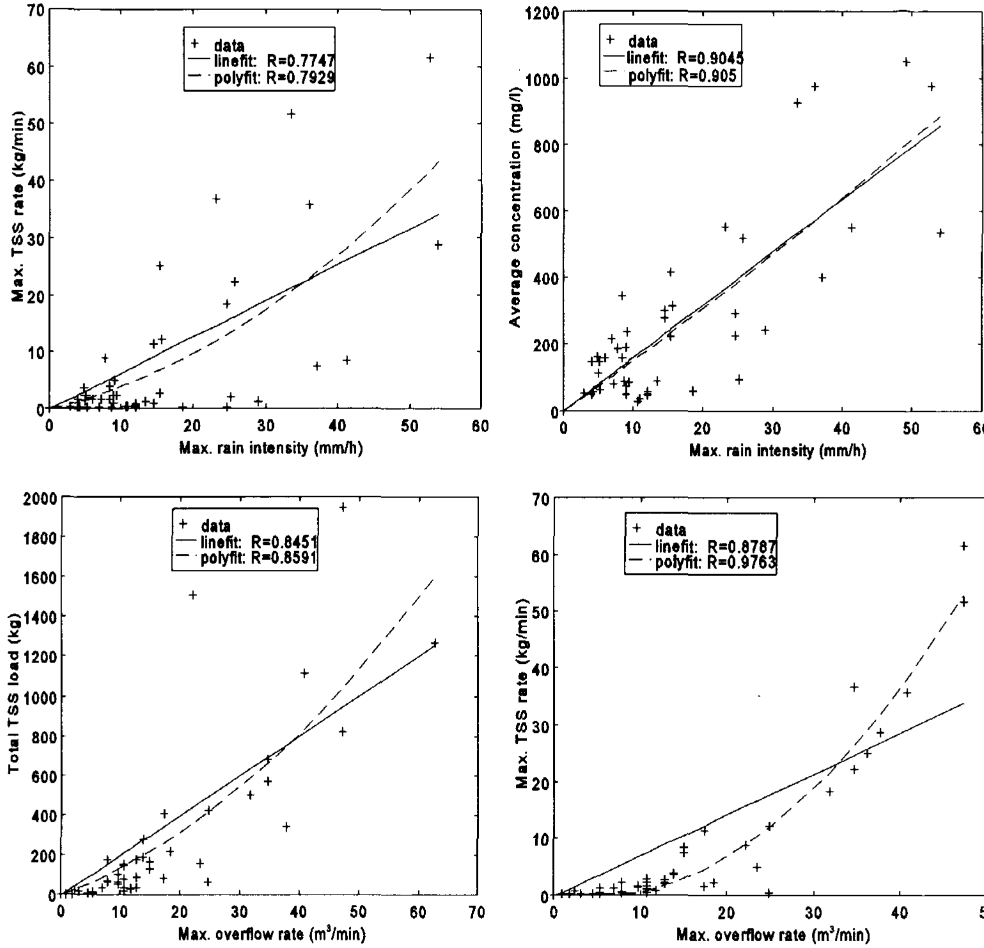

+ data
linefit: R=0.8064
polyfit: R=0.8384
Total TSS load (kg)
Total rain depth*Max.rain intensity (mm²/h)
0
200
400
600
800
1000
1200
1400
1600
1800
2000


+ data
linefit: R=0.8465
polyfit: R=0.8905
Max. TSS rate (kg/min)
Total rain depth*Max.rain intensity (mm²/h)
0
10
20
30
40
50
60
70
200
400
600
800
1000


+ data
linefit: R=0.9038
polyfit: R=0.9038
Average concentration (mg/l)
Total rain depth*Max.rain intensity (mm²/h)
0
200
400
600
800
1000
1200


+ data
linefit: R=0.8607
polyfit: R=0.8904
Total overflow volume (m³)
Total rain depth (mm)
0
1000
2000
3000
4000
5000
6000
10
20
30
40
50
60


+ data
linefit: R=0.8682
polyfit: R=0.8722
Max. overflow rate (m³/min)
Max. rain intensity (mm/h)
0
10
20
30
40
50
60
70
80



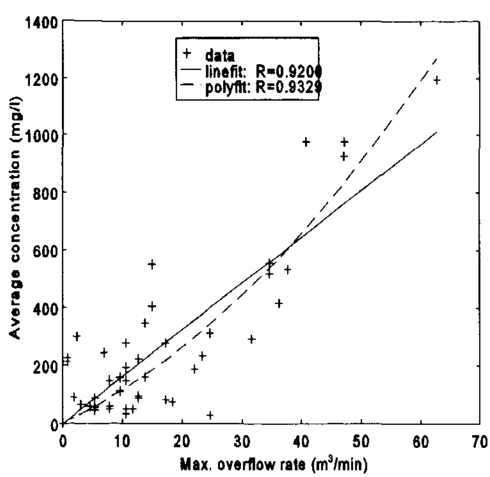


Figure 3.2 Regression analysis among different variables (data from the NWRW database - Loenen)

3.3 Time-series modelling

Most data required for urban storm drainage are time-series data, such as rainfall intensity, water level measured at an outfall, CSO discharge and pollutant load. Consequently, time-series analysis will probably be an alternative for predicting relationships for urban storm drainage, such as (net) rainfall-CSO discharge, rainfall-water level and CSO discharge-pollutant load.

Time-series models are well developed in theory and are widely applied in practice, for example, in urban storm drainage (Capodaglio, 1994; Delleur *et al.*, 1994), river hydrology (Lemke, 1991), and water resources (Homwongs *et al.*, 1994). For model development and application, only representative time-series data of end-pipe observations are needed. These models are less data intensive than physically based models and they are easily updated as new observations become available. More detaild work of time-series modelling can be found in (Ruan and Wiggers, 1996; 1997a; 1997b).

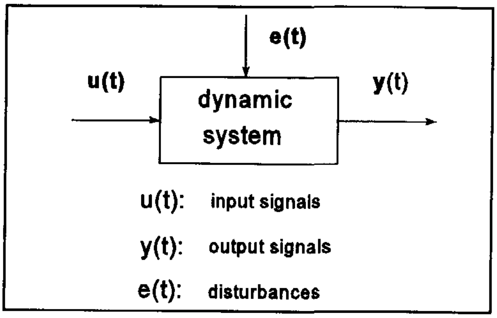


Figure 3.3 Representation of dynamic systems

Time-series analysis is normally performed using dynamic models describing the relationships between measured input signals and output signals (Ljung, 1995). The output signals are determined by the input signals and "unmeasured" disturbance signals. All these signals are functions of time. Any time series data (usually equally spread in time) can be treated as signals, such as rainfall intensity, discharge, TSS concentration, pollutant load etc.. If we denote inputs, outputs, and disturbances by **u(t)**, **y(t)** and **e(t)**, respectively, where **t** is time, the relationship can be depicted in Figure 3.3. A general input-output linear model for a dynamic system with single- or multiple-input $\mathbf{u}_i(t)$ (i=1,2,...), single-output **y**(t) and white noise **e**(t) can be written as follows,

$$A(q)y(t)=\sum_{i=1}^{n}\frac{B_i(q)}{F_i(q)}u_i(t-nk_i)+\frac{C(q)}{D(q)}e(t) \tag{3.8}$$

where nk_i (i=1,2,...,n) is the number of delays from inputs to output and q is the back shift operator, defined as, $q^{-j}\,u(t)=u(t-j)$, $q^{-j}\,y(t)=y(t-j)$, $q^{-j}\,e(t)=e(t-j)$. Here j=1,2,...and A, B_i, C, D, and F_i, are polynomials in the back shift operator q as follows,

$$\begin{aligned}
A(q)&=1+a_1q^{-1}+\dots+a_{na}q^{-na}\\
B_i(q)&=b_1+b_2q^{-1}+\dots+b_{nb_i}q^{-nb_i+1}\\
C(q)&=1+c_1q^{-1}+\dots+c_{nc}q^{-nc}\\
D(q)&=1+d_1q^{-1}+\dots+d_{nd}q^{-nd}\\
F_i(q)&=1+f_1q^{-1}+\dots+f_{nf_i}q^{-nf_i}
\end{aligned} \tag{3.9}$$

where *na, nb_i, nc, nd and nf_i* are the orders of the respective polynomials. The structure of the dynamic model is therefore determined by these parameters (i.e. *na, nb_i, nc, nd, nf_i* and nk_i, where i=1,2,...,*n*), which should be defined by trial and error. The coefficient vectors of the polynomials, $[1, a_1, \ldots, a_{na}]$, $[b_1, b_2, \ldots, b_{nbi}]$, $[1, c_1, \ldots, c_{nc}]$, $[1, d_1, \ldots, d_{nd}]$, and $[1, f_1, \ldots, f_{nfi}]$ are determined by the prediction error approach, so that the difference between the model's output and the measured output is minimised.

Within the general structure of Equation (3.8), virtually all of the usual time-series model structure is obtained as special cases as shown in Table 3.4.

Table 3.4 Various structures of linear time-series model (Ljung, 1995)

Model name	ARX	ARMAX	ARARX	ARARMAX	BJ	OE
coefficient	nc=nd=nf=0	nd=nf=0	nc=nf=0	nf=0	na=0	na=nc=nd=0
polynomial	C=D=F=1	D=F=1	C=F=1	F=1	A=1	A=C=D=1

In general, time-series models deal with a large amount of data and thus need a good software package. The toolbox of MATLAB, *System Identification* has been widely used for developing and analysing time-series models. It must be stated that the selection of model order and structure is somewhat arbitrary. A rule of thumb is that: first, many ARX models should be tested with many combinations of orders; and second, by definition, OE models uses only past inputs to predict future outputs, because of A(q) =1, so they are more powerful tools for applications.

Time-series models are generally applied to the prediction sets of data in two ways:

Prediction: The noise terms may or may not be suppressed. The predicted value $y(t)$ is computed from all available inputs $u(s)$ ($s \le t$) (used according to the model) and all available past outputs up to time t-k, $y(s)$ ($s \le t-k$). This is k step ahead prediction. The accuracy will be improved if k becomes smaller.

Simulation: The noise terms are suppressed. The simulated value $y(t)$ is computed from all available inputs $u(s)$ ($s \le t$) (used according to the model) and simulated outputs $y(s)$ ($s < t$). No past outputs are used at all. Therefore this is formally infinite step ahead prediction. However, for output-error models, there is no difference between the *k*-step ahead predictions and the simulated output, since, by definition, output-error models only use past inputs to predict future outputs.

In order to investigate the potential of time-series models in urban storm drainage, some case studies were carried out using the following simple OE model and ARX model,

$$\begin{aligned} &OE\text{-}I(Output\text{-}Error):\quad y(t)=\frac{B_1(q)}{F_1(q)}u_1(t-nk_1)+e(t) \\ &ARX\text{-}I(Auto\ Regression\ with\ Exogenous\ Input):\quad A(q)y(t)=B_1(q)u_1(t-nk_1)+e(t) \end{aligned} \qquad (3.10)$$

3.3.1 Study location

Loenen is a small Dutch town situated in a mildly sloping area (the mean slope is approximately 0.5%) with a population of about two thousand people (see Figure 5.1). The combined sewer system serves an area of 56.5 ha, of which 28% is impervious. The sewer storage capacity is about 823 m^3 or 5.2 mm related to the impervious area of 15.8 hectare. There is only one pump with a capacity of about 140 m^3 /hour and one overflow weir in this sewer system. The total sewer system can be considered a valid input-output model. The input variables are dry weather flow and rainfall (or runoff) while the output variables are water level and pollutant concentration measured at the overflow weir. In total 63 rainfall events have been quantitatively and qualitatively measured (Veldkamp, 1995). Time-series data, such as rainfall depth, CSO discharge (i.e. calculated from measured water level using the standard discharge formula, see Equation 3.1) and concentrations of overflowing water were measured without a common and constant time interval. Thus these data were linearly interpolated before using time-series models.

3.3.2 CSO discharge

CSO discharge is an important variable for quantifying CSO emission to receiving waters. It was considered useful to develop a simple relationship between CSO discharge and rainfall data, so that CSO discharge can be predicted using easly available rainfall data without having to use cost-intensive hydrodynamic models. For this purpose, NWRW data were used to investigate the potential of time series models. In Loenen, since the water level was measured with non-constant time intervals, first of all, a water level was interpolated linearly per minute. Then, the CSO discharge was calculated from the interpolated water level using Equation (3.1) for each rainfall event. Similarly, rainfall intensity was interpolated linearly per minute. The initial losses at the beginning of each rainfall event were assumed to be 1.0 mm, which were taken off before applying the time-series models. Various model structures were tried to simulate CSO discharge from the effective rainfall intensity. An OE-I model was found to fit this relationship with the best accuracy. Figure 3.4 shows the transformation of this OE-I model.

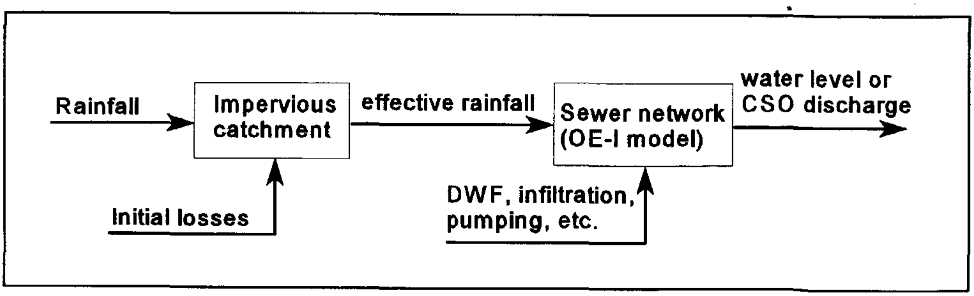


Figure 3.4 Representation of the proposed OE-I model for the sewer network

The dynamic characteristic of the sewer network depicted in Figure 3.4 is captured by an OE-I model. The parameters nb_I ,nf_I and nk_I of the OE-I model were found to be equal to 2, 2 and 1 respectively by trial and error. Figure 3.5 compares the simulated results (disturbance-free) using the same input data with the observed CSO discharge. The correlation coefficient of the simulated and observed CSO discharge was 0.96. The coefficient vectors of the polynomials were $B_1(q) = [b_1, b_2, b_3] = [0,-0.1077,0.1452]$, and $F_1(q) = [1, f_1, f_2] = [1,-1.7606,0.7732]$.

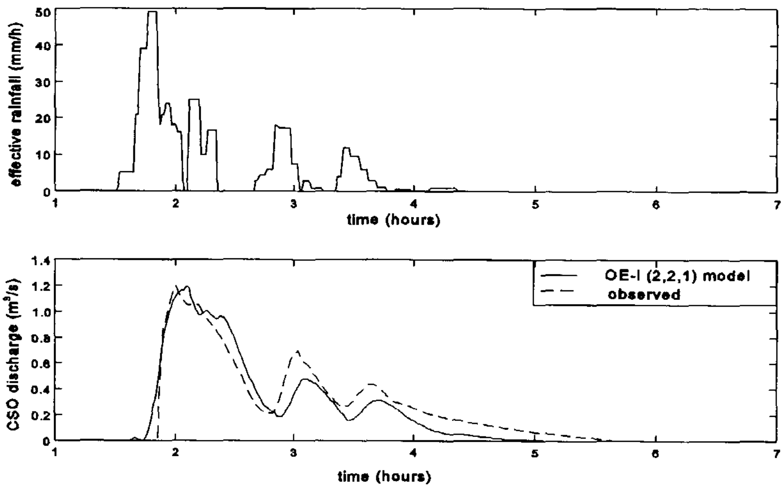


Figure 3.5 Reproduction capacity of the proposed OE-I model (53#, Loenen)

To validate this proposed model, the model was used to model another rainfall event (30#) measured in Loenen, which was very different from the rainfall event (53#) used for model building. The correlation coefficient of the simulated and observed CSO discharge of this event was 0.78.

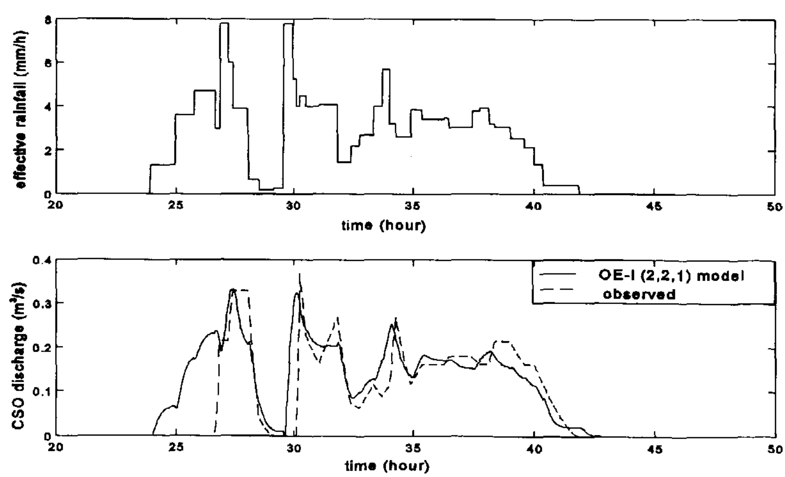


Figure 3.6 Simulated and observed hydrographs (30#, Loenen)

From the comparisons mentioned above, we can draw the conclusion that the simple OE-I(2,2,1) model is able to capture the relationship of CSO discharge versus effective rainfall intensity within a rainfall event. However, Figure 3.5 and 3.6 show that the beginning of each rainfall event was not accurately simulated. In fact, the (total) sewer storage is available at the beginning of each rainfall event and there is a time lag between the effective rainfall and the CSO discharge. These two factors were not taken into account by the proposed OE-I model. The overal accuracy of the OE-I(2,2,1) model, however, would be further improved if the regularly measured data were used, because due to the interpolation of the observed data, bias could be introduced into the dynamic input-output relationship. The same problem remains in the following cases, where CSO concentration, continuous observed rainfall depth (which was processed to rainfall intensity) and water level were linearly interpolated before using the time-series models.

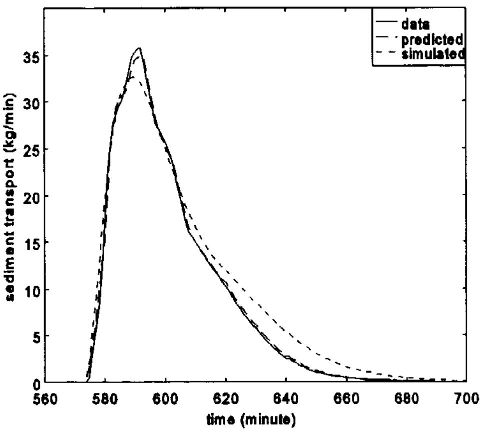
3.3.3 CSO emission

Extensive literature reviews on the applications of time series models indicate that there is little research work (Caroni *et al.*, 1984) done relating the sediment load to the flow rate during a rainfall event using time-series models. One of the reasons for this may be the lack of good measurement data which should be equally spread in time. Based on the NWRW database, some time-series models were used to try and to capture the relationship between the input (CSO discharge) and the output (CSO emission). As in the previous section, various model structures were tried in this case. For the rainfall event (35#), an ARX-I(1,1,0) model was found to fit the relationship between CSO emission and CSO discharge more accurate than others. The proposed ARX-1(1,1,0) model has a simple form,

$$L(t)=0.89L(t-1)+124.3Q(t)+e(t) \tag{3.11}$$

where Q(t) = CSO discharge, m^3/min
L(t) = CSO emission, kg/min
e(t) = unmeasurable noise (disturbance)
t = time, min

Another rainfall event (53#) was used to validate the proposed ARX-I(1,1,0) model. The predicted and simulated results are shown in Figure 3.7 and 3.8. This model was able to represent accurately the rainfall event (i.e. event 35#) used for developing the model (Figure 3.7). Both simulated and predicted results (one-step ahead) were in good agreement with the observed data. However for the validation case, the simulated results were not satisfactory. This was probably due to the bias caused by interpolation and the non-linear relationship between CSO emission and CSO discharge. In this case, the predicted results (one-step ahead) were still very accurate. However, these accurate prediction results were not very useful in practice, because one-step ahead prediction means that the CSO emission may only be predicted one minute in advance. This is even too short for a sewer system with real time control to respond and to take actions.



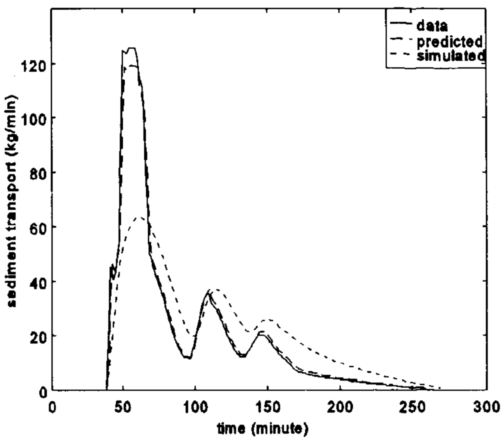


Figure 3.7 ARX model based on event 35#   Figure 3.8 ARX model validated by event 53#

3.3.4 Continuous water level

The rainfall depth and water level at the overflow weir were measured continuously in Loenen. In accordance with the standard rainfall record of De Bilt, these time-series data were interpolated linearly for every 15 minutes. Further the rainfall depth was converted to rainfall intensity. It was investigated whether water level can be predicted from rainfall intensity using time-series models. Such models based on yearly recorded rainfall data are very useful for impact studies of sewer systems, for example, to estimate the overflow frequency and the volume. It would also be possible to find a critical rainfall period when the overflows occur more frequently than normal, which can then be used for further analysis by more detailed models. In addition, the accurately predicted water level is useful for real time control of sewer systems where on-line data are available. From various model structures investigated, an ARX-I(2,2,0) was found to be the best for these time-series data. Figure 3.9 shows the stochastic representation of the proposed ARX-I model.

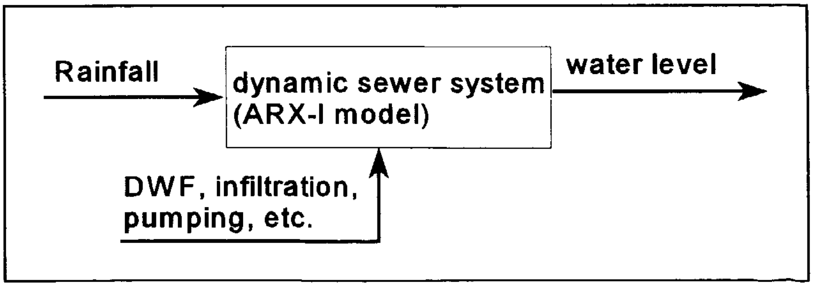


Figure 3.9 Representation of the proposed ARX-I model for the sewer system

Figure 3.10 shows the simulated and 8 step ahead predicted results using the time-series of rainfall intensity and water level measured during the early part of 1984 in Loenen.
The coefficient vectors were A(q)=[1,-1.4662, 0.4866] and B_1(q)=[0, 1.4185, 1.0918]. For the cases of simulation and prediction, the correlation coefficients were 0.92 and 0.95 respectively.

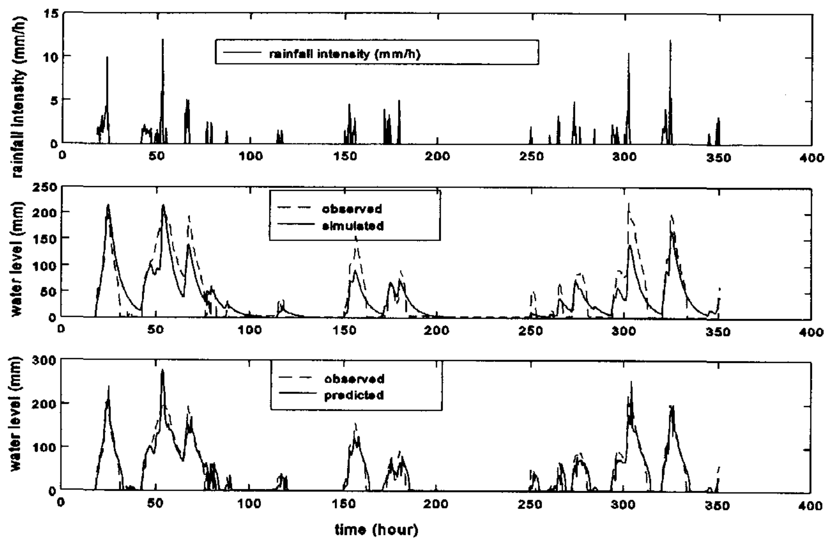


Figure 3.10 Simulated and predicted hydrographs compared with the observed one

To validate this ARX model, another fresh data series (e.g. not used for model building) of rainfall intensity and water level measured in the same year were used. The correlation coefficients were 0.89 and 0.94 for simulation and prediction respectively (see Figure 3.11). Since the time step was 15 minutes, the 8 step ahead prediction means that the water level can be accurately predicted two hours ahead. The accuracy of prediction will be improved further with less time steps. The water level predicted one or two time steps ahead was almost identical to the measured water level (not shown in this thesis). These models are very useful in real time control of sewer systems in practice, where on-line measurement data are available.

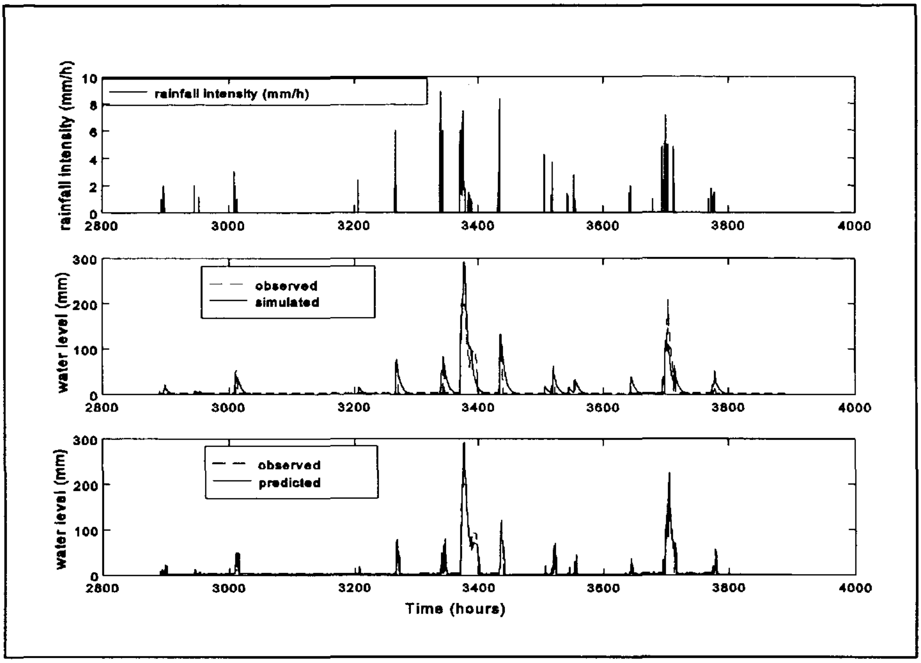


Figure 3.11 Simulated and predicted hydrographs using a fresh data set

3.4 Conclusion

The NWRW database was processed and analysed using regression analysis and time-series models. Some main results of the preliminary studies of the NWRW database are,

- for three combined sewer systems (Loenen, Oosterhout and Bodegraven) involved in the NWRW research programme, the mean TSS load and BOD load are 15 kg/ha and 2.6 kg/ ha (impervious area) respectively for each CSO event.
- the mean TSS and BOD concentrations of CSOs are 150 mg/l and 40 mg/l respectively.
- the CSO volume and emission per CSO event are correlated to the product of the total rainfall depth and the maximal rainfall intensity with correlation coefficients between 0.81 and 0.93. However, no satisfactory relationships can be found between CSO emission versus CSO discharge within each rainfall event.

Based on the NWRW database, for each rainfall event, the CSO discharge in Loenen was found to be predicted by an output-error (OE-I) model from effective rainfall intensity with sufficient accuracy; An ARX-I model has been investigated to fit the pollutograph associated with the CSO discharge. The simulated results are not satisfactory due to the bias caused by interpolation and non-linear relationship between the CSO emission and discharge. Another ARX-I model is capable of predicting the continuous water level from the rainfall intensity measured in Loenen.

In particular, the 8 step ahead prediction is very accurate in the case of water level, which is believed to be useful for applications in real time control of sewer systems.

One of the main advantages of parametric approach is that models can be developed without a deep knowledge of the physical processes going on in the system. Therefore such an approach is suitable for those systems that are not yet undersood or are too complicated to be modelled in detail. However, the parametric approach, particularly time-series modelling, requires regular series of measurement data which are not easy to obtain. There are currently no methods available for analysing irregular time-series data. Hence, these data have to be interpolated (linearly) in order to obtain a sort of synthetic regular time-series data which can then be used for time-series analysis. Bias can be introduced into the synthetic time-series data, which leads to unsatisfactory simulation results. Another limitation of a parametric approach is that the models developed for one site may not be applied in other sites without modifications (i.e. the models are site-specific).

CHAPTER 4 A CONCEPTUAL CSO EMISSION MODEL SEWSIM

4.1 Introduction

Taking into account the stochastic nature of the processes involved in urban storm drainage, a parametric modelling approach has been investigated and described in Chapter 3. The NWRW data were not evenly spread in time, which implies that an interpolation of the data had to be performed. Bias was introduced into the dynamic input-output system due to this interpolation. This caused the prediction of CSO emission to be less accurate than expected. Furthermore, parametric models are site-specific and therefore cannot be used to develop "to be" scenarios to solve "what-if" problems.

In this chapter a new approach, conceptual modelling, will be investigated. Conceptual models are normally based on simple yet sound physical concepts and relatively limited data resources. A conceptual CSO emission model, SewSim, has been specially designed and developed for continuous (quality) simulation using multiple years of recorded rainfall (Ruan and Wiggers, 1997c; 1998a).

The sewer system is conceptualized into three dynamic reservoirs: the first represents the impervious catchment surface (surface reservoir); the second represents the sewer network (sewer reservoir); and the third represents the settling tank behind each overflow (settling tank reservoir). Figure 4.1 shows the general lines of the model structure.

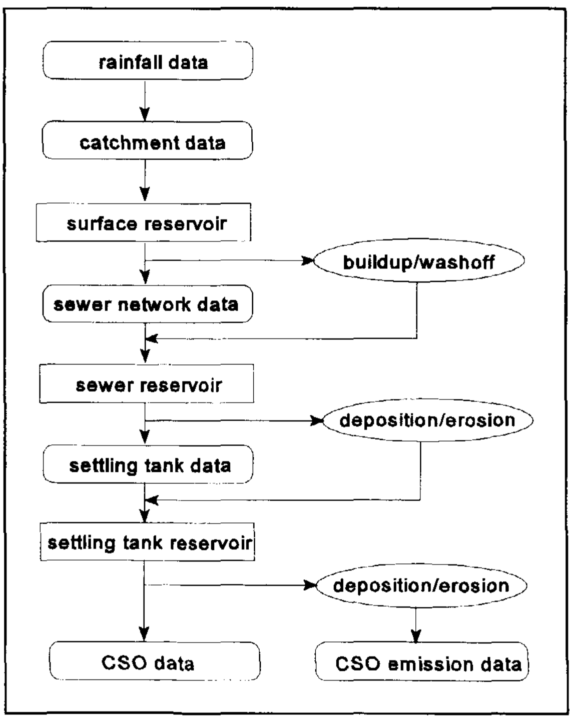


Figure 4.1 The model structure of SewSim

Only important features of each dynamic reservoir have been included in the modelling procedures to keep the model simple and efficient, such as,

• Surface reservoir: The included processes are surface runoff and overland routing (quantity); sediment buildup and washoff (quality).
• Sewer reservoir: The included processes are dry weather flow, pumping capacity and variable sewer storage handling (quantity); sediment deposition and erosion (quality).
• Settling Tank reservoir: The included processes are the filling up and storage of inflow (quantity); sediment deposition and erosion (quality).

4.2 Surface Reservoir Model (SuRM)

In the Dutch practice of urban storm drainage, catchment surfaces are normally classified as pervious and impervious surfaces. In the design of sewer networks, the impervious surface is considered to be much more significant than the pervious surface under Dutch circumstances. One of the main reasons for this is that Dutch catchments are in general very flat. Thus most of the rain falling on the pervious surface may infiltrate into the ground before it reaches the sewer inlets. On the other hand, the losses of rainfall on impervious surfaces are much smaller and most of the storm water finds its way into the sewer inlets. The losses on impervious surfaces include: initial losses (moistening and depression storage), infiltration and evaporation. The last two processes are generally considered negligible compared to the first. Thus only the impervious surface is considered and conceptualised into a surface reservoir. SuRM is required to simulate some important hydrologic and quality processes of the rainfall-runoff relationship. SuRM includes the following processes,

• Surface runoff: the transformation of rainfall to effective rainfall due to initial losses
• Overland flow routing: the transformation of effective rainfall to an inflow hydrograph
• Sediment buildup/washoff: sediment buildup and washoff on impervious surfaces

4.2.1 Surface runoff

Initial losses including moistening, depression storage and interception (i.e. infiltration) depend on the surface type and the slope. Depression storage is dominant on the impervious surface and interception on the pervious surface. Initial losses can be calculated using the following regression equation,

$$D = \frac{k}{\sqrt{S}} \tag{4.1}$$

where D = average depth of initial losses, mm
k = a coefficient, -
S = slope of the catchment, %

Equation (4.1) was first used by HydroWorks. The HydroWorks document suggests that the typical value of k be 0.07 for impervious surfaces and 0.28 for pervious surfaces. However, since the slope and the size of most Dutch urban catchments are rather small, it is possible to use absolute values for initial losses; for example, according to the new Dutch guidelines for urban storm drainage, initial losses are between 0.5 mm and 1.5 mm for flat impervious surfaces, and between 2.0 mm and 4.0 mm for roofs. Initial losses are supposed to occur at the beginning of each rainfall event. For some long rainfall events, dry weather periods during the storm may lead to the recovery of the loss potential of the catchment surface. Therefore it is necessary to take this aspect into account. It can be indirectly quantified by two factors: antecedent dry weather period and rainfall depth. For example, the loss potential can be supposed to recover 5 hours after the storm stops. However, if the antecedent rainfall has a depth smaller than the initial losses, it may need less than 5 hours to recover the loss potential of the impervious surface. The loss potential can be calculated using the following equation,

$$loss(t) = Max[loss_0 - r_{cum}(t) \cdot T_{step},\ 0] \tag{4.2}$$

Where $loss(t)$ = loss potential, mm
$loss_0$ = initial losses, mm
$r_{cum}(t)$ = cumulative rainfall intensity, mm/min
T_{step} = time resolution of rainfall data, min
t = point of time from the beginning of rainfall event, min
Max = function of taking the larger one from two values

In Equation (4.2) the antecedent dry weather period is not included, which implies that the recovery of the loss potential is not taken into account. So the equation is only suitable for short rainfall events for which the recovery of the loss potential during rainfall events can be ignored. For a continuous rainfall record, a programming routine in MATLAB/SIMULINK (1993) has been written to include the recovery of the loss potential when the dry weather period is longer than a certain value (e.g. 300 minutes). Figure 4.2 demonstrates the loss potential of an impervious surface taking into account the recovery of loss potential when the dry weather period is longer than 300 minutes.

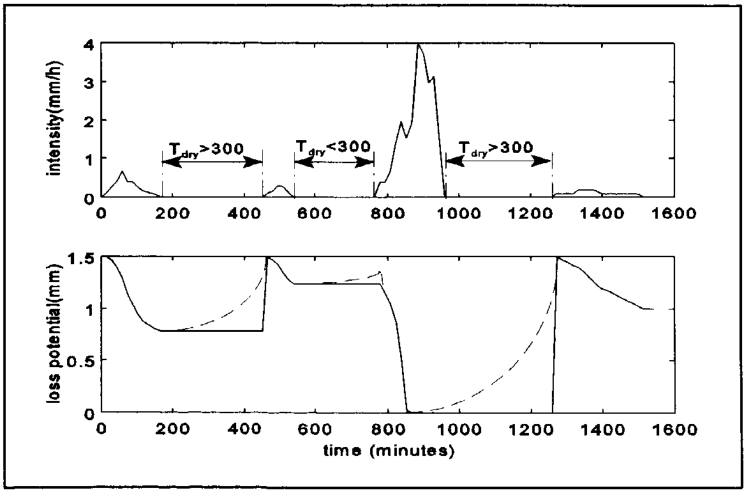


Figure 4.2 The loss potential of impervious surface v.s. rainfall intensity

It can be seen that when the dry weather period is longer than 300 minutes the loss potential recovers to its initial value (e.g. 1.5 mm) and when it is shorter no recovery occurs. The dashed lines are the real situations. However only the solid lines are implemented in the model for the purpose of efficient modelling and simulation. Besides during these dry weather periods, no overflows will occur. Therefore such a simplified process may not influence the model outputs and may give sufficient accuracy in practice. Many detailed hydrodynamic models do not take this point into account. In other words, these models do not include the dry weather periods and the recovery of the loss potential during a long rainfall event or continuous record.

As long as *loss(t)* is known, it is easy to calculate the effective rainfall intensity as follows,

$$r_e(t) = Max[r(t) - \frac{loss(t)}{T_{step}},\ 0] \tag{4.3}$$

where $r_e(t)$ is the effective rainfall intensity in mm/minute and T_{step} is the time resolution of rainfall data (e.g. 15 minutes for the standard rainfall record measured in De Bilt). The effective rainfall intensity will be used as an input variable to the overland flow routing.

4.2.2 Overland flow routing

As stated in **2.4.2,** the overland flow routing transforms the effective rainfall into the inflow hydrograph, using linear reservoirs in a series to represent the storage which is available on the ground and in minor drains, and the delay induced between the peak rainfall and peak runoff. In this way, a reduced peak runoff is generated with a lag after the peak rainfall. The overland flow routing coefficient depends on the rainfall intensity, contributing area, slope and other factors.

It has been shown that simpler reservoir-based models, which are much less computationally intensive, represent the physical processes as accurately as the more physically based approaches. For these reasons overland flow routing is modelled in various hydrodynamic models using reservoir-routing concepts. For example, a non-linear reservoir (NLR) model is used in SWMM and a double linear reservoir (DLR) model is used in HydroWorks. In the Netherlands, the new Dutch guidelines for urban storm drainage demand that a linear one-reservoir model should be used for overland flow routing with the routing coefficient c = 0.5, 0.2 and 0.1 /minute for steep, flat and extremely flat catchments respectively (RIONED, 1995). It is difficult to conclude that one form of overland flow routing model is definitely better than another. In SewSim a flexible overland flow routing model has been developed, including a *n*-reservoir model. The general reservoir-routing concepts will be described briefly below and a *n*-reservoir model for overland flow routing will be discussed. The parameter *n* can be determined by calibration with measurements. However if sewer projects have to be done in the Netherlands according to the new Dutch guidelines, *n* should be 1. For continuous simulation which is calibrated using HydroWorks, *n* should better be equal to 2.

In Figure 4.3, the effective rainfall is transformed via *n* reservoirs into an inflow hydrograph. The first reservoir can be described by the following equations,

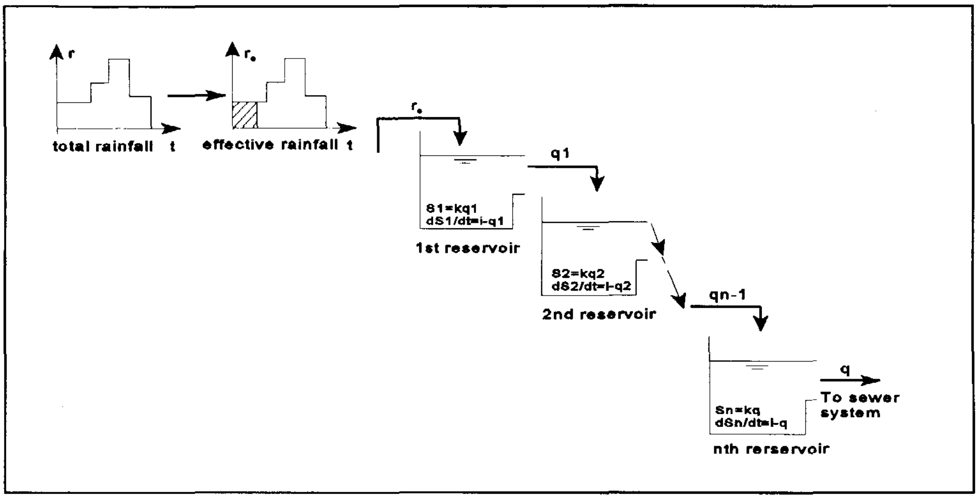


Figure 4.3 Cascade of *n* linear reservoir(s) model for modelling overland flow routing

$$\begin{cases} S_1(t) = k \cdot q_1(t) \\ \dfrac{dS_1(t)}{dt} = r_e(t) - q_1(t) \end{cases} \tag{4.4}$$

where $r_e(t)$ = effective rainfall intensity, mm/min
$q_1(t)$ = outflow of the first reservoir, mm/min
$S_1(t)$ = conceptual storage of the surface, mm
k = storage constant (or time lag), min
t = time, min

Equation (4.4) can be rewritten by eliminating the conceptual storage $S_1(t)$ as follows,

$$k\frac{dq_1(t)}{dt} + q_1(t) = r_e(t) \tag{4.5}$$

Similarly, for the second reservoir, we have

$$\begin{cases} S_2(t) = k \cdot q_2(t) \\ \dfrac{dS_2(t)}{dt} = q_1(t) - q_2(t) \end{cases} \tag{4.6}$$

Equation (4.6) can be rewritten by eliminating the conceptual storage $S_2(t)$ as follows,

$$k\frac{dq_2(t)}{dt}+q_2(t)=q_1(t) \tag{4.7}$$

From Equation (4.5) and (4.7), we have

$$k\frac{d[q_1(t)-q_2(t)]}{dt}+[q_1(t)-q_2(t)]=r_e-q_1(t) \tag{4.8}$$

From Equation (4.7) and (4.8), we have

$$k^2\frac{d^2q_2(t)}{dt^2}+2k\frac{dq_2(t)}{dt}+q_2(t)=r_e(t) \tag{4.9}$$

This is the double linear reservoir (DLR) model for overland flow routing used in HydroWorks.

Similarly, after routing through n reservoirs, we have at last the hydrograph q to the sewer system,

$$a_n\frac{d^nq(t)}{dt^n}+a_{n-1}\frac{d^{n-1}q(t)}{dt^{n-1}}+\ldots+a_1\frac{dq}{dt}+a_0q=r_e(t) \tag{4.10}$$

where the coefficient a_j's are constant defined as follows,

$$a_j=\binom{n}{j}k^j,\ j=0,1,\ldots,n \tag{4.11}$$

The n-reservoir model for overland flow routing can be solved using two numerical methods: one n-order state-space model or n one-order state-space model. For example, the double linear reservoir model (Equation 4.9) can be represented by a two-order state-space model. First we define the state vector as $\mathbf{x}(t) = [x_1(t)\ x_2(t)]^T$, where the superscript T stands for the matrix transpose operator. Let $x_1(t) = q_2(t)$ and $x_2(t) = dx_1(t)/dt$, thus from Equation (4.9), we get

$$\begin{cases}\dot{x}_1=x_2\\ \dot{x}_2=-\dfrac{1}{k^2}x_1-\dfrac{2}{k}x_2+\dfrac{1}{k^2}u\end{cases} \tag{4.12}$$

where the dot above the state variables means one-order daviation, and u is the input to the system, i.e. $r_e(t)$. In matrix notation, it becomes

$$\begin{cases}\dot{\boldsymbol{x}}=\boldsymbol{A}\boldsymbol{x}(t)+\boldsymbol{B}\boldsymbol{u}(t)\\ \boldsymbol{y}(t)=\boldsymbol{C}\boldsymbol{x}(t)+\boldsymbol{D}\boldsymbol{u}(t)\end{cases} \tag{4.13}$$

where $\mathbf{u}(t)$ and $\mathbf{y}(t)$ are the input and output vectors, i.e. $r_e(t)$ and $q_2(t)$ and

$$A = \begin{pmatrix} 0 & 1 \\ -\frac{1}{k^2} & -\frac{2}{k} \end{pmatrix};\ B = \begin{pmatrix} 0 \\ \frac{1}{k^2} \end{pmatrix};\ C = (1 \quad 0);\ D = 0 \tag{4.14}$$

Analogically, if we suppose that,

$\mathbf{x}(t) = [x_1(t)\ x_2(t)\ ...x_n(t)]^T$, where the superscript T stands for the matrix transpose operator and $x_1(t) = q(t)$, $x_2(t) = dx_1(t)/dt$, ..., $x_n(t) = dx_{n-1}(t)/dt$. Then the n-reservoir model (Equation 4.10) can be represented by a n-order state-space model (Equation 4.13) with the matrix defined as follows,

$$A = \begin{pmatrix} 0 & 1 & 0 & 0 & \dots & 0 \\ 0 & 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 0 & 1 & \dots & 0 \\ . & . & . & . & \dots & . \\ c_1 & c_2 & c_3 & c_4 & \dots & c_n \end{pmatrix};\ B = \begin{pmatrix} 0 \\ 0 \\ 0 \\ . \\ \frac{1}{k^n} \end{pmatrix};\ C = (1 \quad 0 \quad 0 \quad 0 \quad \dots \quad 0);\ D = 0 \tag{4.15}$$

where

$$c_j = -\frac{a_{j-1}}{a_n},\ j = 0,1,\dots,n \tag{4.16}$$

This n-order state-space model can be solved using the toolbox SIMULINK from the MATLAB package. The second method to solve this state-space model is, as stated above, to adopt n one-order state-space models. The numerical procedure is as follows,

1) calculate the outflow $q_1(t)$ from the first reservoir with $r_e(t)$ as the inflow to the reservoir
2) calculate the outflow $q_2(t)$ from the second reservoir with $q_1(t)$ as the inflow to the reservoir
3) repeat the procedure n times: the last outflow q(t) is the hydrograph to the sewer system

One of the advantages of this method is that the storage constant k can be non-constant, which is not possible using the n-order state-space model. A disadvantage is that this method cannot make use of the provided state-space model of SIMULINK. A loop routine in MATLAB has to be written to calculate the last outflow q(t).

As an example, a rainfall event has been used as an effective rainfall to demonstrate the overland flow routing model. The routing constant c=0.2 /min, so the storage constant or time lag k=1/c=5 minutes. Figure 4.4 shows that the ten outflow hydrographs resulted from one to ten reservoirs. Figure 4.5 shows the outflow hydrographs using one-reservoir model (c = 0.1, 0.2 and 0.5 /min) compared to those using the double linear reservoir model.

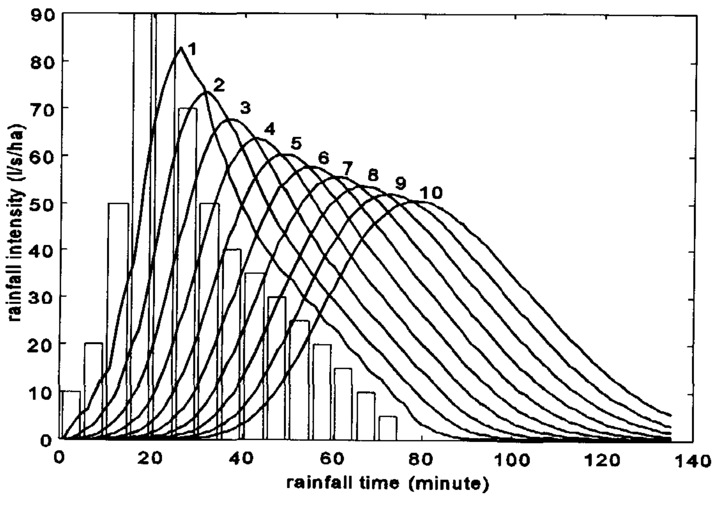


Figure 4.4 Ten ourflow hydrographs resulted from the overflow flow routing model (from 1 to 10 reservoirs)

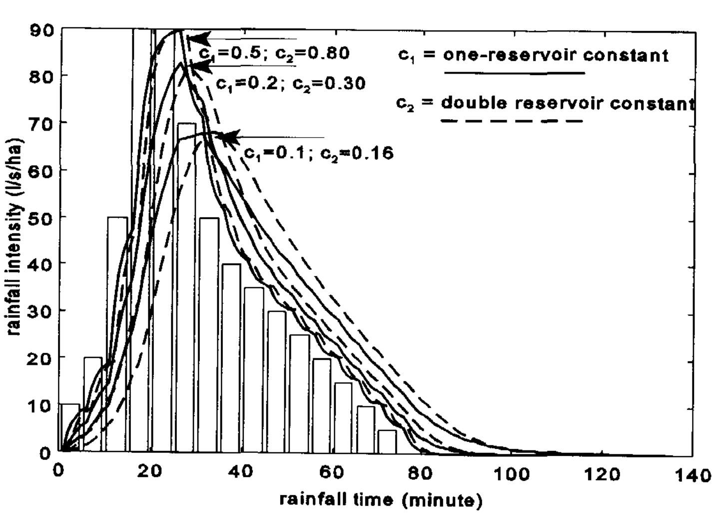


Figure 4.5 Six outflow hydrographs from one-reservoir model (solid lines) and double reservoir model (dashed lines)

The outflow hydrograph q(t) calculated using the above-mentioned method is in fact a discrete function based on one uniform catchment. If the catchment is large and has to be divided into several sub-catchments, then the different time lag of runoff from various sub-catchments to the overflow weir(s) should be taken into account. Suppose that the impervious catchment is divided into *n* sub-catchments with their sub-surface areas as A_1, A_2, A_3,..., A_n. The time lag from these sub-catchments to one of the overflow weirs is assumed to be 1Δt, 2Δt, 3Δt, ..., nΔt respectively, where Δt is the time step of simulation. If no data are available, the catchment can be divided into *n* uniform sub-catchments each with sub-area as *A*/n, where *A* is the total impervious catchment area in hectare (see Figure 4.6).

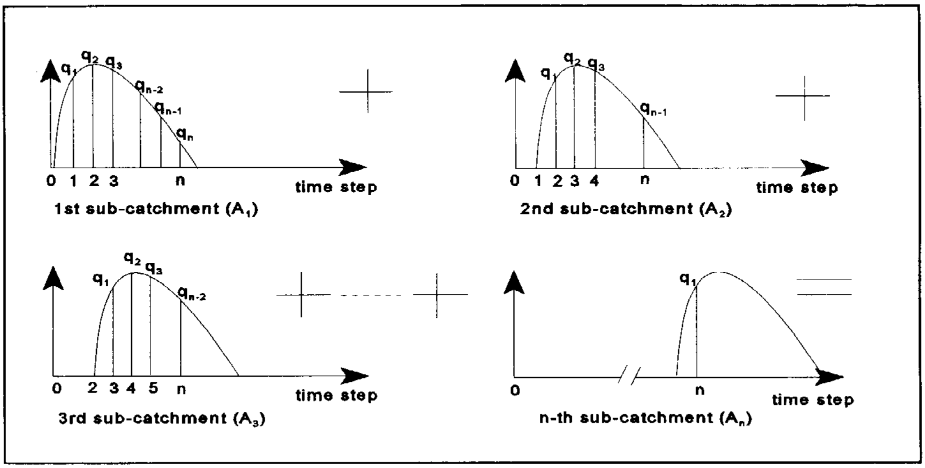


Figure 4.6 Illustration of delayed runoff rate of *n* uniform sub-catchments

Then the delayed runoff rate vector $[q_1', q_2', q_3',..., q_n']^T$ can be calculated as follows,

$$\begin{pmatrix} q_1' \\ q_2' \\ q_3' \\ . \\ q_n' \end{pmatrix} = \begin{pmatrix} q_1 & 0 & 0 & \dots & 0 \\ q_2 & q_1 & 0 & \dots & 0 \\ q_3 & q_2 & q_1 & \dots & 0 \\ . & . & . & . & . \\ q_n & q_{n-1} & q_{n-2} & \dots & q_1 \end{pmatrix} \begin{pmatrix} A_1 \\ A_2 \\ A_3 \\ . \\ A_n \end{pmatrix} \tag{4.17}$$

where in Euation (4.17), $q_i = q(i\Delta t)$ and q_i', $= q'(i\Delta t)$, i = 1, 2, ..., *n*.

The time lag mentioned above is similar to the so-called time of concentration. It is not practical to calculate the real time of concentration, which implies that the time lag should be estimated by "trial and error" using calibration data. However, for small and uniform catchments, and especially for continuous simulation, this time lag is considered not to be significant for simulation results.

4.2.3 Quality processes

As stated previously, it was almost impossible to build a fully physically based quality model due to the fact that the principles of sediment behaviour and transport are still not properly understood, in spite of much research work done on this topic. In the Surface Reservoir Model, quality processes have been modelled in a conceptual way, which, although not fully physically based, was able to give some logical and reasonable predictions of CSO emission if properly calibrated. The quality processes can be distinguished as follows,

- sediment buildup: sediments accumulate on impervious catchment surfaces
- sediment washoff: sediments accumulated on impervious catchment surfaces are washed off to the sewer inlets during wet weather
- sediment deposition/erosion in gully pots

4.2.3.1 Sediment buildup

During dry weather, various types of pollutants (normally attached to sediments) accumulate on catchment surfaces, such as atmospheric fallout, surface erosion, pavement degradation, automobile emissions and decay of organic material, construction, etc..

The build-up processes on the impervious surface were conceptually modelled as an exponential function,

$$\frac{dp(t)}{dt} = p_s - k \cdot p(t) \tag{4.18}$$

where p(t) = mass of sediment on the impervious surface, kg/ha
p_s = buildup factor of sediment, kg/ha/day
k = decay factor of sediment, 1/day
t = buildup time, day

There is a limiting value (p_s/k) for accumulated mass on the impervious surface when the buildup time becomes too long.

The solution of Equation (4.18) for a series of rainfall events is as follows,

$$p(t) = p(t_i)e^{-k \cdot t} + \frac{p_s}{k}(1 - e^{-k \cdot t}), \quad i = 0, 1, 2, ..., n \tag{4.19}$$

In Equation (4.19), $p(t_i)$ is the initial amount of solids already on the surface, which is determined by the washoff processes (see **4.2.3.2**). Figure 4.7 shows the two dependent processes: solids buildup during the period between the time t_i and the beginning of the (i+1)th rainfall event; solids washoff during this rainfall event.

Deletic *et al.* (1997) gave a different solution to Equation (4.18), shown as follows,

$$p(t) = \frac{p_s}{k}(1 - e^{-k \cdot (t' + t)}) \tag{4.20}$$

where t is the duration of antecedent dry weather period, and t' is the virtual time. The virtual time is calculated by assuming that deposition is zero at t' days before the start of the antecedent rainfall, as indicated in Figure 4.7. The virtual t' is used only to assist in the application of the exponential relationship for a rainfall series. Equation (4.19) is identical to Equation (4.20), which can be proven by means of substituting the following equation into Equation (4.19).

$$p(t_i) = \frac{p_s}{k}(1 - e^{-kt'}) \tag{4.21}$$

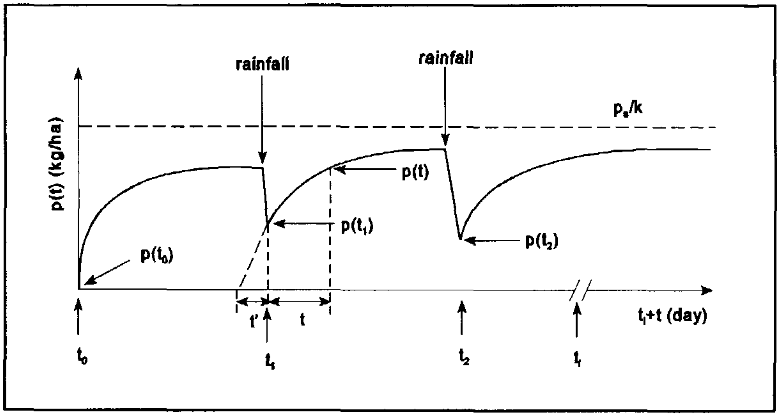


Figure 4.7 Sediment buildup/washoff processes on impervious surfaces

4.2.3.2 Sediment washoff

Sediment washoff includes the processes of erosion and dissolution of constituents from urban impervious surfaces during wet weather. It is caused by raindrop and overland flow. In Deletic *et al.* (1997) a physically based approach is presented. The model contains 1) overland flow; 2) solids entrainment; and 3) suspended solids transport by overland flow.

Due to the lack of calibration data and the uncertainties of the physically based approaches, most modelling activities for washoff from the impervious surface have focused on improvements to the various conceptual formulations (still with some theoretical basis). If properly calibrated, in fact such an approach usually works and is able to approximate observed washoff phenomena. Additionally, the simpler conceptual formulations are consistent with the state-of-the-art of urban storm drainage (Bertrand–Krajewski, 1992).

The accumulated pollutants washoff can be modelled using the "first-order" relationship to the impervious surface,

$$\frac{dp(t)}{dt} = -K \cdot p(t) \tag{4.22}$$

where p(t) = remaining mass of sediment on the impervious surface at time t, kg/ha
K = coefficient, 1/min

The coefficient K is assumed to be proportional to the runoff rate,

$$K = w \cdot r(t)^n \tag{4.23}$$

where w = washoff coefficient, 1/mm
r(t) = runoff rate, mm/min

Substituting Equation (4.23) into Equation (4.22) yields,

$$\frac{dp(t)}{dt} = -w \cdot r(t)^n \cdot p(t) \tag{4.24}$$

where n = exponent for runoff rate, $n>1$

The reason that n should be larger than 1 can be deduced from the following equation,

$$C(t) = -\frac{1}{100}\frac{dp(t)}{dt}\frac{A}{r(t) \cdot A} = \frac{1}{100} w \cdot r(t)^{n-1} \cdot p(t) \tag{4.25}$$

where C(t) = sediment concentration (e.g. TSS), mg/l
A = size of the impervious surface, ha
100 = unit factor

If $n = 1$, the runoff rate r(t) will disappear in Equation (4.25). Thus, the concentration C(t) becomes independent of the runoff rate and directly proportional to a decreasing amount of sediments remaining on the impervious surface. During a rainfall event, although a decreasing sediment concentration is a common phenomenon, it is not the only possible one, namely, it can increase during a rainfall event. Therefore, if $n > 1$, C(t) is proportional to $r(t)^{n-1}$, which implies that C(t) may increase if the runoff rate is large enough to offset the reduced value of p(t).

4.2.3.3 Sediment buildup/ washoff

Sediment buildup and washoff on the impervious surface are continuous and interactive processes, which implies that Equation (4.18) and Equation (4.24) should be solved together. We combine these two equations into one single ordinary differential equation with an equation representing the initial condition,

$$\begin{cases} \frac{dp(t)}{dt} = p_s - k \cdot p(t) - w \cdot r(t)^n \cdot p(t) \\ p(0) = p_0 \end{cases} \tag{4.26}$$

where p_0 (kg/ha) is the initial amount of sediment on the impervious surface. During dry weather, r(t)=0, which implies that sediments are accumulated on the catchment surface. During rainfall events when r(t)>0 then sediments are washed off, but the process of sediment accumulation still continues.

The effect of gully pots was modelled by means of a simple efficiency factor, which multiplies the time-depedent concentrations of sediment (e.g. TSS) calculated from solving Equation (4.26) and Equation (4.25).

4.3 Sewer Reservoir Model (SeRM)

The existing hydrodynamic models tend to use the full Saint-Venant equation to describe the hydraulic processes occurring in the sewer network. However, these models generally make use of a conceptual rainfall-runoff model. In fact the accuracy of a simulation is determined by the least accurate model, in this case, the rainfall-runoff model. Additionally the main input data to the model are rainfall records, which are stochastic in both time and space. Many uncertainties are involved in the model parameters and geometry data of sewer systems (Nielsen *et al.*, 1996). Thus, the accuracy of the model simulation may not be improved much whether or not the more detailed and complicated approaches are adopted for flow routing in the sewer network.

In accordance with SuRM described in **4.2**, the sewer network has been conceptualised into a reservoir with a certain storage capacity (i.e. SeRM). The inflow hydrograph and pollutograph from SuRM are introduced into SeRM for modelling the processes in the sewer network. Other inputs to this model are dry weather flow and if necessary the infiltration flow.

SeRM includes the following processes,

- Dry weather flow
- Pumping station
- Variable storage
- Sediment deposition/erosion

4.3.1 Dry weather flow

Dry weather flow is relatively small in quantity compared to the wet weather flow. In some cases dry weather flow may be negligible for event-based (quantity) simulation. However dry weather flow has been taken into account in SeRM. There are three considerations for this:

1) for mass balance: dry weather flow is important, particularly for continuous simulation, because the dry weather flow may be comparable to almost the total rainfall volume on a yearly basis. For example, in Loenen with a population of about 2000, the yearly dry weather flow amounts to approximately $0.9\text{x}10^5$ m^3 based on the water consumption of 120 liter per person per day, while the yearly runoff from its impervious catchment (15.8 ha) amounts to about $1.2\ \text{x}10^5$ m^3 based on the average depth of rainfall in the Netherlands (approximately 800 mm per year).
2) for initial condition: this is important for the model to describe correctly the hydraulic procecces at the beginning of rainfall events and during dry weather between rainfall events.
3) in-sewer sediment: the high concentration of pollutants in dry weather flow may influence the quality of the CSO emission.

Thus, the dry weather flow should be taken into account when predicting CSO emission. According to the Dutch guidelines for urban storm drainage, dry weather flow is assumed to be 12 liter/hour/person for event-based simulation and 120 liter/day/person for continuous simulation. The variation of dry weather flow within a day was modelled on an hourly basis (RIONED, 1995). The local data of dry weather flow may be used if available. The concentration of dry weather flow may be found in various publications (Verbanck, 1992).

4.3.2 Pumping station

For sewer systems in a flat urban catchment, pumping stations are an important ancillary to increase the hydraulic head of sewer systems. In SeRM, a pump was simply modelled with its capacity and variable working frequency during dry and wet weather. It is assumed that the pump operates regularly with a certain frequency to balance the dry weather flow. The operation time is dependent on the pumping capacity and the volume of the pumping well. During wet weather, the pump is assumed to keep operating with its full capacity when the inflow rate reaches a certain value and stops operating when the inflow rate decreases to a minimum value. These values were obtained through calibration and were found not to be sensitive to rainfall events.

The rainfall events measured in Loenen were used to verify this approach. Figure 4.8 shows the cumulative pumped volumes of the rainfall events using SewSim and HydroWorks. The total pumped volume predicted by HydroWorks was approximately 10% larger than that of SewSim. In HydroWorks, switch-on and -off levels of the pump are taken into account.

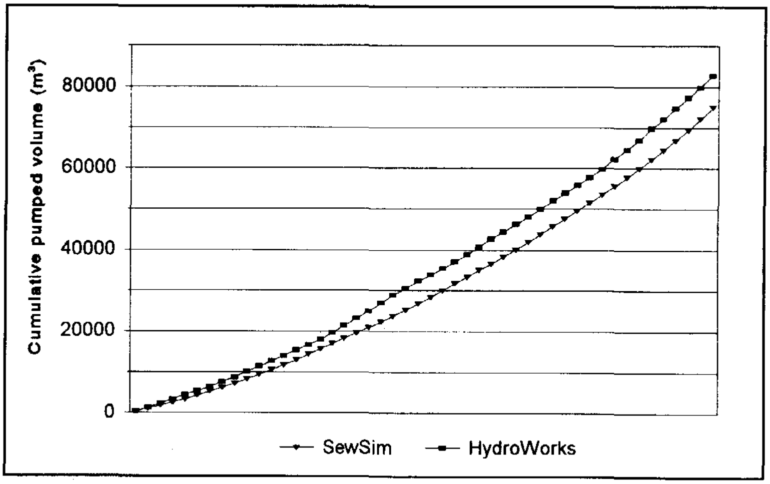


Figure 4.8 Comparison of the cumulative volumes pumped predicted by SewSim and HydroWorks

4.3.3 Variable sewer storage

In this research, the variable storage is defined as the storage capacity of the sewer network available during a rainfall event. The variable storage depends on the inflow rate and the excess pumping capacity (i.e. the total pumping capacity less dry weather flow).

Figure 4.9 is an example illustrating the variable sewer storage during the rainfall event 18# measured in Loenen. After the first initial loss period, the inflow rate was larger than the excess pumping capacity, so that the water level was rising and the variable sewer storage was decreasing from the total sewer storage level (i.e. B=5.2 mm) to zero. At this moment, the full storage was used the inflow rate was still larger than the excess pumping capacity, so an overflow occurred. The overflow lasted a few hours before the rainfall intensity started to decrease and the water level dropped back to the level of dry weather flow. The variable sewer storage recovered from zero to about 2 mm when more rainfall came, but no overflow occurred again because the available storage was larger than the effecive rainfall depth. Finally the variable sewer storage capacity recovered its full value (gradually) when the rain stopped, which was needed for the simulation of the next rainfall event. The real situation (dashed line) has been simplified (solid line) for modelling purpose, which is believed not to have any influence on the prediced CSO emission.

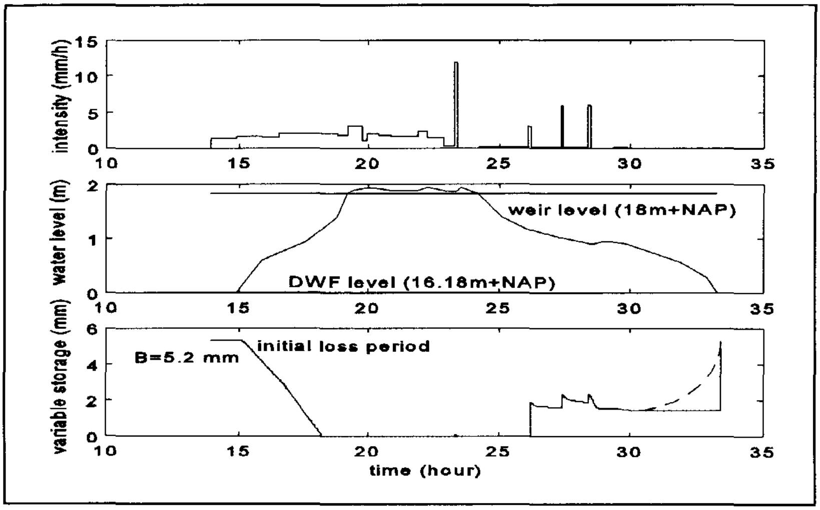


Figure 4.9 Illustration of variable storage during a rainfall event (18#, Loenen)

The principle of the variable sewer storage and excess pumping capacity related to runoff rate can be clarified by means of Figure 4.10 and the following equations.

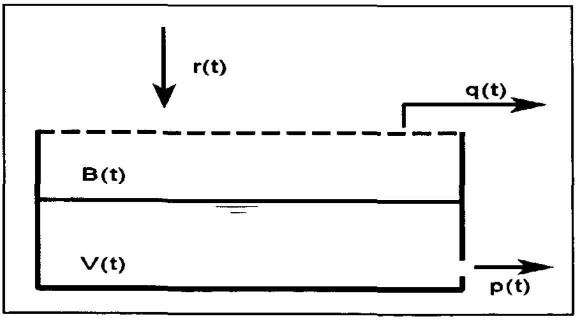


Figure 4.10 Illustration of a dynamic reservoir model

In mathematical form,

$$\frac{dV(t)}{dt} = \frac{d[B_0 - B(t)]}{dt} = -p(t) - q(t) + r(t) \tag{4.27}$$

where V(t) = water volume in the sewer network, mm; $V(t) = B_0 - B(t)$
B_0 = full storage capacity of the sewer network, mm
B(t) = variable sewer storage capacity, mm
p(t) = excess pumping capacity, mm/h
q(t) = overflow rate, mm/h
r(t) = runoff rate, mm/h

In Equation (4.27) there are two unknowns, B(t) and q(t). There are five conditions in which the equation should be solved,

1. filling phase (water level under the swich-on level of the pump), thus
p(t) = 0 and q(t) = 0 then,

$$\begin{cases} \dfrac{dB(t)}{dt} = -r(t) \\ B(0) = B_0 - V_{dry} \end{cases} \tag{4.28}$$

where V_{dry} = volume of initial dry weather flow in the sewer network

2. filling phase (water above the switch-on level of the pump), thus
p(t) > 0 and q(t) = 0 then,

$$\begin{cases} \dfrac{dB(t)}{dt} = -[r(t) - p(t)] \\ B(0) = B(t_0) \end{cases} \tag{4.29}$$

where t_0 is the moment when $p(t_0) > 0$; $B(t_0)$ is calculated from Equation (4.28)

3. overflow phase, thus
q(t) > 0 then dB(t)/dt = 0, so,

$$q(t) = r(t) - p(t) \tag{4.30}$$

4. receding phase (water level above the switch-off level of the pump), thus
p(t) > 0 and q(t) = 0, so,

$$\begin{cases} \dfrac{dB(t)}{dt} = -[r(t) - p(t)] \\ B(0) = 0 \end{cases} \tag{4.31}$$

5. receding phase (water level under the switch-off level of the pump), thus
p(t) = 0 and q(t) = 0, so,

$$\begin{cases} \dfrac{dB(t)}{dt} = -r(t) \\ B(0) = B(t_1) \end{cases} \tag{4.32}$$

t_1 is the moment when $p(t_1) = 0$; $B(t_1)$ is computed from Equation (4.31).

The variable sewer storage is very important for capturing correctly the dynamic effect of flow routing in the sewer network. As commonly known, a conventional reservoir model has two functions: it transfers the input hydrograph and it reduces the discharge peak (see Figure 4.11). It implies that there is always an output discharge if there is an input hydrograph. However, in fact the output discharge may be zero if the (recovered) variable sewer storage is large enough to store the volume indicated by the input hydrograph. Figure 4.11 shows the simulated and observed hydrographs of event 54# in Loenen. The hyetograph consists of three parts. For the first part, an overflow occurred when the total runoff volume was larger than the sum of the initial losses and the full sewer storage. For the second part, the variable sewer storage had recovered partially before an overflow occurred. Finally for the last part, there was no outflow discharge because the recovered variable sewer storage was larger than the total inflow volume.

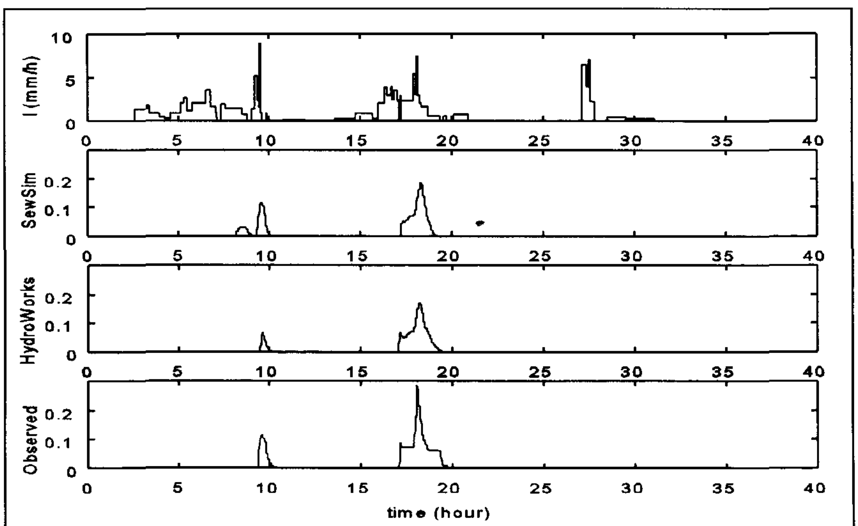


Figure 4.11 Simulated and observed hydrographs of a rainfall event (54#, Loenen)

Thus, it is significant whether or not to take the variable sewer storage into account. For example, the simple Dutch "Kuipers dots-graph" method (see **6.2**) may over-estimate overflow frequency because it does not take into account the variable sewer storage capacity "accumulated" due to the continuous pumping. However in some other cases this method may also under-estimate overflow frequency. For example, during a short but intensive rainfall event, the total effective rainfall depth may not exceed the full sewer storage plus the pumped volume, so no overflow occurs according to this method. In fact if the variable sewer storage is already occupied, it is possible that overflows still occur (Wiggers, 1991).

4.3.4 Sediment deposition/erosion

In the sewer network, there exists a deposition/erosion cycle for sanitary solids corresponding to the normal diurnal and weekly flow patten. Sewer sediments deposit during the night when the flow rate is small, and are partially re-eroded when the flow rate increases in the morning and evening. The pollutographs observed at the outlet of a combined sewer system during dry weather show variations in the sediment concentrations which are well correlated with the flow rate (Verbanck, 1992). During wet weather the deposited sewer sediments may be re-eroded and carried away to the outlets by a large inflow rate. The concentration of CSO is dependent on a large number of factors, such as inflow rate, the amount of available sediment, geometry of sewers etc.. From a conceptual point of view, the processes of deposition/erosion of sediments in sewers can be comparable to the processes of buildup/washoff of sediments on impervious surfaces. Only the boundary conditions of the processes are different. Since these processes are all significantly simplified, it does not make much sense to have a detailed and complex approach to the quality processes involved in the sewer network.

Similarly, sediment deposition and erosion in the sewer network are continuous and interactive processes. Equation (4.26) may be modified for modelling these processes, so that,

$$\begin{cases} \dfrac{dM(t)}{dt} = M_d - k \cdot M(t) - w_e \cdot Q(t)^n \cdot M(t) \\ M(0) = M_0 \end{cases} \tag{4.33}$$

where M(t) = mass of sediment in sewer network, kg/ha
M_d = deposition factor, kg/ha/day
k = decay factor, 1/day
w_e = erosion coefficient, 1/mm
Q(t) = inflow rate in the sewer network, mm/min
M_0 = the initial amount of sediment in sewer network, kg/ha

During dry weather, Q(t) should be equal to DWF plus the infiltration flow. Though the parameters M_d, k and w_e can be determined by calibration, a sensitivity analysis showed that these parameters have less significant influence on CSO emission, when compared to the initial amount of sediment in a sewer network and particularly compared to the washoff processes on impervious surfaces. So it is possible to use some default values for these parameters while the parameters of Equation (4.26) should be calibrated.

4.4 Settling Tank Reservoir Model (TaRM)

The hydraulic process of water transport in the settling tank can be simplified by a reservoir model which is somewhat similar to SeRM mentioned above. The storage (i.e. volume) of the settling tank can be treated as the variable storage capacity of the sewer network; the inflow from the overflow weir can be treated as the effective rainfall in SeRM and the outflow from the settling tank as the overflow rate from SeRM (see Figure 4.10).

If the volume of the settling tank is assumed to be V_s in mm, then the first overflow volume amounting to V_s mm will be stored in the settling tank. Only those overflows with a volume larger than V_s mm will find their way to receiving waters with a flow rate equal to the overflow rate q(t) (from overflow weir to the settling tank). Therefore it is simple to calculate the flow rate to receiving waters.

For continuous simulation, the emptying of the settling tank by means of a pump should be taken into account. The available storage capacity depends on the pump capacity and its operation frequency, which should be known for modelling the continuous functioning of the settling tank.

For quality processes involved in the settling tank, a mathematical model describing the flow and settling of sediments in tanks under time varying flow conditions has been set up by Kluck (1997). Based on the results obtained by Kluck, an effective model was established for computing the sediment settling ratio. However this fast model needs more data than a conceptual sewer model can provide, such as the inflow (horizontal) velocity and the settling velocity of sediments. One possible solution is to use the average values of velocities found in the literatures. This will involve many uncertainties and unaccuracies in the quality simulation results. Therefore this model has not been adopted in TaRM. Instead, the quality processes (deposition/erosion) in TaRM have been modelled in a similar way as in SeRM.

4.5 Summary

The conceptual CSO emission model SewSim consists of three modules: SuRM (Surface Reservoir Model), SeRM (Sewer Reservoir Model) and TaRM (Settling Tank Reservoir Model).

SuRM describes hydrologic and quality processes on impervious surfaces, such as surface runoff, overland routing and sediment buildup/washoff. Surface runoff is computed by dealing with the loss potential of impervious surfaces. Overland routing is modelled by a multi-reservoir model, which can be converted to a state-space model. Sediment buildup is modelled as an exponential function and sediment washoff is modelled using a "first order" relationship. Since the two processes occur interactively, the equations describing them are combined together with an equation for the initial condition. The parameters of SuRM can be determined by calibration.

SeRM describes flow routing in the sewer network, taking into account the varying dry weather flow, the pumping capacity and particularly the variable sewer storage and pumping capacity, which is modelled using a five-phase reservoir model. It is considered to be important for a conceptual reservoir model to include the dynamic effect of flow in the sewer network. The processes of in-sewer sediment deposition/erosion are modelled in a similar way as the quality processes in SuRM. The parameters of SeRM may use default values.

Finally TaRM describes the buffer effect of the settling tank on CSO volume and the similar quality processes, such as deposition and erosion, which are treated in a similar manner as in SeRM.

CHAPTER 5 VERIFICATION OF SEWSIM

5.1 Introduction

In Chapter 4, the conceptual CSO emission model SewSim has been described. This chapter deals with the verification of this model by means of model simulation and sensitivity analysis. The simulation results of SewSim have been compared to the NWRW measurements and the simulation results of the hydrodynamic model HydroWorks. The model simulation can be classified into two groups: quantity simulation (CSO volume and discharge) and quality simulation (CSO load and concentration). Each group consists of event-based simulation and continuous simulation. Sensitivity analysis used only event-based simulations.

Loenen was a small typical Dutch town situated in a mildly sloping area (the mean slope of sewers is approximately 0.5%) with a population of about two thousand (NWRW, 1989). The combined sewer system served an area of 56.5 ha, of which 28% was impervious. The sewer storage capacity was about 5.2 mm related to the impervious area of 15.8 ha. There was only one pump with a capacity of 140 m^3/h and one overflow weir in this sewer system. There were in total 106 nodes and 116 conduits. The largest diameter of conduits was 1250 mm and the smallest 160 mm. This sewer system was also used for the CSO volume and emission analysis described in **2.6**. The sewer network with the pump and the overflow weir is depicted in Figure 5.1.

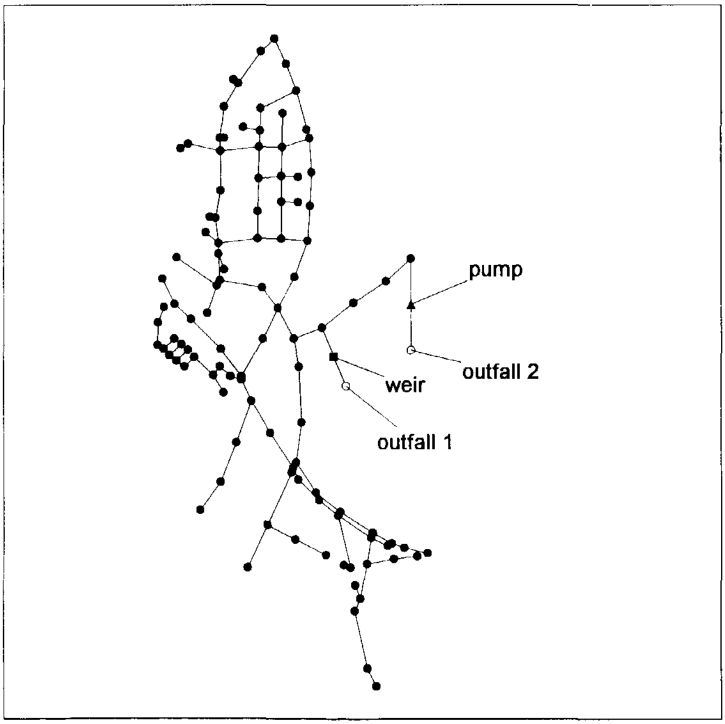


Figure 5.1 The sewer system of Loenen (one weir, one pump, two outfalls)

5.2 Types of simulation

Simulation using numerical sewer models can be classified into two catagories: event-based simulation and continuous simulation, which will be discussed in detail below.

5.2.1 Event-based simulation

Event-based simulation means that only a limited number of rainfall events are used to simulate the detailed hydraulic phenomena in a sewer system. Recently, quality simulation is included as well. In general, such a simulation is rather time-consuming and data-intensive. There are three main purposes of using event-based (hydraulic) simulation,

1) to analyse the detailed hydraulic functioning of a sewer system
2) to study surface flooding during heavy rainfall events
3) to calibrate and to verify conceptual sewer models

For the first purpose, measurement data of rainfall events have to be used. For the second one, however, some standard rainfall events are sufficient for applications. However, the obtained return period of surface flooding is not necessary the same as the return period of the rainfall events used due to the fact that antecedent conditions have a great deal of influence on the severity of a particular rainfall event. For example, a 2-year rainfall event may result in a 5- or 10-year surface flooding if the surface is already at or near saturation. Finally, the calibration of a conceptual sewer model needs several rainfall events with relevant measurement data of water level or discharge observed at outfalls. In some cases, the simulation results of a hydrodynamic model can be used instesad of measurements. However, it should be noted that model parameters adjusted through a calibration exercise for event-based simulation might not be applicable for continuous simulation, because model parameters may be affected by the antecedent catchment conditions (i.e. soil moisture, depression storage etc.) (Moffa *et al.*, 1990).

Most hydrodynamic models are almost not able to use a long series of rainfall record, so it is common practice to separate a long series of rainfall record into a number of independent rainfall events based on the maximum inter-event time. However in some cases it is rather difficult to specify model parameters to reflect the antecedent conditions of the sewer system correctly. For example, suppose that the depression storage of the impervious surace is 1.5 mm and it will be recovered after a dry period of 5 hours or more. If the emptying time of the sewer system is shorter than 5 hours, the maximum inter-event time should be 5 hours to represent the antecedent catchment condition correctly. However, if the emptying time is longer than 5 hours and we still use 5 hours as the maximum inter-event time to separate the long series of rainfall record, then the following situation will occur: the water level has not completely drawn back to the DWF level when the next rainfall event begins, which implies that these two rainfall events are actually not independent and may not be simulated separately as supposed. On the other hand, if we use the real maximum inter-event time which is longer than 5 hours, such a situation may be avoided. But another problem arises: within such rainfall events there may be dry periods longer than 5 hours but the fully recovered depression storage capacity of 1.5 mm is not taken into account for simulation. Thus such multi-events simulations using separated rainfall events are actually not identical with continuous simulation and this method is inadequate to deal with the antecedent catchment conditions and thus may result in wrong conclusions.

5.2.2 Continuous simulation

Continuous simulation involves the use of a long series of rainfall record including all the dry weather periods between the rainfall events. Apparently, continuous simulation may only be affected by the first few events but not by the antecedent condition of the catchment, thus the overall impact would be minimal. However, continuous simulation using a fully hydrodynamic (quality) model is still almost impossible due to the extremely long simulation time using the present computing facilities. There are a few methods to reduce the simulation duration, such as,

1) to separate the long series of rainfall record into "independent events" and not simulating all the dry weather periods and small rainfall events. One of the problems of this method is that it is almost impossible to specify a certain inter-event time which can be used to separate the rainfall series into really independent events as stated in the previous section. Another problem is that in general the reduction of the simulation duration may still not be sufficient for practical applications.

2) to simplify the physical sewer model. The geometry of the sewer system can be simplified, for example, small conduits and some mid-manholes can be excluded so that the simplified physical sewer model consists of less conduits and nodes. However, it is rather difficult to determine which elements of the sewer system should be removed without effecting the overall hydraulic functioning of the sewer system.

3) to use a simplified conceptual model, for example, to use a conceptual flow routing model instead of the full Saint-Vanant equation. This method will be effective in reducing the simulation time. The validity of this method is dependent on the purpose of the continuous simulation.

The general purpose of sewer flow and/or quality simulation is to provide an accurate representation of system performance under wet weather condition. As stated earlier, the simulation time of hydrodynamic models can be very long, so compromises must be made. Usually these involve running the models with only a few design rainfall events. As a result an overall picture of performance is not gained and solutions may not be cost-effective. Thus, Dempsey *et. al* (1996) suggested a simplified approach, i.e. a conceptual modelling of the key processes in urban storm drainage. They argued that although compromises are also involved for this approach, as accuracy in the more detailed description of individual events (i.e. event-based simulation using hydrodynamic models) is lost, this loss of accuracy is more than compensated for by the greater range of simulations and hence the greater overall confidence in performance assessment. Adequate accuracy is preserved by calibrating the simplified model against a small number of detailed model results or measurements. The new Dutch guidelines for urban storm drainage provide a procedure to control the performance of a simplified model against the detailed one using the standard rainfall events and there are three main criteria to check the simplified model performance (RIONED, 1995; see also Appendis B).

5.3 Quantity simulation

5.3.1 Event-based simulation

Four rainfall events were selected from the NWRW database for event-based simulation. Table

5.1 shows these four rainfall events.

Table 5.1 Four rainfall events from NWRW database for event-based simulation

event No.	date	duration (h:m)	depth (mm)	i_{max}* (mm/h)	overflow (mm)
23#	25-05-1983	27:13	34.3	9.0	18.1
30#	26-11-1983	19:50	55.0	7.8	50.9
53#	25-10-1984	03:08	25.4	49.2	30.7
63#	05-11-1984	14:30	11.8	7.4	9.2

* i_{max} is the maximal rainfall intensity

Event 23# is a normal rainfall event in terms of its total rainfall depth and overflow volume; event 30# and 63# have high overflow volumes when compared to their total rainfall depth. In particular, event 53# seems to have an overflow volume larger than the total rainfall depth! Normally no numerical sewer models will generate an overflow volume that is larger than the total rainfall depth! This implies that the deviation between the predicted overflow volume and the measured one for this rainfall event may be unusually large.

Event 23#

For event 23#, the simulated CSO volume was 16.2 mm, which was about 90% of the observed CSO volume. Figure 5.2 shows that the hydrograph simulated by SewSim has a similar distribution compared to the observed one. The simulated peak CSO discharge was 0.25 m^3/s and the observed one was however 0.31 m^3/s. This was partially due to the uncertain weir coefficient chosen for calculating the observed CSO discharge from the observed water level (see **3.2.2**).

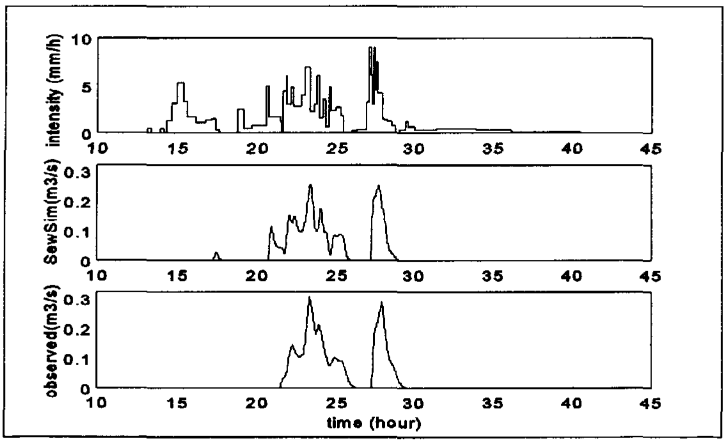


Figure 5.2 Simulated and observed hydrographs (event 23#, Loenen)

Event 30#

For event 30# two simulations using SewSim were carried out: one without calibration when the simulated CSO volume was 42.5 mm, which was approximately 84% of the observed value; the other simulation relied on calibration: the impervious area was simply enlarged to 120% of the original value. This achieved a better simulation result: the simulated CSO volume was then 47.8 mm, which was approximately 94% of the observed CSO volume. The peaks were also in better agreement with those observed (see Figure 5.3). The calibration procedure was much more easy to apply and more efficient than with the hydrodynamic models. For example, when using HydroWorks for calibrating the total contributing area, the area of each sub-catchment has to be adapted.

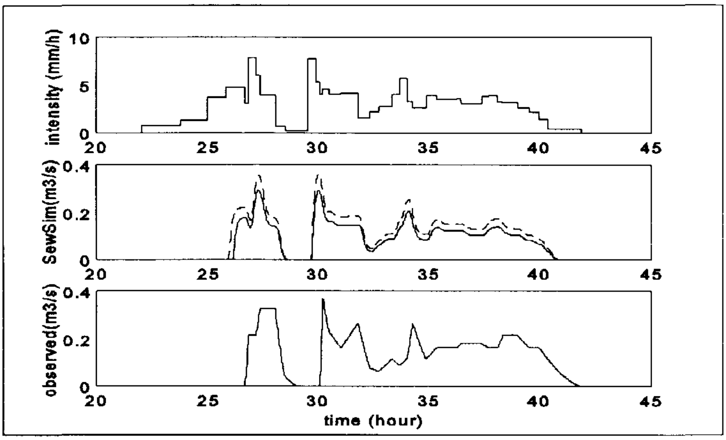


Figure 5.3 Simulated and observed hydrographs (event 30#, Loenen)
(dashed line is the simulation result with calibration)

Event 30# had also been used in Chapter 3 for developing stochastic sewer models (see Figure 3.6). As stated in that section, the beginning of the rainfall event was not well modelled due to the available sewer storage at the beginning which was not taken into account by the time-series model. Figure 5.3 shows that the form of the simulated hydrograph is in very good agreement with that observed. This implies that SewSim has performed better than the time-series model.

Event 53#

As stated above, event 53# is an unusual rainfall event, because the observed total CSO volume was even larger than the total rainfall depth. This was due to the fact that the contributing area under this rainfall event was actually larger than assumed. The simulated CSO volume using SewSim was approximately 16.9 mm (without calibration) which was only about 55% of the observed value! A HydroWorks simulation gave almost the same CSO volume, namely 16.7 mm. However the form of the simulated hydrographs was in good agreement with that observed. The simulated CSO volume after calibration (i.e. the impervious area was enlarged to 110% of the original one and pumping capacity was set to zero) was 23.3 mm, which was 76% of the observed CSO volume (see Figure 5.4). The explanation of the difference can be as follows:
The rainfall event was not uniform in space; the impervious surface was in fact larger than 15.8 ha because runoff from the pervious surface also occurred due to the saturation of the surface; the pump did not operate during the rainfall event; the observed CSO discharge and volume were not accurately calculated from the water level due to interpolation etc.. For comparison with the time-series model, refer to Figure 3.5 in Chapter 3.

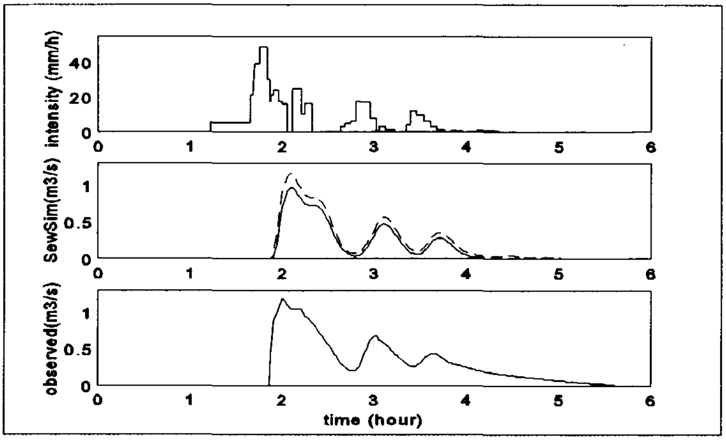


Figure 5.4 Simulated and observed hydrographs (event 53#, Loenen)
(dashed line is the simulation result with calibration)

Event 63#

For the last event 63#, the uncalibrated CSO volume simulated by SewSim was almost negligible - 1.0 mm while the observed one was 9.2 mm. Two calibrations were performed: the first was to enlarge the impervious area up to twice of the original value, and the simulation result concerning the CSO volume was considerably improved. However the form of the hydrogaph was not in good agreement with that observed (not shown here). Another calibration was to set the pumping capacity to zero which gave a simulated CSO volume of 7.4 mm, which was 80% of the observed CSO volume (9.2 mm). The simulated hydrograph was more in agreement with that observed (see Figure 5.5). This case shows that model can help detecting abnormal events observed.

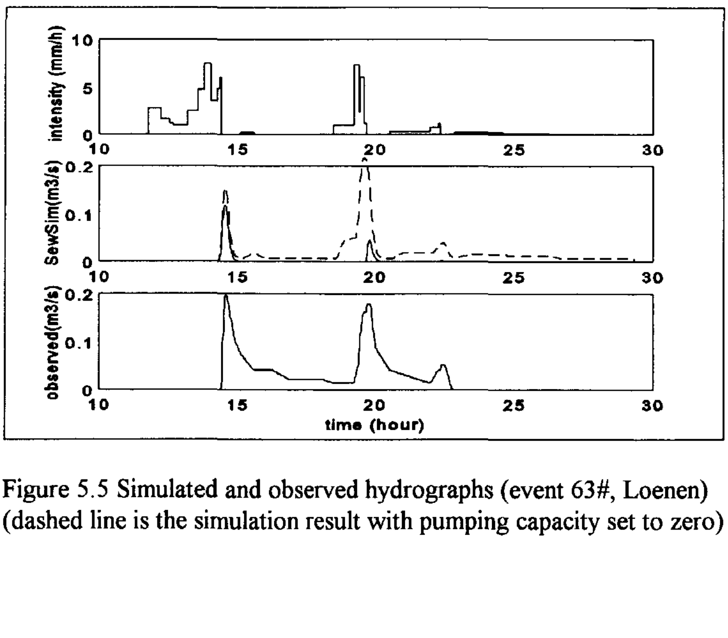


Figure 5.5 Simulated and observed hydrographs (event 63#, Loenen)
(dashed line is the simulation result with pumping capacity set to zero)

5.3.2 Continuous simulation

Verification by means of measurement data

Time-series data of recorded rainfall and overflowing water depth in a period of four and a half years (1981-1985) were processed for continuous simulation using SewSim. The data did not have a constant time step. This causes no problems because SewSim is able to use irregular time-series data. A built-in function of SIMULINK can interpolate the input time-series data automatically. The main input data to SewSim are summarised as follows,

- impervious area: 15.8 ha (imperviousness: 28%)
- in-sewer storage: 5.2 mm (in respect to impervious area)
- pumping capacity: 140 m^3/h (one pump)
- population: 2050 (Loenen)
- dry period: 8 hour (needed for recovery of loss potential)
- initial losses: 0.5 mm (impervious area)
- routing coefficient: 0.2 /min (overland flow: single reservoir model)
- routing coefficient: 0.25 /min (sewer flow routing: double reservoir model)
- time step: 15 min (for continuous simulation)

The simulation time of the recorded rainfall (4.5 years) of Loenen amounted to approximately 10 minutes with a Pentium computer (133 MHz). The outputs have a time interval of 15 minutes, including the hydrograph at the overflow, the overflow frequency and the overflow volume of the total data series. Table 5.2 shows the summary of the continuous simulation results.

Table 5.2 Summary of continuous simulation results (1981 - 1985)

year	Rainfall (mm)	Number of CSO events		CSO volume in mm	
		SewSim	observed	SewSim	observed
1981*	307	8	6	45	32
1982	357	6	6	32	12
1983	701	20	15	166	165
1984	714	23	21	158	173
1985	383	7	9	20	36
Mean	416	12	11	83	84

* only five months (from July to December) data available

The simulation accuracy of dry years (1982 and 1985) was less satisfactory than that of wet years (1983 and 1984). In the two dry years there were more rainfall events with a smaller intensity than in the wet years, for example the two most heavy rainfall events in the dry years had an intensity of approximately 60 mm/h and 80 mm/h while those were 120 mm/h and 140 mm/h in the wet years respectively. The uncertainties of inputs to the sewer system were relatively larger with smaller rainfall events. For example, the initial losses or the infiltration to the sewer system were relatively large compared to the total rainfall depth. Fortunately dry years are less important for studying sewer systems in practice. However even in wet years, uncertainties related to the impervious area still exist. The following two figures illustrate such uncertainties. Figure 5.6

shows rainfall data measured in February, 1984. The rain duration was about 10 hours with the total rainfall depth of 25.5 mm. The observed overflow volume was 59.1 mm based on the impervious area of 15.8 ha. Similarly, another set of rainfall data measured in October 1984 gives an abnormal hydrograph: a rainfall event with a total depth of 25.9 mm gave an observed hydrograph with a total overflow volume of 35.4 mm.

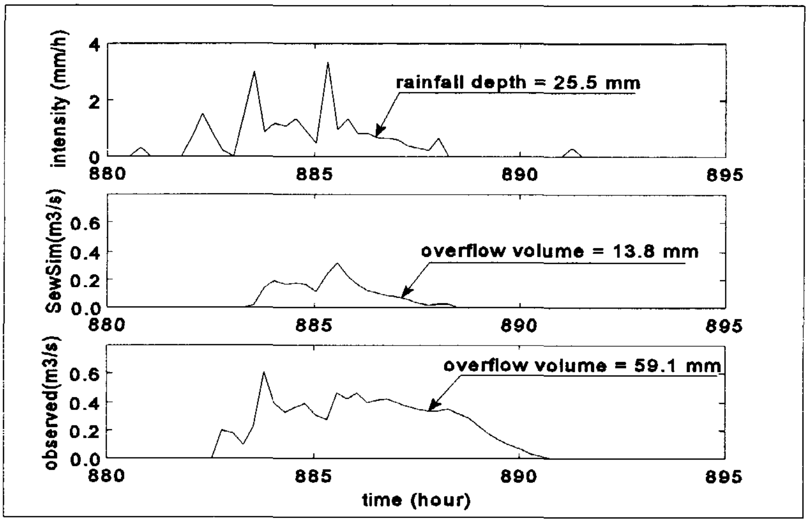


Figure 5.6 A series of rainfall data (February 1984) causing an abnormal hydrograph

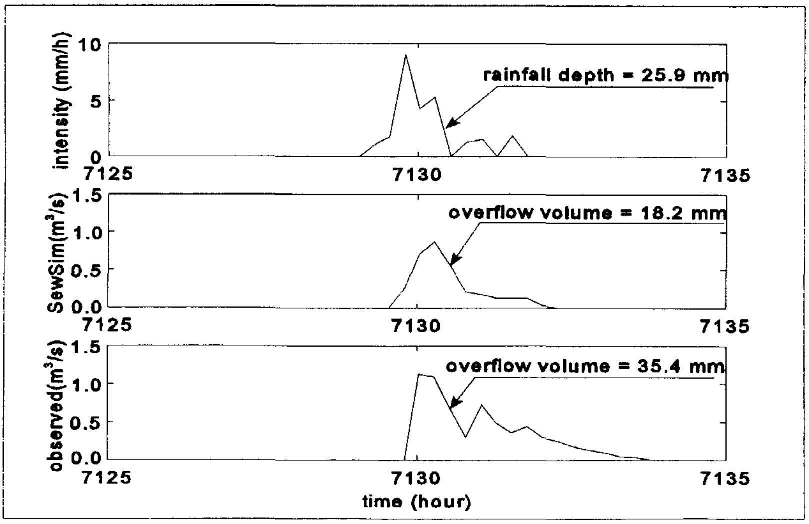


Figure 5.7 A series of rainfall data (October 1984) causing an abnormal hydrograph

In such cases, no numerical models can be verified by such observed values, including SewSim. The model predicted typical hydrographs for these two pieces of rainfall data with total overflow volumes of 13.8 mm and 18.2 mm respectively. There are some reasons for such abnormal phenomena, such as,

- There might be snowfall before the rainfall events, particularly in February. In general a raingauge does not record snowfall. The snow might change some parts of the pervious area into impervious area and the thawing might lead to more runoff to the sewer system.
- The pumping station might not operate normally. But this could only be applicable for the rainfall event in October 1984, because the overflow volume influenced by the pumping was limited.
- The overflow weir might be drowned under the level of receiving water, which might cause backwater in the sewer network.
- The measurement data included errors and the processing of these data contained a bias.

Table 5.3 shows the overflow volume predicted by SewSim compared to the observed values per month for the two wet years. The accuracy of model prediction for each month was not very satisfactory due to many uncertainties involved in the measurement data. However the accuracy over all years was more satisfactory, for instance the average number of CSO events per year predicted by SewSim was only once more than the observed value and the predicted CSO volume was 83 mm/year, which is comparable to the observed value of 84 mm/year (see Table 5.2).

Table 5.3 Overflow volume predicted by SewSim compared to observed values

Year	1983			1984		
	rainfall	overflow volume (mm)		rainfall	overflow volume (mm)	
Month	depth (mm)	SewSim	Observed	depth (mm)	SewSim	Observed
January	65.7	3.5	23.1	119.5	26.7	37.8
February	19.2	0.0	0.0	69.0	13.9	13.9*
March	70.9	6.3	7.9	31.2	0.0	0.0
April	43.1	10.5	1.0	12.2	0.0	0.0
May	113.7	14.9	18.6	62.5	16.3	18.2
June	65.2	26.8	14.7	68.6	24.6	5.9
July	27.3	19.5	7.3	64.0	22.4	11.0
August	6.5	0.0	0.0	1.9	0.0	0.0
September	75.7	14.4	9.0	98.4	19.0	19.2
October	33.2	0.8	0.0	127.9	30.8	40.5*
November	106.2	58.3	67.0	49.2	4.2	26.4
December	74.5	10.7	16.3	24.8	0.0	0.0
Total	701.1	165.7	164.9	729.2	157.9	173.0

* these values have been corrected by the abnormal phenomina mentioned above

Verification by means of using a hydrodynamic model

The verification of SewSim described above was based on the comparison of the simulation results with the observed values. However the observed values (e.g. overflow rate) of sewer systems are not easy to obtain in practice. Particularly for a long rainfall record, a continuous series of observed overflow rates hardly ever exists. In addition, most observed values usually need pre-prossessing, for example, the observed water depth at overflow weir has to be converted into overflow rate, which may cause bias due to the use of interpolation and empirical formulaes. Therefore it is necessary to find an alternative to verify SewSim more easily and completely. This alternative is to use the simulation results of a hydrodynamic model (e.g. HydroWorks) instead of the observed values. In other words, the simulation results of SewSim can be compared to those of HydroWorks. In fact when a calibrated HydroWorks model is applied in practical projects, this model is already treated as a so-called "virtual reality". The simulation results from this model can be regarded as the observed values of this "virtual reality". So if SewSim is able to give comparable simulation results as those of HydroWorks, it may be stated that SewSim is well verified (Ruan, 1998c).

To achieve this goal, the standard rainfall record measured at De Bilt from 1955 to 1979 was used for continuous simulation with the sewer system of Loenen. Since HydroWorks was not able to use a long time-series data of rainfall record, the rainfall record of De Bilt was first "filtered" using two criteria: a minimal inter-event time of 8 hours and a minimal rainfall depth of 5 mm. In total 1235 independent rainfall events were selected. The percentage of rainfall depth per 5 mm is shown in Figure 5.8. This indicates that more than half of the rainfall events have a rainfall depth between 5 and 10 mm; while only 2% of the rainfall events have rainfall depth larger than 40 mm. The largest depth was 111.3 mm and the second largest was 83 mm.

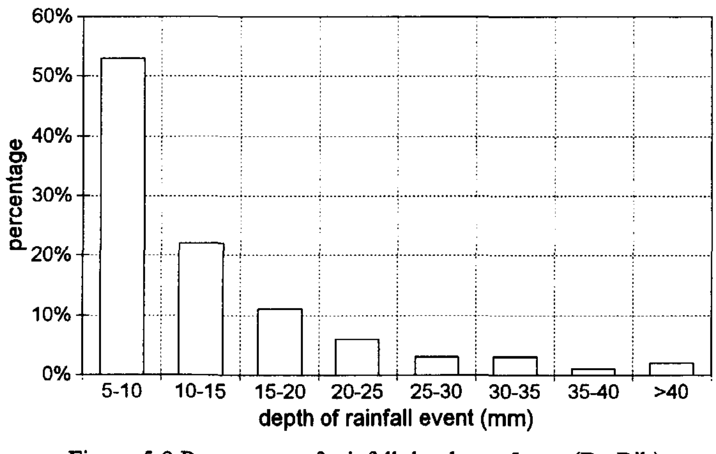


Figure 5.8 Percentage of rainfall depth per 5 mm (De Bilt)

All 1235 rainfall events were used for simulation with HydroWorks and SewSim. The inputs to the two models were made as identical as possible. HydroWorks run in a Pentium computer (133 MHz) required approximately 1 minute to simulate the sewer system of Loenen for a 400 minutes rainfall. The total rainfall events that remained after "filtering" was approximately 400 hours per year. So the total simulation time was about one hour for simulating one year's rainfall record using HydroWorks.

The simulation time of SewSim was approximately one minute for one year's rainfall record. So it is obvious that SewSim is about 60 times more efficient in simulation time than HydroWorks in the case of the sewer system of Loenen.

The following figure compares the total predicted CSO numbers and volume using SewSim and HydroWorks per every two years (Note: 1978 is used twice). The numbers of CSO events predicted by SewSim and HydroWorks were 465 and 461 in total or an average of 18.6 and 18.4 per year respectively. The CSO volumes were 2272 mm and 2303 mm in total or 91 mm and 92 mm per year respectively

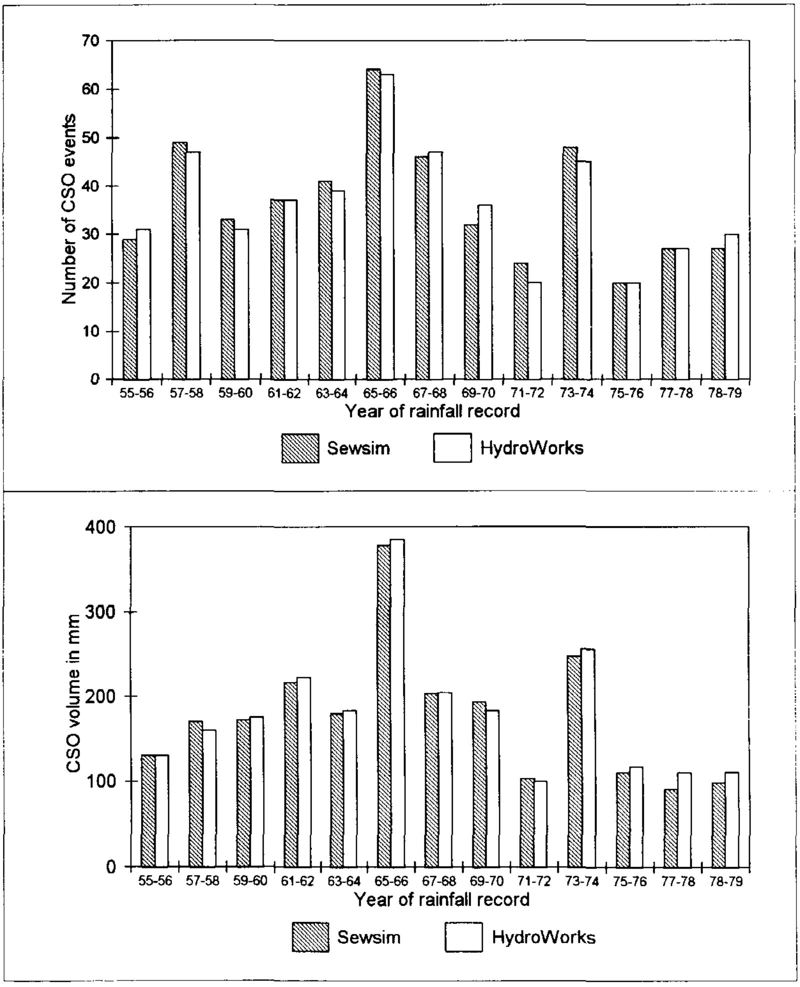


Figure 5.9 Predicted CSO frequency and volume per two years using SewSim and HydroWorks (sewer system of Loenen)

The CSO volumes predicted by both models per event were processed (see Figure 5.10). Most CSO events have a small CSO volume, for example, only 20% of the total CSO events have a volume that is larger than 9 mm; and 60% with a volume larger than 2.5 mm. This implies that 40% of the total CSO events have a volume smaller than 2.5 mm. This fact indicates that enlarging the storage capacity of the sewer system may reduce the CSO frequency significantly. In theory a storage tank of about 2.5 mm behind the overflow weir will reduce the CSO frequency to 60% of the original value, i.e. to an average of 11 CSO events per year. However the reduction in CSO volume is much less significant: the total CSO volumes will be 2090 mm and 2145 mm as predicted by SewSim and HydroWorks respectively. These are only a reduction of 8% and 7% in CSO volume respectively. In this sense only the CSO frequency cannot be used as a criterion for assessing the sewer system concerning the CSO volume or emission to receiving waters.

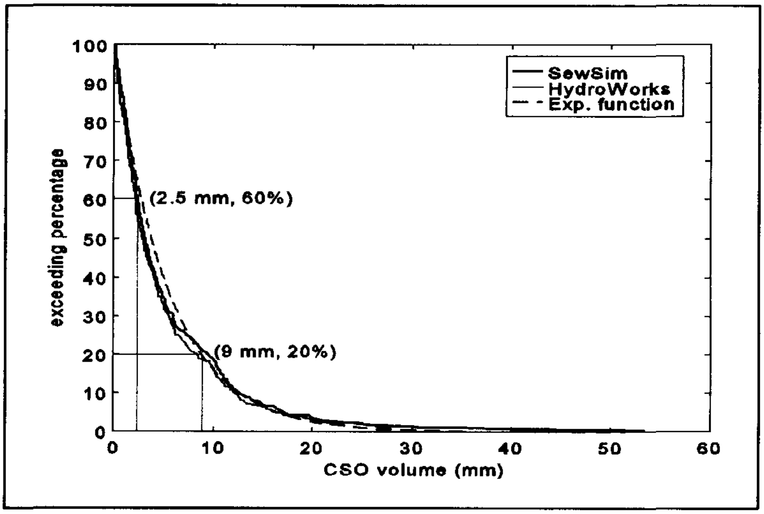


Figure 5.10 Distributions of CSO volume predicted by SewSim, HydroWorks and an exponential function (sewer system of Loenen)

Figure 5.10 shows that the distribution of CSO volume is similar to an exponential distribution. In Wiggers (1991) exponential functions were first used to predict rainfall depth, CSO volume and CSO emission. Similarly, an exponential equation was also fitted to the distribution of CSO volume predicted by SewSim,

$$Ep = e^{-\frac{V}{V_{ave}}} \tag{5.1}$$

where Ep = exceeding percentage, %
V = CSO volume predicted by SewSim, mm
V_{ave} = the average CSO volume, mm

Equation (5.1) is able to fit the distribution of CSO volume with a sufficient degree of precision. This equation is useful for many practical goals, for example, it can be used for planning storage tanks behind overflows: on the one hand, the capacity of the storage tanks can be determined from

Figure 5.10, or Equation (5.1) if the desired reduction of the total CSO volume is known, and on the other hand, vice versa.

The new Dutch guidelines for urban storm drainage recommend that a statistical analysis should be performed on the results of continuous simulations. The return periods of both rainfall and CSO events can be calculated using the extreme values of rainfall depth and CSO volume. Generally 25 largest values of rainfall depth and CSO volume are used to calculate the return period from 1 year to 25 years. Figure 5.11 shows the return periods of rainfall depth and CSO volume predicted by SewSim and HydroWorks. Figure 5.12 presents the comparison of the 25 largest CSO volumes predicted by these two models.

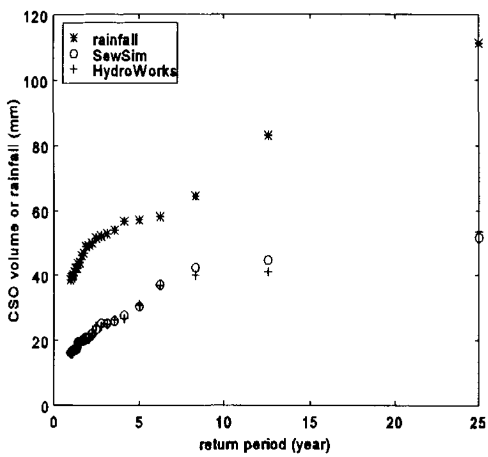


Figure 5.11 Return periods of rainfall depth and CSO volumes predicted by two models

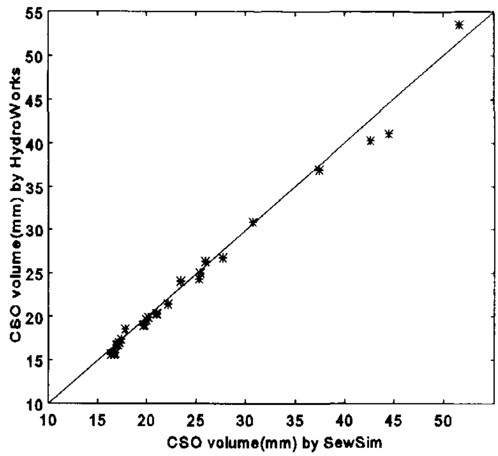


Figure 5.12 Comparison of the 25 largest CSO volumes predicted by two models

5.3.3 Conclusion

SewSim has been verified satisfactorily by means of observed values of the sewer system of Loenen and the simulation results of the hydrodynamic model HydroWorks. Event-based simulation has shown that SewSim is able to predict accurately CSO hydrographs of the sewer system of Loenen. Continuous simulation using the processed NWRW data has demonstrated that the simulation accuracy during wet years was better than that of dry years, and the total accuracy of overflow numbers and volume is satisfactory. The simulation time is about one minute for one year rainfall record with a simulation time step of 15 minutes.

SewSim has also been verified by comparison wtih the simulation results obtained using HydoWorks. This shows that from a statistical points of view, SewSim is able to predict CSO volume in an almost identical way as HydroWorks does. The significant reduction of simulation time (about 1:60) is the greatest advantage of using the conceptual model. The distribution of predicted CSO volume may be expressed by an exponential function.

5.4 Quality simulation

5.4.1 Event-based simulation

Three rainfall events used in section **5.2.1** - event 23#, 30# and 53# were used for event-based quality simulation in this section. SewSim and HydroWorks simulated these rainfall events for the sewer system of Loenen. The goal of the simulation was to verify the predicting capacity of SewSim compared to HydroWorks and the observed data. The default data of both models were used for quality parameters, such as the initial sediment amount on impervious catchment surface, sediment buildup rate, washoff coefficient etc.. The simulation results are shown in Figure 5.13 - 5.15.

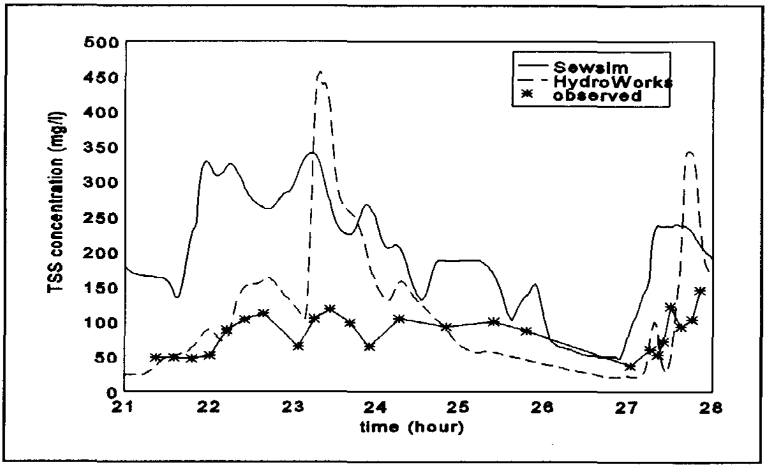


Figure 5.13 Pollutographs predicted by SewSim and HydroWorks (event 23#, Loenen)

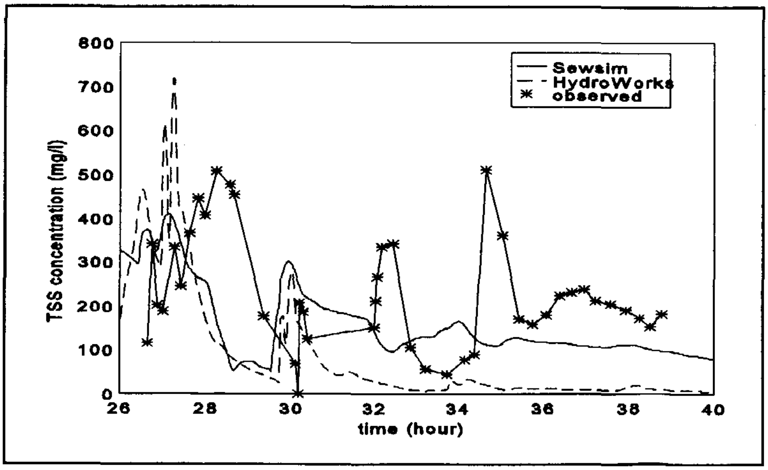


Figure 5.14 Pollutographs predicted by SewSim and HydroWorks (event 30#, Loenen)

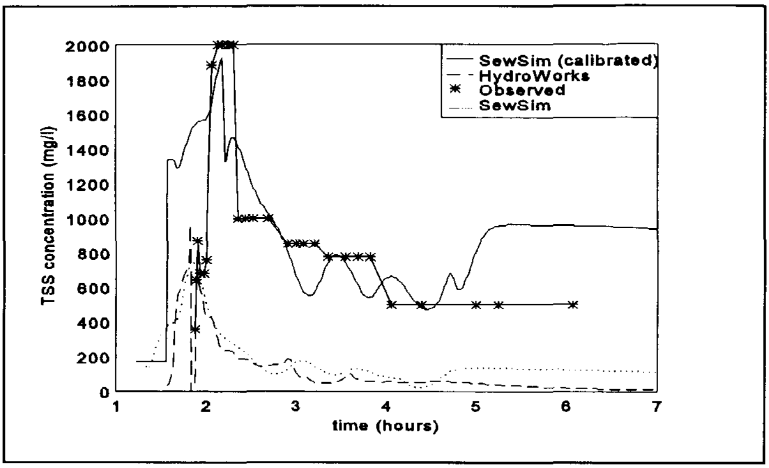


Figure 5.15 Pollutographs predicted by SewSim and HydroWorks (event 53#, Loenen)

The first impression of these figures is that TSS concentration of CSO emission is rather unpredictable. Both SewSim and HydroWorks were not able to produce accurate pollutographs compared to those observed. However some remarks should be given for these figures separately. Figure 5.13 shows that SewSim gave somewhat better simulation results than HydroWorks did. Particularly the peak concentration predicted by HydroWorks was much too large compared with the observed value. Figure 5.14 shows that the peak concentration predicted by SewSim was in better agreement with that observed than that by HydroWorks. However the time of peak concentration of SewSim was also some time earlier than that of the observed one. The problem of the time lag (i.e. the difference between the time of peak concentrations) can be easily solved in SewSim if the model is calibrated. Figure 5.15 provides an different picture: the two pollutographs predicted by SewSim and HydroWorks are similar to the observed one. However the peak of the observed concentration was much larger than those predicted by the models and the time of the peak concentration was also not in agreement with that of the models. However the calibrated pollutograph predicted by SewSim was in good agreement with that observed.

The other rainfall events that caused an overflow during the period 1981-1985 were also simulated using the two models. The total mass (TSS) predicted per event was compared to the observed value in Figure 5.16. The simulation results without calibration were not satisfactory, although SewSim performed somewhat better than HydroWorks. In general the TSS mass was underestimated by the models, particularly for the heavy rainfall events. In fact there were only six rainfall events (30#, 34#, 35#, 39#, 45# and 53#) that caused a CSO emission which was larger than 1000 kg TSS. The simulation results of the calibrated SewSim model (i.e. changing impervious area) were in good agreement with the observed data. The total CSO volume and TSS emission predicted by the calibrated SewSim model were 56220 m^3 and 18689 kg respectively, whiles those of observed data were 56914 m^3 and 21386 kg. It can be stated that due to the uncertainties involved in the sewer quality processes, the quality simulation using models is still unable to give safisfactory results. More detailed simulation results can be found in Appendix A.

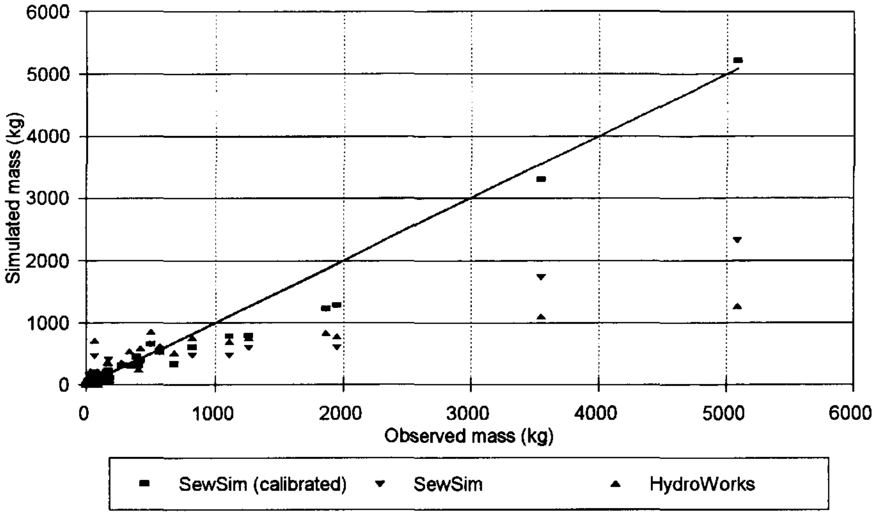


Figure 5.16 Predicted CSO emission (TSS) by SewSim and HydroWorks

5.4.2 Continuous simulation

The same rainfall record measured in Loenen from 1981 to 1985 was used for continuous quality simulation. The initial amount of sediment on impervious catchment surface was calibrated to be 100 kg/ha. The initial amount of sediment in the sewer network grossly calculated from the uniform sediment depth (10 mm) in sewers with an average diameter of 500 mm. This resulted in 100 kg/ha approximately. Figure 5.17 presents the total CSO emission (TSS) per year. It shows that the average CSO emission per year predicted by SewSim was 180 kg/ha per year compared to the observed value of 174 kg/ha per year.

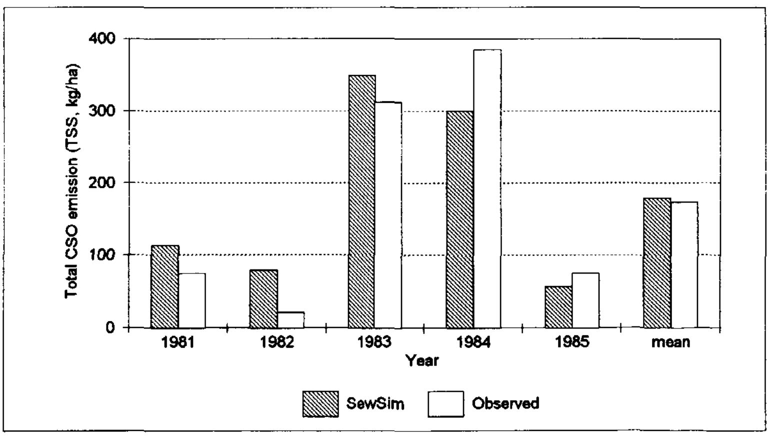


Figure 5.17 Total CSO emission in terms of TSS per year (Loenen)

The calibrated SewSim model (e.g. system variables and parameters)was applied to the standard rainfall record of De Bilt. As Figure 5.18 shows, the mean CSO frequency and volume predicted in the period of 25 years were 19 and 91 mm per year. The CSO volume was about 11% of the mean rainfall depth (800 mm/year). The mean CSO emission in terms of TSS was 187 kg/ha per year. The mean CSO concentration of TSS was calculated as CSO emission divided by CSO volume times a factor of 100, which resulted in 216 mg/l.

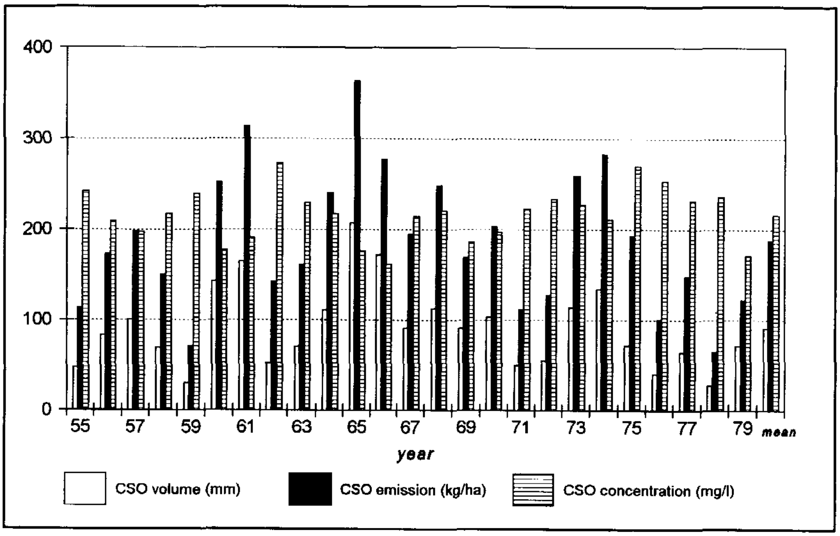


Figure 5.18 CSO volume, emission and concentration (TSS) of the sewer system of Loenen predicted by SewSim using the rainfall record of De Bilt

Continuous quality simulation using the standard rainfall record of De Bilt (25 year) was not carried out by HydroWorks, due to the extremely long simulation time and a tremendous amount of output data. In addition, the last section (**5.4.1**) showed that the pollutographs predicted by HydroWorks (event-based simulation) were not accurate compared to the observed values.

Table 5.4 shows the simulation results (SewSim) by using the rainfall data of Loenen (4.5 years) and those of De Bilt (25 years) compared to the observed values. In particular, the difference of the predicted CSO volume and emission by using the two series of rainfall data is small, which implies that the rainfall data of De Bilt may be applied for simulation of the sewer system of Loenen.

Table 5.4 Comparison of results of continuous simulation for the sewer system of Loenen

rainfall data source	results obtained	CSO	CSO	CSO	TSS conc.
		per year	mm/year	kg/ha/year	mg/l
Loenen (4.5 years)	measured	11	84	174	207
Loenen (4.5 years)	SewSim	12	83	180	217
De Bilt (25 years)	SewSim	19	91	187	216

5.4.3 Conclusion

The pollutographs predicted by SewSim and HydroWorks (event-based simulation) were not in good agreement with the observed ones. It should be stated, however, that the measurements (rainfall, water level at the CSO weir, TSS concentration) of NWRW data were not necessarily correct. In **5.3**, two examples have been given of the uncertainties related to snowfall and consequently the measured water level at the CSO weir. Additionally the data processing of the uncomplete measurement data series may also lead to bias in the observed pollutographs. Nevertheless, at present it may be concluded that it is still not possible to predict CSO emission (i.e. CSO concentration or load) accurately using numerical models.

Continuous quality simulation using SewSim showed that the average CSO emission of the sewer system of Loenen during 1981-1985 was 180 kg/ha per year compared to the observed value of 174 kg/ha per year. The simulation results of the standard rainfall record of De Bilt (25 year) resulted in 187 kg/ha/year (continuous simulation using SewSim).

5.5 Sensitivity analysis

In Chapter 2, a sensitivity analysis was carried out to analyse the sentivity of five system variables and five quality parameters using HydroWorks. It proved that CSO volume and emission are rather sensitive to most system variables and parameters investigated. Similarly, a sensitivity analysis was performed on the conceputal CSO emission model SewSim. For the hydraulic part of the model, four key system variables - impervious area (A), sewer storage (B), pumping capcity (*poc*) and tank storage (*tank*) were chosen. For the quality part, four key system parameters - initial amount of sediment on impervious surface (p_0), buildup rate (p_s), decay factor (k), initial amount of sediment in sewer network, were investigated.

The sensitivity analysis used the same eight rainfall events (see Table 5.5 and **2.6.2**) so that the simulation results could be compared to those of HydroWorks. The sewer system of Loenen was chosen due to its simplicity (i.e. one pump and one overflow) and the availablity of data. SewSim was applied to the sewer system, each time modifying one key system variable or parameter and keeping the others unchanged.

Table 5.5 The eight rainfall events used for sensitivity analysis

rainfall event (yy-mm-dd)	rainfall depth (mm)	overflow volume (mm)		
		HydroWorks	SewSim	
		Δt =1 min	Δt =5 mins	Δt =1 min
75-07-18	23.5	12.4	11.7	12.7
76-07-16	14.7	7.2	6.1	7.1
76-08-25	31.3	19.8	20.2	20.7
78-08-19	18.0	10.5	9.9	10.8
79-04-16	20.1	11.1	11.6	12.0
80-06-24	16.8	9.4	7.1	9.4
82-07-26	27.2	15.9	15.7	16.1
84-09-05	35.6	14.8	14.7	14.8

Table 5.5 shows the overflow volumes calculated using HydroWorks with a simulation time step of one minute and those using SewSim with two simulation time steps - one and five minutes. It is evident that SewSim gives accurate simulation results compared to those of HydroWorks. There are some differences between the simulation results of SewSim using the two different simulation time steps. The time step Δt = 1 minute was chosen for the sensitivity analysis, corresponding to the simulation time step used by HydroWorks.

5.5.1 CSO volume

Size of impervious surface

The first key system variable studied was the size of the impervious surface (*A*): the original value was 15.8 ha. In total 20 simulations were run with *A***c* where *c* = 50-150% with an increase of 5% each time. The overflow volume (in m^3) was then converted to millimeter based on *A*. Figure 5.19 shows that a -50% error in the size of the impervious surface (*A*) will result in a percentage change of -75% to -35% in overflow volume for the eight different rainfall events; a +50% error will result in a percentage error of 10% to 25% in the same model output. Thus CSO volume is rather sensitive to the size of the impervious surface. In particular, under-estimated values of the size of the impervious surface will result in a larger error in CSO volume than those over-estimated. Normally the size of the impervious surface may be estimated within a percentage of ±25%.

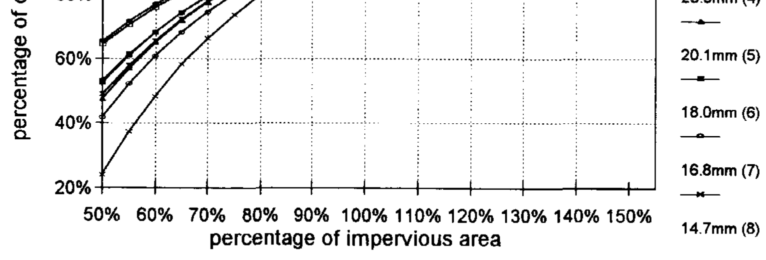


Figure 5.19 Sensitivity analysis of CSO volume against impervious area

Storage capacity of sewers

The second key system variable studied was the capacity of sewer storage (in millimeters based on the impervious area *A*). The same strategy of changing the original value as described above was applied to this variable. Figure 5.20 shows that a ±50% error in the sewer storage capacity (*B*) will result in a percentage error of 10% to 35% in overflow volume for the eight rainfall events. Unlike the size of impervious surface, for sewer storage capacity, the under- or over-estimated errors in the sewer storage capacity result in the same order of error in the model output. Normally the capacity of sewer storage may be estimated within a percentage of ±15%.

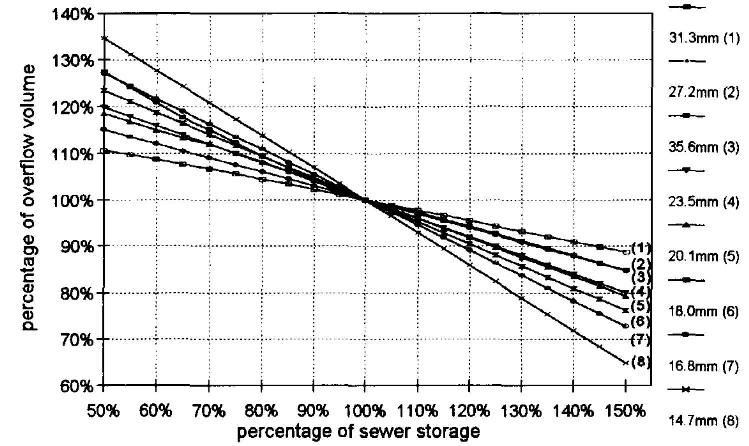


Figure 5.20 Sensitivity analysis of CSO volume against sewer storage

Pumping capacity

The third key system variable was the pumping capacity of the sewer system (*poc*). Figure 5.21 shows that CSO volume is not very sensitive to this variable, except for one rainfall event observed on 84-09-05 (total rainfall depth was 35.6 mm). In general, a ±50% error in the pumping capacity (*poc*) will result in a percentage error of 3% to 15% in CSO volume for the eight rainfall events. The rainfall event observed on 84-09-05 seems to be sensitive when the pumping capacity is reduced. The reason is probably related to the rainfall patten. If the deviation is compared to Figure 4.5 in which the simulation results of HydroWorks are presented, this rainfall event has a somewhat similar deviation. This fact proves indrectly but convincingly that SewSim is able to simulate the pumping process correctly, at least in a similar way to HydroWorks. Normally the pumping capacity can be estimated at a percentage of ±20%.

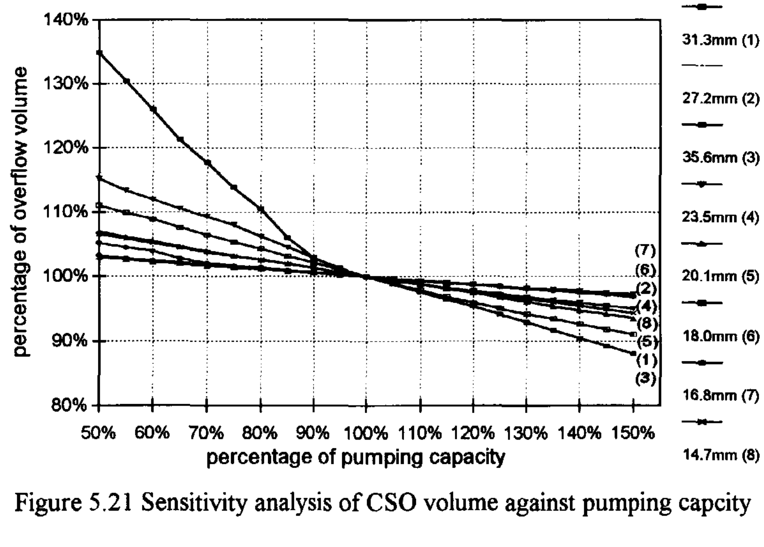


Figure 5.21 Sensitivity analysis of CSO volume against pumping capcity

Storage capacity of settling tank

The last key system variable studied was the storage capacity of the settling tank, which is also defined in millimeters based on the size of the impervious surface. The total storage was increased by enlarging the tank storage by means of $B*c$, where c = 100-150% with an increase of 5% each time. Like the storage capacity of sewers, a ±50% error in the storage capacity of a settling tank will result in a percentage of 10% to 35% error in overflow volume for the eight rainfall events. The simulation results showed that the effects on CSO volume by means of changing the storage capacity of sewers or the storage capacity of settling tank on CSO volume are almost the same (not shown here). More about CSO volume analysis can be found in Ruan and Wiggers (1998b).

5.5.2 CSO emission

Initial amount of sediment (impervious surface)

The first system parameter for sensitivity analysis of CSO emission was the initial amount of sediment on the impervious catchment surface, p_0 in kg/ha. The original value was assumed to be 60 kg/ha. The other system parameters were kept constant, for example, the buildup rate of sediment p_s was equal to 6 kg/ha/d and the decay factor k 0.08 /d. In total, seven values of p_0 (varied from 0% to 150% of the original value, i.e. from 0 to 90 kg/ha) were used for simulation, which resulted in the following figure,

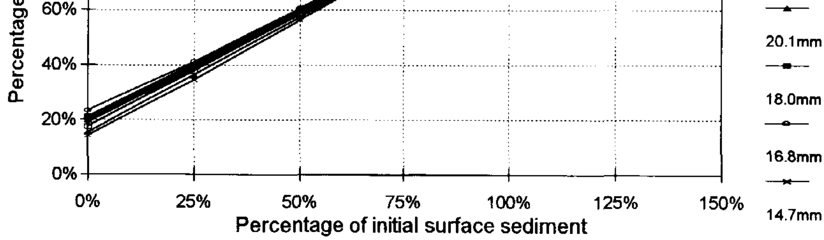


Figure 5.22 Sensitivity analysis of CSO emission against initial surface sediment

Figure 5.22 shows that CSO emission is rather sensitive to p_0. However, when p_0 changed from 75 kg/ha to 90 kg/ha (i.e 125% to 150% of the original value), the total CSO emission remained constant which is similar to the simulation results of HydroWorks shown in section **2.6.3**. This is because there is a limiting value for accumulated mass on impervious surface in the case that the buildup time becomes too long. This limiting value was p_s/k = 6/0.08 = 75 kg/ha. This means that the initial mass of sediment will never exceed 75 kg/ha. The sensitivity analysis has proved that SewSim is capable of simulating the sediment buildup/washoff processes in a way similar to the detailed hydrodynamic model - HydroWorks.

Buildup rate of sediment

The second system parameter for sensitivity analysis was the sediment buildup rate on impervious catchment surface, p_s (kg/ha/day). The original value was assumed to be 6 kg/ha/day. This value was multiplied by a factor varying from 0% to 150% while the other system parameters were kept constant. Figure 5.23 shows that there are two domains within which the sensitivity of CSO emission against p_s can be analysed. The first domain of p_s is from 0% to 80% of the original value or 0 kg/ha/day to 4.8 kg/ha/day. In this domain, CSO emission seems to be rather sensitive to sediment buildup rate. However, further investigation shows that this is not a correct interpretation, because in this domain the limiting factor varies between p_s/k = 0/0.08 = 0 and 4.8/0.08 = 60 kg/ha. Thus p_0 (=60 kg/ha) was not used as a constant due to the limiting factor, because SewSim uses the limiting factor instead of p_0 if the limiting factor is smaller than p_0. This implies that the sensitivity analysis in this domain is not reliable. In the other domain (p_s>4.8 kg/ha/d) it is evident that CSO emission is also not sensitive to p_s. This is due to the short buildup time of each rainfall event.

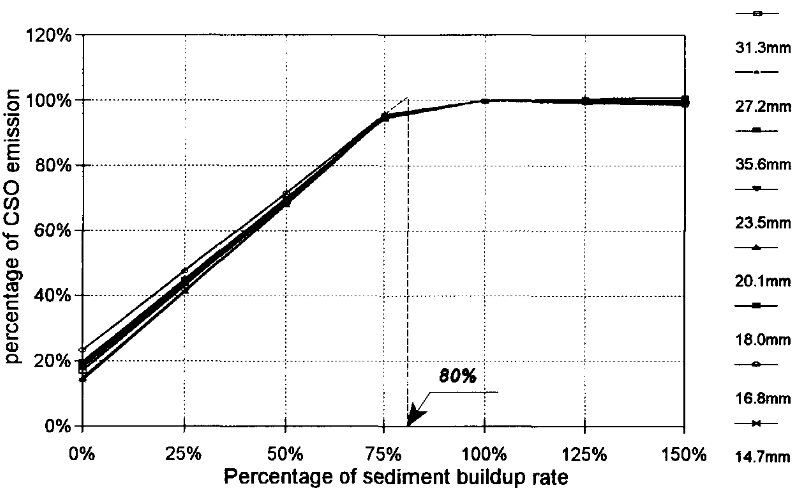


Figure 5.23 Sensitivity analysis of CSO emission against buildup rate

Buildup decay factor

The third system parameter for sensitivity analysis was the buildup decay factor k. The original value was assumed to be 0.08 /d. The multiplying factor was the same as the one used in the second sensitivity analysis of buildup rate of sediment. The other parameters were kept constant; for instance, p_0 = 60 kg/ha, p_s = 6 kg/ha/d, etc..

Similar to the last case, Figure 5.24 shows that there are two domains within which the sensitivity of CSO emission to buildup decay factor can be analysed. The boundary point lies on the x-axis at 125%, that is 125% x 0.08 = 0.1 /day. Since p_s = 6 kg/ha/day, the limiting factor is p_s/k = 6/0.1 = 60 kg/ha. Therefore in the second domain (125% - 150%) the limiting factor is smaller than p_0 and is used instead of p_0 itzelf. This implies that p_0 is not a constant and the sensitivity analysis is not reliable. On the other hand, the first domain shows that the buildup decay factor is not sensitive for CSO emission, also due to the short buildup time. Another remarkable point is that one rainfall event (observed on 84-09-05) has a rather abnormal behaviour compared to the others. It was the same rainfall event that caused deviation when the pumping capacity of the sewer system was reduced (see Figure 5.21).

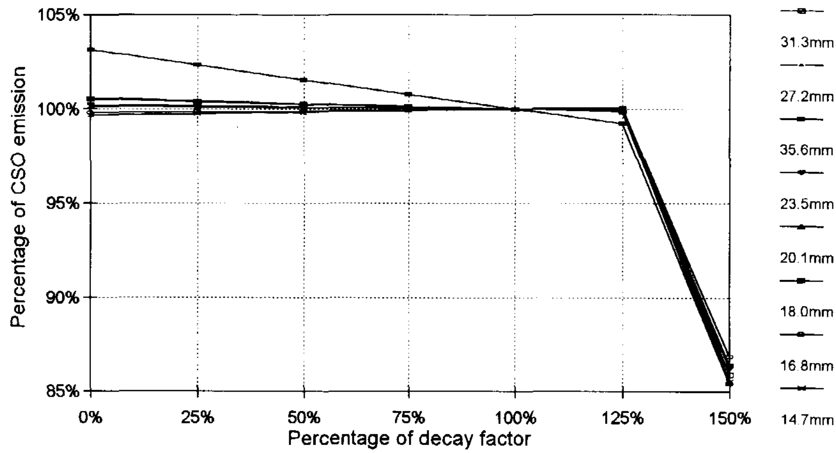


Figure 5.24 Sensitivity analysis of CSO emission against decay factor

<u>Initial amount of sediment</u> (sewer network)

Figure 5.25 shows that the initial amount of sediment in the sewer network is not very important for the simulated CSO emission. This is a similar conclusion drawn from the simulation results of HydroWorks (see **2.6.3**). HydroWorks uses a uniform sediment depth in the sewer network for deposition/erosion processes. SewSim uses the initial amount of sediment for these processes. In fact, the initial amount of sediment in the sewer network has a significant impact on CSO emission. However, the quality aspects related to the sewer quality processes were not sufficiently taken into account by the present numerical sewer quality models, due to the lack of some uncertainties involved in this area. In SewSim, however, the impact of in-sewer sediment movement on CSO emission is partially taken into account by means of appropriate modelling of sediment buildup and washoff on impervious surface. In general, the model has to be calibrated by end-pipe measurements. In such cases, SuRM (Surface Reservoir Model) and SeRM (Sewer Reservoir Model) have some similar functions concerning quality modelling (see **4.2** and **4.3**).

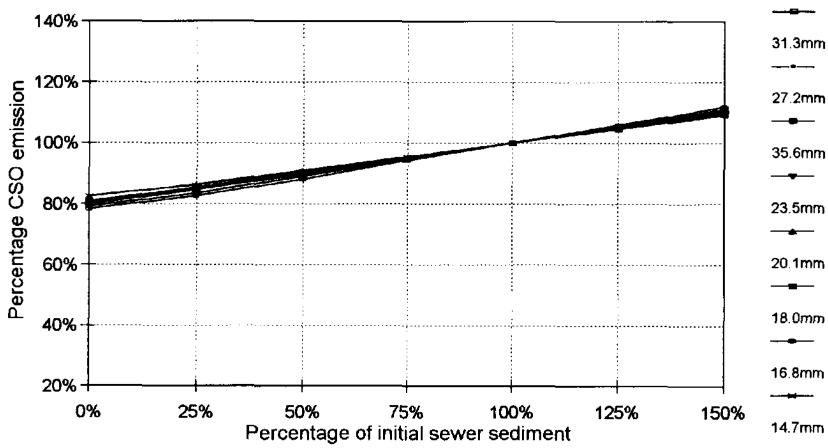


Figure 5.25 Sensitivity analysis of CSO emission against initial amount of sewer sediment

5.6 Conclusion

Particularly for quantity simulation (event-based), SewSim is able to represent the sewer system of Loenen with a reasonable accuracy. The predicted hydrographs can be easily improved by modifying a limited number of system variables (impervious area, storage capacity, pumping capacity etc.). SewSim is able to capture the dynamic characteristics of the sewer system with an accuracy comparable to that of HydroWorks. For continuous simulation, SewSim was first verified by means of measurement data, which resulted in accurate predicted CSO frequency and volume on a yearly basis (Table 5.2). Due to some abnormal phenomena related to rainfall depth and the measured CSO volume (e.g. snowfall etc.), the CSO volume predicted per month was of less accuracy. Furthermore, SewSim was verified successfully by the simulation results of HydroWorks based on the standard rainfall record of De Bilt, which showed an almost identical model behaviour of both models. But SewSim is approximately 60 times more efficient in simulation time than HydroWorks. The distribution of the predicted CSO volume may be expressed by a simple exponentail function.

For quality simulation, the accuracies of SewSim and HydroWorks are of less satisfactory for event-based simulation when comparing the predicted pollutographs with those observed. The simulation results (CSO concentration or load) are not reliable without sufficient calibration data. However the predicted CSO emission in terms of TSS for a long period is acceptable; for example, the mean emission (TSS) from the sewer system of Loenen in the period of 1981-1985 predicted by SewSim was 180 kg/ha/year compared with the observed value of 174 kg/ha/year.

A sensitivity analysis has been carried out on water quantity and quality modelling against several important system variables and parameters. As with HydroWorks, CSO volume is rather sensitive to the sewer storage and impervious area, and less to pumping capacity; CSO emission is rather sensitive to these system parameters, such as the initial amount of sediment on the impervious surface, and the buildup rate of sediment, particularly for continuous simulation when the buildup time is long. The comparison of the simulation results has shown that SewSim may function similarly as the more detailed hydrodynamic model - HydroWorks, but much more efficiently.

CHAPTER 6 APPLICATIONS OF *SEWSIM*

6.1 Introduction

This chapter deals with some applications using the conceptual CSO emission model SewSim in Dutch sewerage practice.Two sewer systems in the Netherlands, namely Loenen and Apeldoorn-West, were studied. The traditional Kuiper's method was analysed and its prediction capacity of CSO frequency was compared to those of HydroWorks and SewSim. The so-called reference sewer system recommended by (CUWVO VI, 1992) was investigated using SewSim.

6.2 Prediction of CSO frequency

In the Netherlands, the traditional criterion of assessing or designing a combined sewer system is the Theoretical Overflow Frequency (TOF). The TOF was derived from the so-called Kuiper's graph (Ribbius, 1951). Subsequently this graph included all the rainfall events with a rainfall depth larger than 4 mm measured in De Bilt from 1926 to 1962 (37 years). Each event was characterised by its total rainfall depth (y-axis in mm) and its duration (x-axis in minute), and was represented by a dot on the graph. The principle of the method using Kuiper's graph is as follows: the sewer system is simplified to be a single reservoir. The in-sewer storage capacity is represented by a horizontal line and the excess pumping capacity (POC line) by a sloping line in the graph. As an example, two years' rainfall data from the standard 25 years' rainfall record of De Bilt were applied on the sewer system of Loenen (represented by the dots and '+'s in Figure 6.1). According to Kuiper's method, only the rainfall events lying above the POC line ('+'s) are supposed to cause overflows. In total there were 13 overflows within these period. In order to test the prediction capability of Kuiper's method, the sewer system of Loenen was simulated using the hydrodynamic model HydroWorks. The rainfall events which may cause overflows according to the simulation results of HydroWorks are represented by all the '+'s in Figure 6.1. There are in total 33 overflows. This implies that the overflow frequency in this period was significantly underestimated if using Kuiper's method compared to the simulation results of HydroWorks.

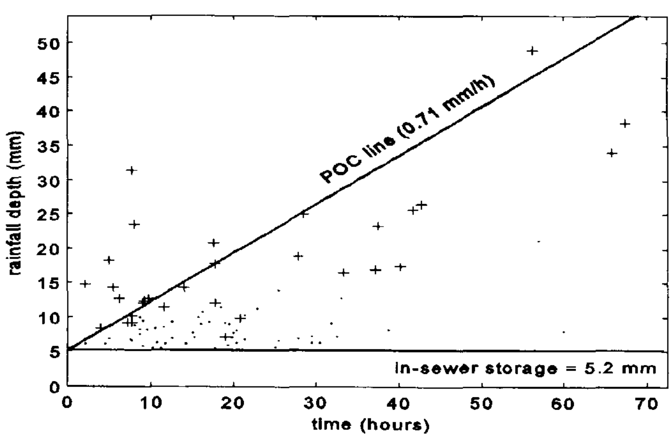


Figure 6.1 Prediction results of HydroWorks and Kuiper's method (rainfall data: 1955-1956 De Bilt; sewer system: Loenen)

In Wiggers and Langveld (1998) several causes that make the TOF of Kuipers' method inaccurate were identified, such as,

- pervious surface may become partially impervious during heavy storms
- initial losses are not taken into account (i.e. no rainfall-runoff transformation)
- excess pumping capacity is not constant due to the fluctuation of dry weather flow
- rainfall intensity is not constant temporally and spatially
- sewer storage may not be treated correctly
    - full storage may not be available at the beginning of a storm
    - "dynamic" storage is not taken into account
    - storage of collectors is not taken into account

More recently, hydrodynamic models have been used to calculate CSO frequency instead of the TOF derived from Kuiper's graph. However the extremely long simulation time is still a problem for applications, even with the aid of modern computing facilities. For example, a small sewer system like the one of Loenen, needs at least 25 hours of HydroWorks simulation for the 1235 rainfall events created from the 25 years' rainfall record of De Bilt (see **5.3.2**). For a large sewer system, like the one of Apeldoorn-West (impervious area: 570 ha), it is almost impossible for HydroWorks to simulate the 25 years' rainfall record (see **6.4**) using standard PCs.

On the other hand, it is rather simple for SewSim to predict the CSO frequency of the sewer system of Loenen. Only five system variables are needed for continuous simulation or multiple events simulation. These are: impervious area of 15.8 ha, in-sewer storage of 5.2 mm, pumping capacity of 0.71 mm/h, no storage tank and a population of 2050. Default values may be used for all other parameters of the model. The simulation efficiency was at least 60 times that of HydroWorks. The simulation results were processed and presented as follows,

- the total 1235 events were classified into ten domains according to their rainfall depth, with an interval of 5 mm for the first eight domains, one of 10 mm for the next two domains and one of 35 mm for the last domain.
- each domain was again classified into five sub-domains according to their rainfall duration, with an interval of 10 hours for the first four sub-domains and the last one for extremely long events, i.e. between 40 and 140 hours.
- the numbers of rainfall events and overflows for each sub-domain predicted using SewSim and HydroWorks are listed in Table 6.1.

Table 6.1 shows that SewSim is able to predict the overflow frequency with a high degree of precision when compared with the prediction results of HydroWorks. The total number of overflows predicted by SewSim was 427 compared to 460 predicted by HydroWorks. The overflow numbers predicted by the two models are in better agreement for those domains with larger rainfall depth and longer duration. The overal precision of SewSim shows that it is a good alternative to predict TOF instead of the traditional Kuiper's dots graphical method.

In cases where end-pipe observed data are available, SewSim can be calibrated using these data. Then it is possible to predict the real overflow numbers in a certain period using the calibrated SewSim model.

Table 6.1 The number of rainfall events and overflows predicted by SewSim and HydroWorks

time (h)	depth (mm)	[5,10)	[10,15)	[15,20)	[20,25)	[25,30)	[30,35)	[35,40)	[40,50)	[50,80)	[80,115)	sum
	events	229	76	16	9	1	2	1	0	1	0	335
[0,10)	SewSim	44	68	16	9	1	2	1	0	1	0	142
	HydroWorks	51	71	16	9	1	2	1	0	1	0	152
	events	261	97	29	16	4	5	0	1	1	0	414
[10,20)	SewSim	10	42	27	16	4	5	0	1	1	0	106
	HydroWorks	13	48	27	16	4	5	0	1	1	0	115
	events	101	50	45	12	10	6	3	0	1	0	228
[20,30)	SewSim	0	12	32	11	10	6	3	0	1	0	75
	HydroWorks	3	14	34	12	10	6	3	0	1	0	83
	events	43	39	25	17	4	5	2	2	0	0	137
[30,40)	SewSim	0	0	13	17	3	5	2	2	0	0	42
	HydroWorks	0	1	14	16	4	5	2	2	0	0	44
	events	0	19	21	18	15	17	10	9	5	2	116
[40,140)	SewSim	0	0	5	6	12	13	10	9	5	2	62
	HydroWorks	0	0	6	8	13	14	10	9	4	2	66
	events	639	281	136	72	34	35	16	12	8	2	1235
sum	SewSim	54	122	93	59	30	31	16	12	8	2	427
	HydroWorks	67	134	97	61	32	32	16	12	7	2	460

time (h): rainfall duration in hours
depth (mm): rainfall depth in mm
$[a,b)$: domain (i.e. equal or larger than a and smaller than b)

6.3 Reference sewer system

6.3.1 CSO volume and emission

The reference system is a hypothetical sewer system first proposed by the Dutch sewer committee in 1992 (CUWVO VI, 1992). This reference sewer system is supposed to have an in-sewer storage capacity of 7 mm, an excess pumping capacity of 0.7 mm/h and 2 mm extra storage in the form of a storm water settling tank behind each CSO weir. The committee recommended that a combined sewer system in practice should not pollute receiving waters more than the reference sewer system does. It is not necessary for a sewer system to satisfy completely the three criteria mentioned above. However such a sewer system is only accepted if it emits a smaller or equal pollution load to receiving waters. Additionally the committee proposed that the CSO frequency may still be used to assess the functioning of the sewer system.

Up to now, no research work has been performed to investigate CSO load from the reference sewer system, since this hypothetical sewer system is rather abstract. For example, no network of this sewer system is known or required. Besides long simulation time has to be considered when using a long series of rainfall data (e.g. 25 years' rainfall record of De Bilt). These aspects make a hydrodynamic model unsuitable for such a sewer system. However, since no network is required with SewSim and also due to its efficient simulation power, so it is an ideal tool to investigate the reference sewer system. The basic system variables of SewSim for the reference sewer system are as follows,

1) impervious catchment surface A = 10 ha
2) in-sewer storage capacity B = 7 mm or 700 m^3
3) (excess) pumping capacity P = 0.7 mm/h or 70 m^3/h
4) storage capacity of the settling tank B_t = 2 mm or 200 m^3
5) no dry weather flow

The standard 25 years' rainfall record of De Bilt was used for continuous quantity and quality simulation for the reference sewer system. The simulation results are shown in Figure 6.2.

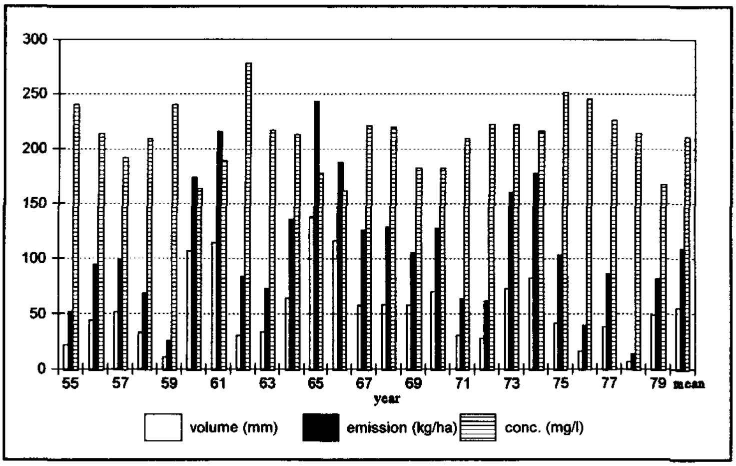


Figure 6.2 CSO pollution from the reference sewer system predicted by SewSim using the 25 years' rainfall record of De Bilt

The mean CSO frequency, CSO volume and CSO emission are 9, 55 mm and 109 kg/ha per year respectively. The CSO concentration (mg/l) was obtained by dividing CSO emission (kg/ha) by CSO volume (mm) per year times 100. These values can be used for evaluating existing sewer systems concerning CSO emission to receiving waters. As an example, the simulation results of the reference sewer system are compared to those of the sewer system of Loenen (see **5.3.2**).

Table 6.2 Comparison of results of continuous simulation for the sewer system of Loenen and the reference sewer system

sewer name	rainfall data source	CSO frequency per year	CSO volume mm/year	CSO emission kg/ha/year	TSS conc. mg/l
Loenen	De Bilt	19	91	187	216
Reference	De Bilt	9	55	109	211

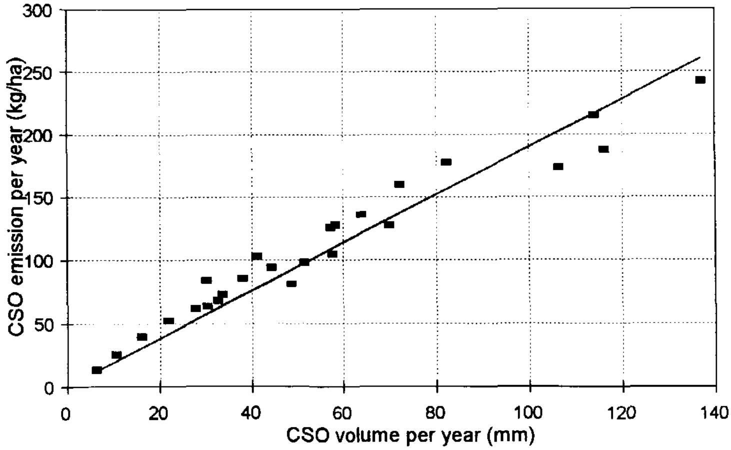
Table 6.2 shows clearly that the sewer system of Loenen did not meet the requirements of the reference sewer system. Some measures have to be taken to improve the sewer system so that it will not cause more CSO emission to receiving waters than the reference sewer system allows.

Regression analysis was applied to fit CSO emission versus CSO volume from the reference sewer system, which resulted in,

$$L_{CSO} = 1.90 V_{CSO}, \quad r = 0.93 \tag{6.1}$$

where V_{CSO} = CSO volume per year, mm/year
L_{CSO} = CSO emission (TSS) per year, kg/ha/year

On a yearly basis, CSO emission has very high correlation with CSO volume ($r = 0.93$). So, if CSO volume is known, which may be (relatively easily) predicted by using numerical sewer models, then CSO emission may be calculated using Equation (6.1) or Figure 6.3.



Figuer 6.3 Total CSO emission (TSS) v.s. CSO volume per year (reference sewer system)

6.3.2 Iso-lines of CSO frequency, volume and emission

Another application case of SewSim was performed using the standard 25 years' rainfall record of De Bilt. Different combinations of sewer storage (B), excessing pumping capacity (POC) and tank storage (Bt) were chosen for continuous simulation using SewSim with the standard rainfall record of De Bilt. The dark blocks mean that such combinations do satisfy the reference system based on the simulation results of CSO volume (or emission) on a yearly basis.

Table 6.3 Different combinations of sewer storage, excess pumping capacity and settling tank storage compared to the reference system

POC (mm/h)	0.4	0.5	0.6	0.7	0.8	0.9	1.0
storage of settling tank Bt = 2.0 mm							
B=4							
B=5						■	■
B=6					■	■	■
B=7				■	■	■	■
B=8				■	■	■	■
B=9			■	■	■	■	■
B=10			■	■	■	■	■
storage of settling tank Bt = 1.5 mm							
B=4							
B=5							■
B=6						■	■
B=7					■	■	■
B=8				■	■	■	■
B=9				■	■	■	■
B=10			■	■	■	■	■
storage of settling tank Bt = 1.0 mm							
B=4							
B=5							
B=6							■
B=7					■	■	■
B=8					■	■	■
B=9				■	■	■	■
B=10				■	■	■	■
storage of settling tank Bt = 0.5 mm							
B=4							
B=5							
B=6							■
B=7						■	■
B=8					■	■	■
B=9				■	■	■	■
B=10				■	■	■	■
storage of settling tank Bt = 0 mm							
B=4							
B=5							
B=6							
B=7							■
B=8						■	■
B=9					■	■	■
B=10				■	■	■	■

Table 6.3 has only a limited application potential, for example, it is known that

(B, POC, Bt) = (5, 0,9, 2,0) satisfies the reference sewer system,
(B, POC, Bt) = (5, 0,8, 2,0) does not satisfy the reference sewer system and
(B, POC, Bt) = (4, 0,9, 2,0) does not satisfy the reference sewer system either.

But, how about the following combinations?

(B, POC, Bt) = (5, 0,82, 2,0), (5, 0,84, 2,0), (5, 0,86,2,0) and (5, 0,88, 2,0) ?
(B, POC, Bt) = (4,2, 0,9, 2,0), (4,4, 0,9, 2,0), (4,6, 0,9,2,0) and (4,8, 0,9, 2,0) ?

It is impossible to determine whether these combinations satisfy the reference sewer system or not from Table 6.3. Therefore these combinations were simulated using SewSim, together with other combinations that cannot be determined from Table 6.3. These simulations resulted in the following figure.

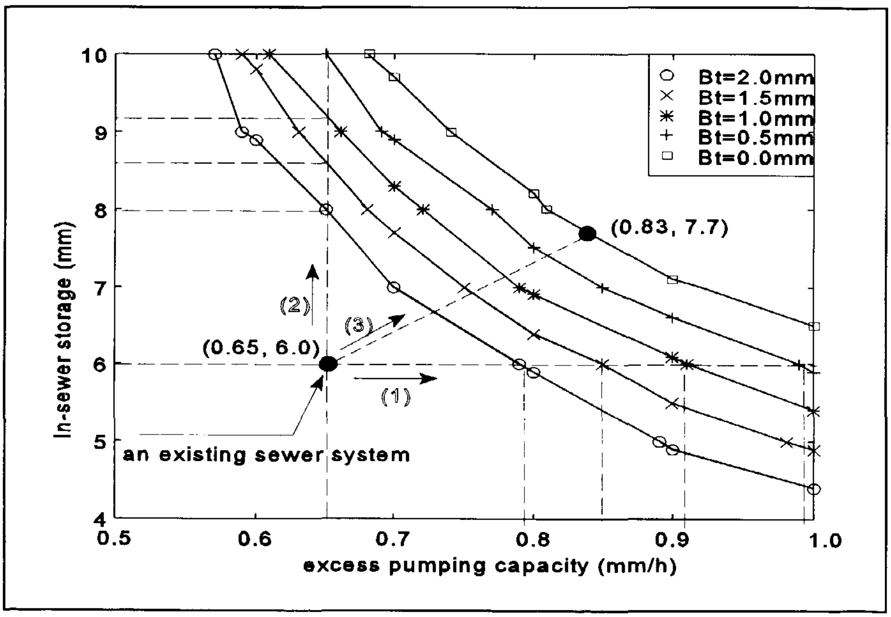


Figure 6.4 Iso-lines of CSO frequency and volume for the reference sewer system

In fact, each combination that can be read from the iso-lines of Figure 6.4 is equivalent to the reference sewer system. These iso-lines are very useful for determing whether an existing sewer system satisfies the reference sewer system or not. They can also be used to find optimal solutions to make a sewer system satisfying the reference sewer system. The costs of the adjustments are a function of the three variables, i.e. costs = f (B, POC, Bt). Figuur 6.4 shows an example: an existing sewer system has an in-sewer storage of 6.0 mm and a POC of 0.65 mm/h without a settling tank. Of course this sewer system does not satisfy the reference sewer system.

From Figure 6.4 different scenarios can be found to make the sewer system satisfying the reference sewer system. The first is that the in-sewer storage remains unchanged while the POC is increased from 0.65 mm/h to between 0.79 mm/h and 0.99 mm/h with a settling tank behind the overflow weir (Bt is between 2.0 and 0.5 mm). The second is that the POC remains unchanged while the in-sewer storage is increased from 6.0 mm to between 8.0 and 10 mm with the same settling tank behind the overflow weir. The third is the so-called source control method - i.e. reducing the impervious surface area such that the sewer system will satisfy the reference sewer system. For example, suppose the impervious surface area can be reduced with a factor *pr*, then the in-sewer storage and the excess pumping capacity will be B**pr* (in mm) and poc**pr* (in mm/h). The factor *pr* can be found to be 0.83/0.65 or 7.7/6.0 = 1.28 from Figure 6.4.

If the costs of the adjustments in terms of in-sewer storage, POC, the storage of the settling tank and source control are known, the optimal solution can be found. Table 6.4 gives the summary of the different solutions disscussed above.

Table 6.4 Summary of different solutions to improve the existing sewer system

if	then	Bt= 2.0mm	Bt= 1.5mm	Bt= 1.0mm	Bt= 0.5mm	Bt= 0.0mm
(1) B = 6.0mm	poc=	0.79	0.85	0.91	0.99	n.a
(2) poc=0.65mm/h	B =	8.0	8.6	9.2	10	n.a
	B+Bt	10.0	10.1	10.2	10.5	n.a(
(3) *pr*= 1.28	Bt=0	B=7.7 mm and poc = 0.83 mm/h (source control)				

Figure 6.5 shows that by means of changing the in-sewer storage and the excess pumping capacity of a sewer system with no settling tanks, the CSO emission may change accordingly in respect to the reference sewer system. The "100%" line represents actually the reference sewer system. Using Figuer 6.4 and 6.5, similar percentage of CSO emission may be predicted for sewer sytems with settling tanks behind outfalls.

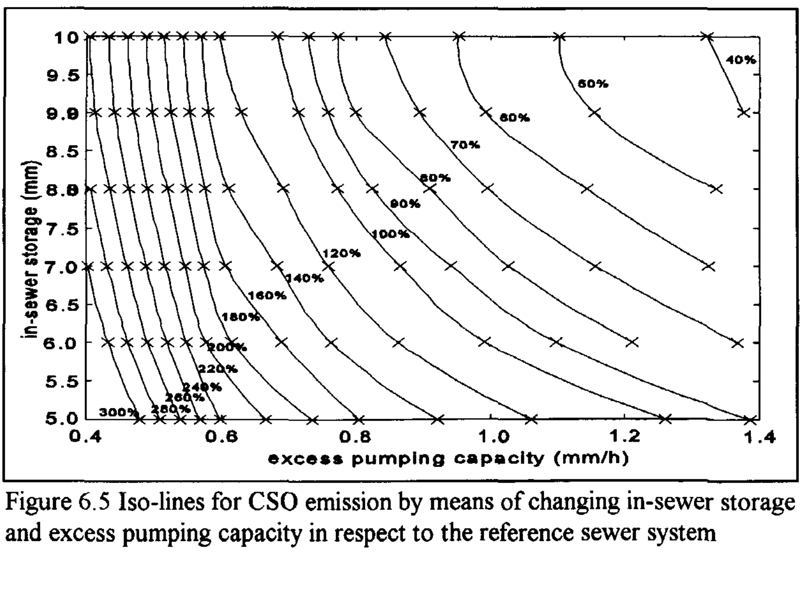


Figure 6.5 Iso-lines for CSO emission by means of changing in-sewer storage and excess pumping capacity in respect to the reference sewer system

6.4 Case study (Apeldoorn-West)

6.4.1 Introduction

Apeldoorn-West is a large Dutch catchment with a population of about 55000. The mean slopes of the catchment and of the sewers are approximately 0.2% and 0.31% respectively. The catchment consists of five subcatchments: BouWhof (BW), BeekVertraagd (BV), Wormen (WO), WormenVertraagd (WV) and ZuidWest (ZW). The total impervious catchment area is 570 ha. The sewer network consists of approximately 7000 nodes and conduits with eleven pumps, and seven external overflow weirs. The in-sewer storage varies from 5.2 mm to 10.2 mm dependent on the level of the crests of the external (outfall) weirs. The following figure shows the relation between the in-sewer storage and the level of crests of the external overflow weirs.

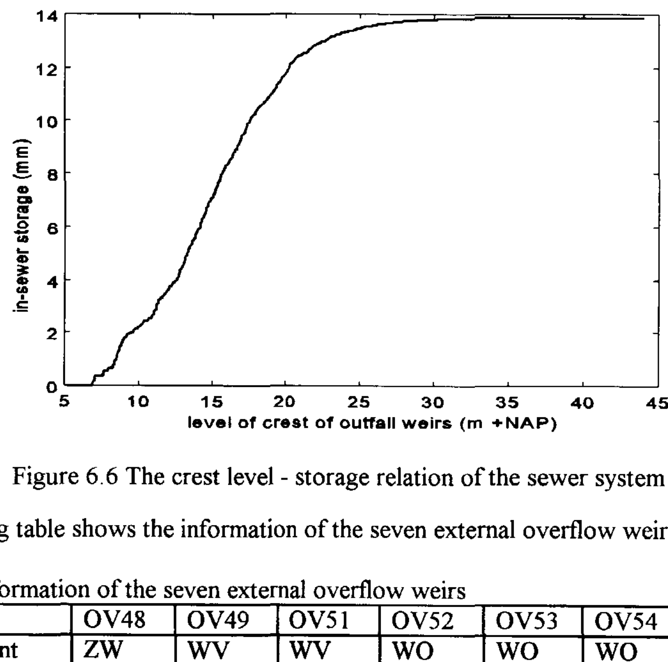


Figure 6.6 The crest level - storage relation of the sewer system

The following table shows the information of the seven external overflow weirs.

Table 6.5 Information of the seven external overflow weirs

	OV48	OV49	OV51	OV52	OV53	OV54	OV55
subcatchment	ZW	WV	WV	WO	WO	WO	WV
Crest (m+NAP)	17.76	13.67	14.22	13.45	13.35	13.40	15.28
Width (m)	9.0	1.2	3.0	4.4	3.0	9.4	1.9

The overflow weir OV48 has a somewhat complicated structure as depicted in Figure 6.7. The water flows through two large conduits with a diameter of 1000 mm and 2000 mm into the node of an internal weir (crest: 17.66 m+NAP). There is a round opening in the wall (i.e. internal weir) for the return of flow when necessary. After this wall, the water flows through a conduit with a diameter of 1500 mm into the node and over the first wall (crest: 17.53 m+NAP) of the storage tank. In this wall, there are three square flap valves to prevent any reverse flow and the water in the storage tank can flow back into the sewer system after storms. If the water level in the storage tank is higher than the crest level (17.76 m+NAP) of the external overflow weir (i.e. the second wall of the tank), the water will flow over this wall to receiving waters.

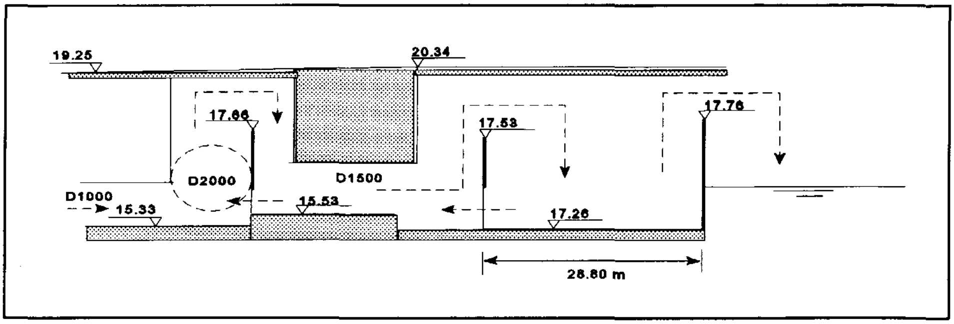


Figure 6.7 The constructure of overflow OV48 and its storage tank

The overflow from the seven external overflow weirs may pollute receiving waters. In accordance with the new Dutch guidelines for uban storm drainage, continuous simulation using the standard 25 year's rainfall record of De Bilt is required for evaluating the sewer system. In addition, it will be useful to compare the performance of the sewer system of Apeldoorn-West in terms of CSO frequency and volume with those of the reference sewer system. Flooding may cause many inconveniences, like traffic jams and accidents as well as damages to property. However this case study focuses only on the problem of overflow.

6.4.2 Calibration of SewSim

Due to the lack of sufficient measured data, HydroWorks was used to calibrate the SewSim model. In order to limit the simulation time, the first three years of the 25 years' rainfall record of De Bilt were chosen, namely 1955, 1956 and 1957. However the driest year (1959) and the wettest year (1966) were added. These five years of rainfall record were assumed to be representative of the total rainfall record. As stated previously, HydroWorks was not able to use a long data series of rainfall record. Thus the five years' rainfall record was separated into independent rainfall events. In total 121 rainfall events remained after filtering based on two criteria: the minimum dry period between the independent rainfall events is assumed to be 300 minutes and the minimum rainfall depth is 6 mm.

It should be stated that the maximum number of nodes of a sewer system that HydroWorks can cope with at present is 5000. Therefore the sewer system of Apeldoorn-West was simplified by means of removing unimportant nodes. This was carried out by the municipality self - a simplified version of the sewer network consisting of approximately 3500 nodes was the result. This version of the sewer network was used for all simulations.

The simulation efficiency of HydroWorks run on a Pentium computer (133 MHz) was approximately 1:6 - one minute of simulation time is needed for 6 minutes of rainfall duration. The simulation time of the first three years (1955-1957, in total 69 rainfall events) was about 240 hours or 10 days. The driest and wettest year (1959 and 1966, in total 62 rainfall events) needed a simulation time of the same order. The simulation results are summarised in Table 6.6, which shows the following facts,

- OV48, OV51 and OV54 contribute roughly three quarters of the total CSO volume.
- OV49 and OV 52 could be negligible compared to the total CSO volume (355,100 m^3).
- OV49 has a very high overflow frequency (51 times in 5 years).
- the first three years have a CSO volume of 164,200 m^3.
- the driest year (1959) has the smallest CSO volume (25,900 m^3)
- the wettest year (1966) has the largest CSO volume (165,000 m^3), which amounts almost equally to the CSO volume of the first three years.

Table 6.6 Summary of simulation results of the five years' rainfall record (HydroWorks)

names		1955	1956	1957	1959	1966	mean	total	perc.(%)
	volume	9,9	14,4	13,9	6,8	49,8	19,0	94,8	26,7
OV48	frequency	2	4	6	2	9	5	23	7,7
	volume	0,9	1,3	1,2	0,5	2,5	1,4	7,1	2,0
OV49	frequency	7	9	12	6	17	10	51	17,2
	volume	10,5	14,5	14,8	6,0	39,2	17,0	85,0	24,0
OV51	frequency	7,0	10,0	15,0	7,0	18,0	11,0	57,0	19,2
	volume	1,1	1,2	1,6	0,7	5,1	2,0	9,9	2,8
OV52	frequency	2	3	7	2	8	4	22	7,4
	volume	3,7	5,4	6,2	2,3	14,5	6,4	32,1	9,0
OV53	frequency	7	7	13	5	10	8	42	14,1
	volume	10,8	15,2	17,5	6,3	34,1	16,8	83,9	23,6
OV54	frequency	8,0	9,0	15,0	6,0	13,0	10,0	51,0	17,2
	volume	5,2	6,8	7,9	3,3	19,2	8,5	42,4	11,9
OV55	frequency	8	8	14	6	15	11	51	17,2
	volume	42.2	58.7	63.3	25.9	165	71	355.1	100
Total	frequency	41	50	82	34	90	59	297	100

(volume in 1000 m^3)

To calibrate SewSim, default values were used for most model parameters, such as the initial loss potential, inter-event time, reservoir coefficients etc.. The five important system variables for each overflow can be determined as follows,

- impervious area: it has to be calibrated by "trial and error" for each overflow. However as long as the impervious area of <u>one</u> overflow has been determined, the others may be determined more easily by considering the percentage of CSO volume predicted by HydroWorks (Table 6.6).
- in-sewer storage: it can be read from the storage-crest relation shown in Figure 6.6 using the information of the crest level of the overflow weirs from Table 6.5.
- pumping capacity: it has to be calculated by "trial and error" for each overflow using the simulation results of HydroWorks (Table 6.6).
- tank storage: tank volume divided by the relevant impervious area, for example, the volume of the tank behind OV48 is: L x B x h = 28.8 x 9.0 x 0.5 = 129.6 m^3; the impervious area is calculated to be 60 ha, so the tank storage is 129.6/60/10 which is approximately 0.2 mm.
- DWF: the total population was 55,000 and the total impervious area was about 570 ha, so the population density was approximately 100 person/ha.

To determine the five system variables and to calibrate the SewSim model, the same five year's rainfall record (i.e. 1955-1957, 1959 and 1966) was used for continuous simulation. The five system variables determined for each overflow and the calibration results are summarised in Table 6.7 and 6.8.

Table 6.7 Five system variables for each overflow required for SewSim

	impervious area (ha)	in-sewer storage (mm)	pumping capacity (mm/h)	tank storage (mm)	population (-)
OV48	60	10.2	1.0	0.2	6000
OV51	40	6.2	1.3	0.0	4000
OV53	15	5.2	1.6	0.0	1500
OV54	40	5.2	1.6	0.0	4000
OV55	20	7.6	1.0	0.0	2000

Table 6.8 Calibration results (overflow numbers and volume) of SewSim against HydroWorks

	year	1955		1956		1957		1959		1966		total	
	models	V_{OV}	f_{OV}	V_{OV}	f_{OV}	V_{OV}	f_{OV}	V_{OV}	f_{OV}	V_{OV}	f_{OV}	V_{OV}	f_{OV}
OV 48	SewSim	6.1	3	17.5	5	13.8	7	3.4	1	53.7	8	94.5	24
	HydroW	9.9	2	14.4	4	13.9	6	6.8	2	49.8	9	94.9	23
OV 51	SewSim	8.8	6	16	11	14.7	16	4.7	5	42.5	13	86.6	51
	HydroW	10.5	7	14.5	10	14.8	12	6.0	7	39	18	84.8	54
OV 54	SewSim	8.2	6	15.4	10	16.4	17	4.7	5	40.6	13	85.3	51
	HydroW	10.8	8	15.2	9	17.5	15	6.3	6	34.1	13	83.9	51
OV 53	SewSim	3.1	6	5.8	10	6.1	17	1.8	5	15.2	13	32	51
	HydroW	3.7	7	5.4	7	6.2	13	2.3	5	14.5	10	32.1	43
OV 55	SewSim	4.3	4	8.4	13	7.8	12	2.1	3	22.9	14	45.4	46
	HydroW	5.2	8	6.8	8	7.9	14	3.3	6	19.2	15	42.4	51

(overflow volume V_{OV} in 1000 m^3; overflow frequency f_{OV} per year)

Table 6.8 shows that SewSim is able to predict overflow volume and overflow frequency accurately if compared to the simulation results of HydroWorks, particularly for wet years. Since the first three years were chosen arbitrarily and the other two years were the driest and wettest years, which implies that these five years' rainfall record is representative of the total rainfall record of De Bilt. So it can be stated that SewSim was successfully calibrated for the sewer system of Apeldoorn-West.

6.4.3 Simulation using SewSim

The calibrated SewSim model was used for continuous simulation of 25 years' rainfall record of De Bilt. The reference sewer system defined in section **6.3** was included for comparison. The simulation results are summarised in Table 6.9. The total simulation time is only a fraction of that needed when using HydroWorks (5 years' record).

Table 6.9 Simulation results of Apeldoorn-West using the rainfall record of De Bilt (SewSim)

	reference sewer system		OV48		OV51		OV53		OV54		OV55	
year	Volume (mm)	OV (year)	Volume (mm)	OV (year)	Volume (mm)	OV (year)	Volume (mm)	OV (year)	Volume (mm)	OV (year)	Volume (mm)	OV (year)
55	21.7	4	10.1	3	22.0	6	20.4	6	20.4	6	21.3	4
56	44.2	11	29.2	5	40.0	11	38.6	10	38.6	10	41.9	13
57	51.5	14	23.0	7	36.8	16	41.0	17	41.0	17	39.0	12
58	32.7	7	15.3	4	29.2	6	30.5	7	30.5	7	29.5	7
59	10.6	3	5.7	1	11.6	5	11.8	5	11.8	5	10.3	3
60	106.4	10	67.3	9	75.6	11	68.4	9	68.4	9	89.6	14
61	114.0	17	68.7	11	91.6	16	86.5	16	86.4	16	100.8	15
62	30.2	3	24.2	3	34.2	3	35.9	5	35.9	5	32.6	3
63	33.7	7	22.3	4	38.8	8	42.0	10	41.9	10	36.2	8
64	63.9	12	37.5	7	54.9	10	52.3	11	52.3	11	58.1	12
65	137.1	21	75.4	8	104.4	19	97.4	17	97.4	18	113.0	18
66	116.1	15	89.5	8	106.2	13	101.5	13	101.5	13	114.4	14
67	57.2	7	28.0	5	42.7	8	41.9	8	41.9	8	45.3	8
68	58.3	13	23.1	6	50.3	15	50.0	16	49.9	16	52.8	13
69	57.6	11	37.0	8	51.1	10	48.3	9	48.3	10	54.8	10
70	70.0	11	45.4	5	53.5	10	48.7	11	48.7	11	62.1	9
71	30.4	9	21.0	5	23.4	6	19.4	5	19.4	5	27.7	6
72	27.8	5	16.1	4	29.4	7	30.8	7	30.8	7	27.6	5
73	72.2	11	44.8	7	61.5	9	58.2	11	58.2	11	67.0	9
74	82.0	10	56.6	8	78.1	9	74.4	9	74.4	9	79.2	8
75	41.1	6	29.6	5	47.8	8	48.0	8	48.0	8	44.5	8
76	16.0	4	2.9	1	14.4	5	15.6	5	15.6	5	11.9	4
77	38.0	8	8.3	3	14.7	5	14.2	5	14.2	5	20.9	6
78	6.3	3	1.4	2	10.1	4	11.7	4	11.7	4	7.4	3
79	48.6	7	40.3	4	41.6	6	42.2	5	42.3	6	44.2	5
mean	54.7	9	32.9	5	46.6	9	45.2	9	45.2	9	49.3	9

Some conclusions may be drawn from the table shown above:
- The predicted overflow numbers and volume show that all the five overflows meet the requirements of the reference sewer system, in particular, the overflow volume in mm of each overflow is smaller than that of the reference sewer system.
- OV48, OV51 and OV54 are again the most important overflows.
- Due to the high crest level of OV48 and the storage tank behind it, OV48 has a lower average overflow number (i.e. 5 times per year). The other four have an average overflow number of 9 times per year, which is equivalent to the reference sewer system.

6.5 Conclusion

SewSim is able to predict CSO frequency with a higher degree of accuracy than the Kuiper's dot graphical method for the sewer system of Loenen. These prediction results, which were obtained using the standard 25 years' rainfall record of De Bilt, were compared with those of HydroWorks, which resulted in a high degree of consistency. This provides a reliable proof of using SewSim for predicting CSO frequency instead of the Kuiper's dot graphical method.

The so-called reference sewer system was extensively investigated for CSO frequency, volume and emission. Based on the standard rainfall record of De Bilt, it appears that the reference sewer system may cause 9 CSO events per year with a mean CSO volume of 55 mm and CSO emission (TSS) of 109 kg/ha per year. The average TSS concentration is 211 mg/l. These values are much smaller than those of the sewer system of Loenen, which implies that the latter did not meet the reference sewer system concerning CSO pollution.

The regression analysis of the yearly CSO emission versus CSO volume results in a good corelation ($r = 0.93$). Therefore this regression equation can be used for estimating CSO emission in practice. SewSim is able to produce a useful table to determine which combinations of impervious surface area, sewer storage capacity, excess pumping capacity and tank storage capacity of an existing sewer system will satisfy the reference system. Furthermore two figures have been developed showing iso-lines of CSO frequency, volume and emission for the reference sewer system. These figures have more application potentials to evaluate whether an existing sewer system satisfies the reference sewer system, and if not, to find the best cost-effective scenario for improvements.

The case study of the sewer system of Apeldoorn-West has shown that it is possible to apply SewSim to a complicated sewer system with multiple overflow weirs. The calibration procedure of the five important system variables is not time-consuming and may result in good model performance. The simulation results of the standard rainfall record of De Bilt have shown that the sewer system in Apeldoorn-West meets the requirements of the reference sewer system.

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

In the Netherlands, as in most other European countries, the majority of sewer systems are of the combined type. Usually physically based hydrodynamic models are used to quantify CSO emission to receiving waters. However these detailed models are very elaborate and complicated due to complex physical, chemical and biological processes occurring in combined sewer systems. Consequently, the application of these models is rather data-intensive and time-consuming, and therefore not cost-effective, particularly if the models are used as long-term planning tools for (combined) sewer systems.

The aim of the Ph.D research presented here is to develop alternatives to the currently used detailed, hydrodynamic models: parametric modelling and conceptual modelling.

Parametric modelling

Measurement data (rainfall, water level and pollutants concentration etc.) from NWRW research programme (1989) were processed and analysed using regression analysis and time-series models. It has been found that the mean TSS load (concentration) and BOD load (concentration) from three combined sewer systems are 15 kg/ha (150 g/m^3) and 2.6 kg/ha (40 g/m^3) per CSO event respectively. These values are useful for estimating CSO emission in preliminary studies of combined sewer systems. For the sewer system of Loenen, regression analysis has shown that CSO volume and emission of each CSO event are correlated to the product of the rainfall depth and the maximum rainfall intensity (r>0.85). However, no satisfactory relationships can be found between CSO emission versus CSO discharge within each rainfall event.

For the same sewer system, CSO hydrographs can be predicted by an *OE-I* (output-error) model from effective rainfall intensity. An *ARX-I* model has been found to be capable of predicting the continuous water level at the outfall from rainfall intensity. It has been investigated to predict CSO emission from CSO discharge within a rainfall event, which results in accurate pollutographs (one-step ahead prediction with an *ARX-I* model). The research has shown that time-series models are in general very efficient in simulating various input and output relationships of dynamic (sewer) systems. These models are able to capture the stochastic characteristics of hydrologic and hydraulic processes, and to a less extent, also the behaviour of sediment movement within the combined sewer system. In particular, they are very useful for real-time control of (combined) sewer systems, where on-line data are available. On the other hand, these models need evenly spread input measurement data which are not easily available in practice. They are also quite site-specific and unable to solve “what-if” problems.

Conceptual modelling

A sensitivity analysis of a detailed model (e.g. HydroWorks) has shown that four important system variables that have significant influence on CSO volume are: impervious area, sewer storage, pumping capacity and settling tank storage (if available). Some quality parameters, such as the initial amount and buildup rate of sediment on the impervious surface, are important for quantifying CSO emission. Consequently, based on these findings, a conceptual CSO emission model (SewSim) has been developed. The model is capable of generating end-pipe simulation results, such as CSO hydrographs and pollutographs using single rainfall events or time-series data of recorded rainfall (i.e. event-based and continuous simulation). Much attention was paid to the simulation efficiency of the model performance in predicting CSO emission using the standard 25 years' rainfall record of De Bilt.

In SewSim, a sewer system is conceptualised into three linked reservoirs. They represent the impervious catchment surface, the sewer network and the settling tank respectively. In principle, most physical processes involved in the reservoirs are modelled in a similar and in some cases an improved way compared with some existing detailed, hydrodynamic models.

In the first reservoir, rainfall-runoff process is modelled in two stages: first, surface runoff is computed taking into account initial losses (i.e. wetting and depression storage) and continuous recovery of loss potential of impervious surfaces during dry weather. Second, a cascade of n linear reservoir model has been set up for overland flow routing, which can be converted into a n-order state-space model or n one-order state-space models. The delay induced among runoff rates from a large catchment is dealt with the time of concentration of each sub-catchment via a transformation matrix. For quality aspects of modelling, the interactive processes of sediment buildup/washoff on the impervious surface are modelled based on an exponential function/"first-order" relationship respectively, similar with those adopted by detailed hydrodynamic models.

In the second and third reservoir, no detailed flow routing (e.g. the Saint-Venant equation) is included. However, SewSim is able to simulate the dynamic effect of flow routing in the sewer system by means of a five-phase handling of runoff rate, variable sewer storage and pumping capacity. For modelling the processes of sediment deposition/scouring in the sewer network and the settling tank, a similar modelling approach is adopted, comparable to the one for sediment buildup/washoff on the impervious surface.

SewSim has been developed using a powerful programming package MATLAB/SIMULINK. The model may be verified by means of both measurement data and the simulation results of HydroWorks. It is able to predict CSO frequency and volume (event-based and continuous simulation) with a sufficient accuracy. To predict CSO pollutographs, neither SewSim nor HydroWorks performed in a convincing way. However for continuous simulation, the results from SewSim on a yearly basis were acceptable concerning the simulation accuracy and efficiency. In using SewSim, compared with HydroWorks, much less input data for system variables and model parameters are needed, and the simulation time is considerably reduced. Further, the model calibration and verification, and the implementation of model outputs are much less labour-intensive, thus more cost-effective than detailed models, particularly for long-term planning studies of (combined) sewer systems.

SewSim was successfully applied to the sewer system of Loenen. The predicted CSO frequency and volume based on the rainfall record of De Bilt are very similar to those of HydroWorks, but much more accurate than the traditional Kuipers' graphical method concerning CSO frequency. The reference sewer system recommended by CUWVO VI (1992) can be very well represented by SewSim. Based on the rainfall record of De Bilt, it appears that the reference sewer system may cause 9 CSO events per year with a mean CSO volume of 55 mm and CSO emission (TSS) of 109 kg/ha per year. The average TSS concentration is 211 mg/l. The regression analysis of the yearly CSO emission versus volume results in a good correlation (r = 0.93). A useful table and two figures (i.e. iso-lines for CSO emission) have been produced for determining which combinations of impervious surface area, sewer storage, excess pumping capacity and settling tank storage of an existing (combined) sewer system satisfy the reference sewer system, and if not, to find the best cost-effective scenario for improvements. For example, according to the table and the figures, the sewer system of Loenen did not satisfy the reference sewer system.

The case study of the sewer system of Apeldoorn-West has demonstrated that it is possible to apply SewSim to more complicated sewer systems with multiple ancillaries (e.g. overflow weirs). The simulation results based on the rainfall record of De Bilt have shown that the sewer system of Apeldoorn-West meets the requirements of the reference sewer system. These results can not be obtained using HydroWorks, because the simulation time is still too long using standard Pcs.

The main achievements of this research may be summarised as follows,

- The NWRW database has been processed and analysed, providing useful values of mean pollutant load and concentration for preliminary studies of combined sewer systems.

- Time-series models have been investigated for predicting CSO hydrographs and pollutographs. These models are efficient in modelling stochastic characteristics of input - output relationships of dynamic systems. They are particularly useful for real-time control of combined sewer systems.

- A robust conceptual model (SewSim) has been developed for CSO emission prediction. The model may be applied to various sewer systems and rainfall data with a satisfactory accuracy. The use of the model is much less labour-intensive and thus more cost-effective than detailed models.

- The reference sewer system has been thoroughly investigated using SewSim. A useful table and two figures of iso-lines for CSO frequency, volume and emission have been produced.

7.2 Recommendations

This research covers three basic modelling approaches (deterministic, parametric and conceptual), each of which has its advantages and disadvantages. According to the objective of studies of sewer systems, the available data and computing facilities, numerical sewer models should be chosen appropriately and should not be under- or over-used. Some recommended improvements of computational sewer modelling are the following,

1. More experimental work is needed for developing more accurate hydrodynamic (deterministic) models. Such models are still useful in practice, not only for design studies of sewer systems but also for calibrating conceptual sewer models. For this purpose, such models should be as "deterministic" as possible so that they can be used as the "virtual reality" or "electronic laboratory" for research and as practical tools concerning sewer systems. This can only be achieved if more measurement data become available to verify and improve the present hydrodynamic models, particularly for water quality modelling.

2. The theory of time-series modelling should be further developed, in particular the methods for analysing irregular time-series data, since most existing measurement data in urban storm drainage are not evenly spread in time. Bias may be introduced into the input-output relationship due to interpolation of measurement data. It should therefore be emphasised that constant time intervals should be used when taking measurements in the future. For example, if (financial) resources are limited, it is preferred that one long and regular series of measurement data rather than two or more series (e.g. TSS, BOD, COD etc.) that are short or/and irregular.

3. The conceptual CSO emission model SewSim may be improved in the following ways,

1) A method may be found to separate the impervious catchment into sub-catchments more easily so as to enable SewSim to simulate large and complicated sewer systems more efficiently.

2) Some important model parameters, such as the storage constants of reservoir models, the coefficients of sediment buildup/washoff may be further investigated to relate them to physical features of sewer systems and/or rainfall data so as to reduce calibration efforts.

3) Some concepts built in SewSim need to be modified so that the model can be applied also to sewer systems in sloping catchments.

4) Modelling techniques in SIMULINK may be further improved to provide a clearer structure and better performance of the model.

5) MATLAB/SIMULINK code of SewSim may be converted to C/C++ in order to develop stand-alone software.

LIST OF SYMBOLS

Symbols

A_{aw} = numerical coefficient of Acker-White's model, -
A = contributing area, ha
A = cross-sectional area, m^2
a, a_1, a_2= numerical coefficient, -
B, B_0 = storage capacity of sewers, mm
B = width of overflow weir, m
B_t = storage capacity of settling tank, mm
b = numerical coefficient, -
C_0 = sediment concentration of inflowing wastewater, mg/l
C_{0i} = dry weather concentration of sediment, mg/l
C_i = concentration of pollutant at outlet, mg/l
C_{aw} = numerical coefficient of Acker-White's model, -
C_{ave} = average TSS concentration, mg/l
D = (average) sewer diameter, m
D = average depth of initial losses, mm
d_{35} = particles diameter (35% of particles have a diameter of less than d_{35} in mass), μm
e = residual square error
e = unmeasurable noise (disturbance)
F_{gr} = dimensionless mobility particle number, -
F_v = impervious catchment area, ha
g = acceleration due to gravity, m/s^2
G_{gr} = dimensionless solid flow number, -
H = water level, m
H_0 = level of the weir crest, m
i = rainfall intensity, mm/h
i_{max} = maximum rainfall intensity, mm/h
k = numerical coefficient, -
k = decay factor, 1/d
K = conveyance, -
K_r = numerical coefficient of Fletcher and Pratt's model, -
L = (total) sewer length, m
L = total load of sediment, kg/ha
L = CSO emission, kg/min
L_{tot} = total TSS load, kg/min
L_{CSO} = CSO emission, kg/ha/year
m, n = numerical coefficient (of Acker-White's model), -
M, M_0= mass of sediment in sewer network, kg/ha
M_d = deposition factor, kg/ha/day
OV_t = total overflow duration, min
OV_v = total overflow volume, m^3
P = amount of sediment present on subcatchment, kg
P_L = limiting surface sediment load, kg
p = mass of sediment, kg/ha

p_0 = initial mass of sediment before dry weather, kg/ha
p_s = buildup factor, kg/ha/day
p, POC= excess pumping capacity, mm/h
Q, q = discharge or overflow rate, m^3/s
Q_{max} = maximum overflow dischage, m^3/min
q_1,q_2 = outflow of reservoir, mm/min
q_t = total solid flow or concentration, kg/l
R = hydraulic radius, m
R = cumulative rainfall depth, mm
R_0 = solids removal ratio due to settling, %
Ri_{max} = product of total rainfall depth and maximum rainfall intensity, mm^2/h
r = correlation coefficient, -
r = runoff rate, mm/min
r_e = effective rainfall intensity, mm/min
r_{cum} = cumulative rainfall intensity, mm/min
s_0 = suface loading, m/h
S = mean slope of sewers or sub-catchment, m/m or %
S_f = friction slope, -
S_0 = bed slope, -
S_1,S_2 = conceptual storage of impervious surface, mm
s = specific gravity of particles, kg/l
t, t_1, t_2 = time, h or s
T = storage capacity of settling tank, mm
T_{step} = time resolution of rainfall data, min
U = mean flow velocity, m/s
u^* = friction velocity, m/s
v_s = settling velocity, m/h
V = flow velocity, m/s
V = overflow or water volume, m^3 or mm
V_{CSO} = CSO volume, mm or mm/year
W_e = effective deposited sediment width, m
w = wash-off coefficient, -
w_e = erosion coefficient, 1/mm
x = longitudial direction, m
y = depth of flow, m
λ_d = deposition coefficient, $time^{-1}$
λ_e = erosion coefficient, $volume^{-1}$
ν = kinematic viscosity,
τ = bed shear stress, N/m^2
ρ = fluid density, g/m^3
θ = angle of bed horizontal, °
σ = standard deviation

LIST OF REFERENCES

Ackers P.(1984). Sediment transport in sewers and the design implications, *Int. Conf. on the Planning, Construction, Maintaince & Operation of Sewerage Systems,* 12-14 Sept.

American Public Works Association.(1969). Water pollution aspects of urban runoff. *Federal water pollution control administration,* Contract WP-20-15, Washington, DC.

Ammon D.C.(1979). *Urban stormwater pollutant buildup and washoff relationships.* Master of Engineering thesis, University of Florida, Dept. of Environmental Engineering Sciences, Gainesville.

Ashley R.M. and Crabtree R.W.(1992). Sediment origins, deposition and build-up in combined sewer systems. *Wat. Sci. Tech.*, **25**(8), 1-12.

Ashley R.M., Arthur S., Coghlan B.P. and McGregor I.(1994). Fluid sediment in combined sewers. *Wat. Sci. Tech.*, **29**(1-2), 113-123.

Assel J. van, Dierickx M. and Heip L.(1997). Practical Application of Deterministic Sewer Flow Quality Models (MouseTrap and HydroWorks™DM), *2nd Int. Con. on "The Sewer As a Physical,Chemical and Biologyical Reactor"*, Aalborg, Denmark, 25-28 May.

Bachoc A.(1992). Location and general characteristics of sediment deposits into man-entry combined sewers. *Wat. Sci. Tech.*, **25**(8), 47-55.

Bertrand–Krajewski J.L.(1992). A model for solid production and transport for small urban catchments: preliminary results, *Wat. Sci. Tech.*, **25**(8), 29–35.

Bertrand-Krajewski J.L.,Briat P.,Scrivener O.(1993). Sewer sediment production and transport modelling: A literature review. *J. Hydrau. Res.*, **31**(4), 435-460.

Blanc D., Kellagher R., Phan L. and Price R. (1995). FLUPOL-MOSQITO, models, simulations, critical analysis and development, *Wat. Sci. Tech.*, **32**(1), 185-192.

Bogaerts C., Kevers-Leclercq J., Capart H. and Zech Y.(1998). Robust numerical treatment of flow reversal, drowning, and transcriptical transitions at drainage pipe boundaries. Fourth Int. Conf. on Developments in urban drainage modelling, 21-24 Sept. 1998, London, U.K.

Butler D., Thedchanamoorthy S. and Payne J.A. (1992). Aspects of surface sediment characteristics on an urban catchment in London, *Wat. Sci. Tech.*, **8**(25), 13-19.

CHAM (1991). The PHOENICS reference manual part a+b, CHAM Ltd., London, UK

Capodaglio A.G.(1994). Transfer function modelling of urban drainage systems, and potential uses in real-time control applications, *Wat. Sci. Tech.*, **29**(1-2), 409-417.

Crabtree R.W.(1989). Sediments in sewers. *J.IWEM.*, **3**, 569-578.

Caroni E., Singh V.P. and Ubertini L.(1984). Rainfall-runoff-sediment yield relation by stochastic modelling, *J. Hydrological Science*, Vol. 29, No. 2, pp. 203-218

Cunge J.A.and Wegner M.(1964). 'Integration numerique des equations d'ecoulement de Barre de Saint-Venant par un schema implicite de differences finites: Application au cas d'une galerie tantot en charge, tantot a surface libre', La Houille Blance, No.1.

CUWVO VI(1992). Aanbevelingen voor het beleid en de vergunninglening met betrekking tot overstorting uit rillostelsels en regenwaterlozingen, CUWVO VI: subwerkgroep Eisen rioolwateroverstorten (in Dutch).

Delleur J.W. and Gyasi-Agyei Y.(1994). Prediction of suspended solids in urban sewers by transfer function model, *Wat. Sci. Tech.*, **29**(1-2), 171-179.

Dempsey P.(1996). SIMPLOL – A simplifed urban pollution modelling tool, Vol. III, 1365-1370, *7th ICUSD*, Hannover, Germany.

Deletic A., Maksimovic č. and Ivetic M.(1997). Modelling of storm wash-off of suspended solids from impervious surfaces. *J. Hydraulic Research*, **35**(1).

Einfalt T., Arnbjerg-Nielsen K. and Fankhauser R.(1998). Historical rainfall series: crucial and doubtful model input. Fourth Int. Conf. on Developments in urban drainage modelling, 21-24 Sept. 1998, London, U.K.

Fletcher I.J. and Pratt. C.J.(1981). Mathematical simulation of pollutant contributions to urban runoff roadside gully ponds, *2nd Int. Conf. On Urban Storm Drainage*, Urbana, 116-124.

Gong N., Denoeux T. and Bertrand-Krajewski J.L.(1995). Neural networks for solids transport modelling in sewer systems during storm events. *Int. Con. On Sewer Solids*, 5-8 Sept.

Grottker M.(1990). Pollutant removal by catch basins in West Germany. State of the art. New design, proceedings of "*Urban stormwater quality enhancement - source control, retrofitting and combined sewer technology*", New York (USA), 1990, 29p.

Homwongs C., Sastri T. And Foster III J.W.(1994). Adaptive forecasting of hourly municipal water consumption, *J. Water Res. Planning and Management*, Vol. 120, No. 6, pp. 888-856

Huber W.C.(1986). Deterministic modelling of urban runoff quality. In: *Urban Runoff Pollution*, Torno H.C., Marsalek J. and Desbordes M.(Ed.), Springer-Verlag, Berlin.

Huber W.C. and Barnwell T.O.(1992). Storm Water Management Model, Version 4: User's Manua. EPA/600/3-88/001a, NTIS PB88-236641/AS.

HydroWorks, Wallingford Software Ltd., U.K, 1998

Kleijwegt R.A.(1993). On the predication of sediment transport on sewers with deposits. *Wat. Sci. Tech.*, **27**(5-6), 69-80.

Kluck J.(1997). The design of optimally functioning storm water seeeling tanks. Ph.D. thesis, Delft University of Technology, the Netherlands

Lei J. and Schilling W.(1994). Parameter uncertainty propagation analysis for urban rainfall runoff modelling. *Wat. Sci. Tech.*, **29**(1-2), 145-154.

Lemke K.A.(1991). Transfer function models of suspended sediment concentration, *Water Res. Research*, **27**(3), 293-305.

Lindberg S., Nielsen J.B., Tetersen S., Amdisen L.K. and Harremöes P.(1990). Real time optimization of a sewer system as part of a large municipal prototype project including treatment plant operation. *5th ICUSD*, Osaka, July 23-27.

Ljung L.(1995). System identification toolbox user's guide (for use with MATLAB), The MathWorks.

Mason J.C., Price R.K. and Tem'me A.(1996). A neural network model of rainfall-runoff using radial basis functions. *J. of Hydraulic Research*, **34**(4).

Michelbach and Wöhrle (1993). Settleable solids in a combined sewer system, settling characteristics, heavy metals, efficiency of storm water tanks. *Wat. Sci. Tech.*, **27**(5-6), pp. 153-164.

Moffa P.E., Nix S.J., Freedman P.L, Marr J.L. and Field R.(1990). *Control and treatment of Combined-sewer overflows*, Van Nostrand Reinhold, New York.

Mutzner H.(1991). The significance of areal rainfall distribution for flows from a very small urban drainage catchment, *Atmospheric Research*, **27**, 99-107.

Nix S.T.(1994). Urban Stormwater Modeling and Simulation. Lewis, Boca Raton, pp.212

Nalluri C. and Alvarez E.M.(1992). The influence of cohesion on sediment behaviour. *Wat. Sci. Tech.* **25**(8), 151-164.

Nielsen J.B., Lindberg S., Amdisen L.K. and Jensen N.E.(1987). Towards the Fifth Generation of Numerical Modelling Systems. *4th ICUSD*, Lausaunne.

Nielsen K.A. and Harremoës P.(1996), Assessment of uncertainties in state-of-the-art urban storm drainage, Vol III, 1497-1502, *7th ICUSD*, Hannover, Germany.

Niemczynowicz J.(1990). Necessary level of accuracy in rainfall input for runoff modelling, *Proc. 5th Int. Conf. Urban Storm Drainage*, 593-602, Osaka, Japan, 23-27 July.

NWRW (1989). Final report of the 1982-1989 NWRW research programme. Ministry of Housing, Physical planning and environment, the Netherlands.

Price R. and Wixcey J.R.(1994). Background Experience in Urban Drainage Modelling - A review of 'safe-design' heuristics used in model development, Report IT 420, HR Wallingford

Ribbius (1951). "Publieke werken II", nr. 164 (in Dutch)

RIONED (1995), Guidelines for urban storm drainage, module 'Calculations in urban storm drainage, hydrodynamics' (in Dutch). Org. title: Leidraad Riolering, module 'Hydraulisch functioneren'

Ruan M.(1995). Preliminary research of sediment behaviour in sewer systems. TWAIO report, Delft University of Technology, the Netherlands

Ruan M. and Wiggers J.B.M.(1996). Stochastic Models for Predicting Sewer Sediment Load. 7th Int. Con. on Urban Storm Drainage, Hannover, Germany, 9-13 September.

Ruan M. and Wiggers J.B.M.(1997a). Time-series Models for CSO Prediction. *2nd Int. Con.* "The Sewer as a Physical and Biological Reactor", Aalborg, Denmark, 26-28 May.

Ruan M. and Wiggers J.B.M.(1997b). Applications of Time-series Analysis to Urban Storm Drainage. *Wat. Sci. Tech.*, **36**(5), 125-131.

Ruan M. and Wiggers J.B.M.(1997c). Modelling Sewer Emission Using Simulink. *Wat. Sci. Tech.*, **36**(5), 185-192.

Ruan M. and Wiggers J.B.M.(1998a). A Conceptual CSO Emission Model SewSim. *Wat. Sci. Tech.*, **37**(1), 259-267.

Ruan M. and Wiggers J.B.M.(1998b). A New Approach to CSO Volume Analysis. *3rd Int. Con. on Innovative technologies in urban storm drainage*, Lyon, France, 4-6 May.

Ruan M.(1998c). Continuous Simulation of CSO Emission. *4th Int. Con. on Developments in Urban Drainage Modelling*, London, UK, 21-24 September

Sartor J.D. and Boyd G.B.(1972). Water pollution aspects of street surface contaminants. *EPA-R2-72-081*, Environmental protection Agency, Washington, DC.

Saul A.J. and Ellis D.R.(1992). Sediment deposition in storage tanks. *Wat. Sci. Tech.*, **25**(8),189-198.

Shannon R.E.(1975). *Systems simulation: the art and science*, Prentice-Hall, Englewood Cliffs, New Jersey.

MATLAB/SIMULINK User's Guide for Microsoft Windows, The MathWorks, Inc., 1993.

Singh V.P.(1988). Hydrologic systems, volume I - rainfall-runoff modeling, Prentice-Hall, Englewood Cliffs, New Jersey.

Troutman B.(1982). An analysis of input in precipitation-runoff models using regression with errors in the independent variables,*Wat. Resour. Res.*, **18**(4).

Veldkamp R.G.(1995). Sewer overflow pollution - Standardized research data of NWRW project 1982-1989.

Verbanck M.A.(1992). Field investigations on sediment occurrence and behaviour in Brussels combined sewers. *Wat. Sci. Tech.*, **25**(8), 71-82.

Verbanck M.A., Ashley R.M. and Bachoc A.(1994). International workshop on origin, ccurrence and behaviour of sediments in sewer systems: summary of conclusions. *Wat. Sci. Tech.*, **28**(1), 187-194.

Wiggers J.B.M.(1991). Overleeft de overstortingsfrequentie ? H_2O (24), No. 6, 1991 (in Dutch)

Wiggers J.B.M. and Langeveld J.G.(1998). Verzameling en transport van afvalwater I, Ctgz4490, TU Delft, Nederland (in Dutch)

Wada Y. and Miura H.(1988). Characteristics of accumulated loads in the street inlets in urban area and its flushing, Technology Reports of Kansai Univ., No. 30, 153-166.

Xanthopoulos C. and Augustin A.(1992). Input and characterization of sediments in urban sewer systems. *Wat. Sci. Tech.*, **25**(8), 21-28.

Yen B. (1994). Is hydraulics over-used or under-used in storm drainage? *Wat. Sci. Tech.*, **29**(1-2), 53-61.

Zheng S. and Novotny V.(1991). Stochastic modelling of combined sewer flows. *Wat. Sci. Tech.*, **24**(6), 35-40.

APPENDIX A SUMMARY TABLE OF NWRW DATA ANALYSIS

The NWRW data were analysed in detail: based on the limited measurement data, the duration, depth and maximum intensity of each rainfall were calculated, as well as the duration, volume and maximum rate of each CSO event. Furthermore, various quality variables, such as CON, SSV, COD, BOD, KJN, PTO,CL_ and TSS were calculated. Linear interpolation was used for any unavailable data. The table in the next page shows the summary table of NWRW data of Loenen, wherein "-99" means that it is impossible to calculate this value due to the lack of data, even using interpolation method. The variables and their units are explained below,

R: rainfall duration (minute) or depth (mm)
imax: maximum rainfall intensity (mm/h)
CSO: CSO duration (minute) or volume (m^3)
Qmax: maximum rate of CSO (m^3/minute)
CON: electric conductivity (μm/s)
SSV: settleable solids volume
1.total mass (m^3/ha)
2. maximum load (m^3/minute)
3. Concentration (l/m^3)
COD: chemical oxygen demand
1.total mass (kg/ha)
2. maximum load (kg/minute)
3. Concentration (g/m^3)
BOD: biochemical oxygen demand
1.total mass (kg/ha)
2. maximum load (kg/minute)
3. Concentration (g/m^3)
KJN: Kjeldahl-nitrogen
1.total mass (kg/ha)
2. maximum load (kg/minute)
3. Concentration (g/m^3)
PTO: total phosphate
1.total mass (kg/ha)
2. maximum load (kg/minute)
3. Concentration (g/m^3)
CL_: chlorine
1.total mass (kg/ha)
2. maximum load (kg/minute)
3. Concentration (g/m^3)
TSS: total suspended solids
1.total mass (kg/ha)
2. maximum load (kg/minute)
3. Concentration (g/m^3)

Summary table of NWRW data analysis (Loenen)

Event	R	R	imax	CSO	CSO	Qmax	CON	SSV	COD	BOD	KJN	PTO	CL_	TSS
No.	mins	mm	mm/h	mins	m3	m3/m	-	m3/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha	kg/ha
1	1172	29.2	6.7	530	1743.6	7.9	13.5	0.02	-99	3.72	-99	-99	-99	-99
2	548	13.2	12.8	116	294.3	12.8	1.6	0.02	-99	1.27	-99	-99	-99	-99
3	809	16.4	8.7	33	30.7	1.9	0.3	0	0.35	0.15	0.03	0	0.04	0.16
4	456	10.1	37.2	72	404.9	15.0	2.2	0.11	7.59	1.57	0.27	0.08	0.42	10.27
5	958	19.9	57.6	75	952.4	37.7	-99	-99	-99	-99	-99	-99	-99	-99
6	954	14.6	4.1	176	1042.4	10.7	9.4	0.16	10.48	1.06	0.41	0.11	1.36	9.66
7	842	15.4	5.2	236	1193.0	7.9	11.1	0.15	12.46	2.12	0.57	0.15	2.08	11.18
8	685	-99	-99	139	536.1	10.7	3.0	0.08	9.22	1.08	0.37	0.09	0.76	9.35
9	1025	18.6	5.1	197	869.1	9.7	13.4	0.06	8.32	1.7	0.53	0.16	1.07	6.14
10	589	12.39	29.0	56	142.1	7.0	1.4	0.01	1.7	0.32	0.09	0.02	0.2	2.18
11	464	7.7	15.4	69	394.4	12.8	3.2	0.06	5	0.94	0.24	0.06	0.39	5.51
12	505	10.4	7.0	33	69.2	4.5	0.5	0	0.27	0.05	0.02	0.01	-99	-99
13	835	15.6	12.0	174	618.9	11.7	5.9	0.03	4.26	1.05	0.31	0.06	0.64	1.9
14	597	9.6	4.1	16	3.2	0.5	-99	-99	-99	-99	-99	-99	-99	-99
15	704	10.4	8.4	68	328.0	9.7	2.6	0.03	3.34	0.74	0.2	0.04	0.36	3.31
16	1761	25.3	4.0	606	1421.6	7.9	16.5	0.01	7.2	1.46	0.53	0.16	1.66	4.38
17	1752	15.5	10.7	479	2431.8	24.8	24.5	0.02	10.3	1.74	0.97	0.17	2.72	4.23
18	1161	19.4	12.0	300	1179.8	7.9	9.6	0.01	8.68	2.36	0.55	0.12	2.21	4.16
19	921	11.9	2.9	109	258.6	5.3	-99	0.03	1.67	0.38	0.12	0.03	0.46	0.84
20	970	18	12.0	176	316.4	5.3	0.9	0	0.5	0.12	0.05	0.01	0.28	0.24
21	722	11.3	13.4	35	88.9	5.3	0.4	0	0.42	0.07	0.02	0.01	0.06	0.43
22	578	8.5	6.9	37	11.6	0.9	0.1	0	0.17	0.02	0.01	0	0.03	0.16
23	1746	34.3	9.0	424	2853.9	18.5	11.4	0.17	22.34	2.49	0.92	0.28	1.82	13.61
24	451	8.2	24.7	22	9.1	0.9	0.1	0	0.14	0.03	0.01	0	0.02	0.13
25	634	18.8	25.7	148	1099.8	34.7	-99	0.67	38.02	8.23	1.08	0.26	0.83	35.92
26	139	13.9	52.8	49	843.0	47.2	7.7	0.64	38.5	6.26	1.23	0.33	1.53	52.1
27	491	18.2	36.6	120	1451.3	62.8	-99	-99	-99	-99	-99	-99	-99	-99
28	1414	28.2	24.0	166	754.9	23.5	-99	-99	-99	-99	-99	-99	-99	-99
29	1300	27.4	15.7	246	1347.7	24.8	8.9	0.42	31.59	3.9	0.95	0.26	4.28	26.62
30	1568	55.09	7.8	855	8047.5	22.2	30.3	0.8	84.04	6.12	2.46	0.87	2.31	95.57
31	1335	24.2	14.6	359	1461.8	17.3	9.1	0.66	20.89	2.12	0.41	0.28	2.54	25.59
32	585	11.5	6.0	76	398.5	9.7	2.8	0.09	5.45	1.23	0.24	0.05	0.67	3.97
33	811	15.8	9.2	108	688.0	23.5	3.8	0.23	9.95	2.14	0.31	0.1	0.61	10.19
34	2079	29.7	33.6	305	2100.9	47.2	10.3	0.19	73.83	8.57	1.56	0.76	1.5	123.24
35	1211	14.2	36.0	127	1141.9	40.8	7.6	0.48	57.04	-99	1.26	0.49	0.88	70.48
36	826	9.5	9.0	86	384.3	10.7	3.2	0.06	4.51	0.41	0.23	0.07	0.65	4.62
37	966	14.9	4.8	314	1721.4	13.9	11.4	0.09	15.54	1.21	0.75	0.2	3.24	17.51
38	974	9.5	8.4	111	536.8	13.9	4.5	0.08	9.91	0.8	0.33	0.1	0.66	11.68
39	2031	32.6	15.4	743	8590.9	36.2	48.9	1.5	215.4	9.73	5.53	2.17	11.52	226.46
40	898	8.2	4.2	170	415.6	6.1	-99	-99	-99	-99	-99	-99	-99	-99
41	982	11.2	14.6	69	84.7	2.5	1.4	0.01	1.28	0.17	0.05	0.02	0.25	1.45
42	1728	31.9	9.5	413	2060.9	12.8	21.7	0.14	20.33	4.08	0.99	0.35	2.52	11.24
43	834	14.3	54.0	60	633.9	37.7	3.9	0.22	20.5	3.25	0.58	0.15	1.59	21.47
44	679	13.1	18.6	34	62.9	4.5	0.6	0	0.45	0.09	0.04	0.01	0.15	0.24
45	404	13.6	93.0	60	1058.3	62.8	11.2	-99	58.46	9.45	1.76	0.48	2.38	80.09
46	447	7.8	41.3	47	234.9	15.0	2.2	0.03	5.11	0.72	0.18	0.06	0.45	8.17
47	783	21.2	24.6	166	1708.2	31.7	7.8	0.42	33	5.55	0.96	0.25	1.32	31.68
48	875	12.4	11.0	76	440.6	10.7	4.4	0.01	2.6	0.56	0.15	0.06	0.59	0.97
49	1086	18.28	9.1	156	739.1	10.7	2.3	0.01	2.91	0.52	0.15	0.04	0.2	2.39
50	825	11.3	5.3	126	243.0	3.1	3.4	0	1.87	0.37	0.1	0.03	0.3	0.99
51	868	14.4	4.4	111	228.0	5.3	1.4	0	1.19	0.22	0.11	0.02	0.53	0.82
52	1427	18.6	25.2	183	367.4	12.8	3.9	0.06	3.04	0.76	0.2	0.05	0.25	2.18
53	908	25.4	49.2	232	4851.9	72.0	-99	-99	204	14.26	5.06	2.12	3.06	321.9
54	2075	25	7.2	227	1010.7	17.3	12.5	0.13	13.33	2.28	0.76	0.21	1.06	5.17
55	1276	16.7	23.1	305	1232.1	34.7	6.6	0.61	37.01	3.31	1.04	0.3	0.71	43.08
mean	976	17.5	18.6	190	1147.9	18.3	7.7	0.18	23.4	2.5	0.7	0.24	1.3	28.2

CON	SSV	COD	BOD	KJN	PTO	CL_	TSS	CON	SSV	COD	BOD	KJN	PTO	CL_	TSS
-	m3/m	kg/m	kg/m	kg/m	kg/m	kg/m	kg/m	-	l/m3	g/m3	g/m3	g/m3	g/m3	g/m3	g/m3
2.28	0.01	-99	0.4	-99	-99	-99	-99	122.2	0.18	-99.0	33.7	-99.0	-99	-99.0	-99.0
1.68	0.03	-99	1.16	-99	-99	-99	-99	85.9	1.32	-99.0	68.0	-99.0	-99	-99.0	-99.0
0.29	0	0.35	0.15	0.03	0	0.05	0.16	151.0	0.52	182.5	76.9	15.1	2.03	23.0	82.4
1.45	0.09	5.86	1.33	0.17	0.06	0.26	7.47	85.5	4.27	296.3	61.3	10.6	3	16.4	400.6
-99	-99	-99	-99	-99	-99	-99	-99	-99.0	-99	-99.0	-99.0	-99.0	-99	-99.0	-99.0
2.17	0.03	1.8	0.17	0.06	0.02	0.29	1.65	142.2	2.48	158.8	16.1	6.2	1.66	20.6	146.4
1.88	0.03	2.12	0.32	0.07	0.02	0.49	2.23	147.5	1.97	165.0	28.0	7.6	2.03	27.5	148.1
0.96	0.04	3.51	0.41	0.11	0.03	0.25	2.94	89.6	2.23	271.7	31.9	10.9	2.77	22.4	275.5
3.78	0.03	1.81	0.43	0.09	0.07	0.22	1.42	243.6	1.01	151.4	30.9	9.7	2.87	19.5	111.6
1.05	0	0.9	0.26	0.05	0.01	0.15	1.32	158.7	0.55	189.5	35.3	9.5	1.76	22.3	242.4
1.45	0.03	2.54	0.43	0.11	0.04	0.19	2.74	126.9	2.25	200.3	37.8	9.5	2.35	15.8	220.6
0.51	0	0.3	0.06	0.03	0	-99	-99	109.3	0.1	62.2	11.8	5.6	1.11	-99.0	-99.0
2.27	0.03	1.81	0.38	0.11	0.02	0.22	0.79	150.7	0.84	108.7	26.9	7.9	1.41	16.3	48.4
-99	-99	-99	-99	-99	-99	-99	-99	-99.0	-99	-99.0	-99.0	-99.0	-99	-99.0	-99.0
1.24	0.01	1.57	0.35	0.1	0.02	0.17	1.54	124.1	1.25	160.8	35.5	9.7	2.15	17.4	159.4
2.32	0	0.9	0.21	0.05	0.02	0.26	0.35	183.8	0.1	80.1	16.3	5.9	1.77	18.5	48.7
3.52	0	1.2	0.22	0.12	0.02	0.37	0.44	159.3	0.1	66.9	11.3	6.3	1.12	17.7	27.5
1.08	0	1.18	0.32	0.06	0.01	0.25	0.57	128.0	0.15	116.2	31.6	7.3	1.57	29.6	55.7
-99	0.01	0.65	0.15	0.04	0.01	0.15	0.33	-99.0	1.73	101.9	23.1	7.5	1.79	28.3	51.2
0.2	0	0.11	0.03	0.01	0	0.06	0.05	44.4	0.03	24.9	6.0	2.6	0.48	13.9	12.1
0.84	0	1.01	0.18	0.06	0.02	0.15	1.15	61.4	0.04	74.7	12.8	4.4	1.22	11.0	76.5
0.16	0	0.2	0.02	0.01	0	0.04	0.19	181.5	1.31	234.9	22.3	11.4	3.44	44.9	213.9
1.77	0.05	4.43	0.83	0.17	0.04	0.26	2.27	63.1	0.96	123.7	13.8	5.1	1.56	10.1	75.3
0.2	0	0.22	0.05	0.01	0	0.03	0.2	223.5	2.72	250.8	53.4	13.7	3.37	38.6	224.2
-99	0.53	23.9	6	0.72	0.18	0.45	22.08	-99.0	9.65	546.2	118.3	15.5	3.78	12.0	516.0
10.29	1.11	51.4	9.23	1.83	0.49	1.83	61.53	144.2	11.97	721.6	117.4	23.1	6.12	28.6	976.4
-99	-99	-99	-99	-99	-99	-99	-99	-99.0	-99	-99.0	-99.0	-99.0	-99	-99.0	-99.0
-99	-99	-99	-99	-99	-99	-99	-99	-99.0	-99	-99.0	-99.0	-99.0	-99	-99.0	-99.0
2.78	0.48	24.7	1.81	0.45	0.12	1.24	12.15	103.9	4.96	370.4	45.7	11.1	3.04	50.1	312.0
1.5	0.13	7.3	1.38	0.15	0.06	0.89	8.78	59.5	1.57	165.0	12.0	4.8	1.7	4.5	187.6
1.3	0.38	7.38	0.62	0.14	0.1	0.4	11.3	98.5	7.18	225.8	22.9	4.5	2.98	27.5	276.6
1.08	0.06	2.22	0.56	0.09	0.02	0.27	1.7	109.4	3.56	216.0	48.7	9.7	1.8	26.4	157.5
1.93	0.23	5.36	1.47	0.16	0.05	0.35	4.94	86.6	5.27	228.5	49.1	7.0	2.37	14.0	234.0
5.1	0.55	28.7	4.4	0.64	0.32	0.5	51.72	77.8	1.46	555.3	64.4	11.7	5.72	11.3	926.9
6.67	0.53	30.4	-99	0.62	0.24	0.66	35.75	105.1	6.59	789.3	-99.0	17.4	6.76	12.2	975.2
2.07	0.03	1.69	0.19	0.12	0.03	0.33	2.19	130.3	2.47	185.5	16.8	9.3	2.72	26.9	190.1
2.14	0.03	2.88	0.28	0.1	0.03	0.49	3.79	104.5	0.86	142.6	11.1	6.8	1.87	29.8	160.7
1.76	0.06	3.61	0.53	0.13	0.04	0.3	3.99	131.1	2.39	291.8	23.6	9.8	3.03	19.4	343.9
6	0.39	25.6	3.6	0.55	0.21	1.09	25.04	90.0	2.76	396.1	17.9	10.2	3.99	21.2	416.5
-99	-99	-99	-99	-99	-99	-99	-99	-99.0	-99	-99.0	-99.0	-99.0	-99	-99.0	-99.0
0.81	0	0.67	0.1	0.03	0.01	0.14	0.82	265.4	1.58	239.6	31.6	10.0	3.12	46.9	271.0
2.02	0.03	2.48	0.6	0.11	0.04	0.27	2.22	166.3	1.04	155.9	31.3	7.6	2.65	19.3	86.2
4.03	0.34	22.3	4.03	0.61	0.16	1.7	28.7	97.8	5.37	511.0	80.9	14.5	3.71	39.6	535.2
0.68	0	0.55	0.1	0.05	0.01	0.17	0.29	145.4	0.2	113.3	21.7	11.0	1.98	36.6	59.1
13.5	-99	71.7	16.95	2.39	0.71	3.01	92.96	167.8	-99	872.8	141.0	26.3	7.22	35.5	1195.7
2.65	0.04	5.16	0.83	0.18	0.06	0.54	8.35	148.4	1.93	344.1	48.7	12.0	3.92	30.0	549.5
2.54	0.4	17.9	3.61	0.43	0.11	0.43	18.17	71.9	3.91	305.2	51.3	8.9	2.33	12.2	293.0
2.06	0.01	1.24	0.25	0.06	0.02	0.24	0.36	158.7	0.33	93.2	20.1	5.4	2.09	21.3	34.9
0.63	0.01	0.96	0.26	0.05	0.01	0.07	0.97	49.2	0.18	62.3	11.1	3.3	0.97	4.2	51.0
0.78	0	0.44	0.09	0.02	0.01	0.08	0.21	223.6	0.13	121.9	24.0	6.8	2.23	19.8	64.4
0.48	0	0.43	0.08	0.04	0.01	0.19	0.38	98.6	0.1	82.1	15.4	7.3	1.55	36.7	56.9
3.61	0.07	2.45	0.63	0.16	0.04	0.22	1.97	169.7	2.48	130.8	32.5	8.5	2.29	10.6	93.6
-99	-99	88.6	10.03	2.26	0.8	1.06	125.5	-99.0	-99	664.2	46.4	16.5	6.91	10.0	1048.2
3.28	0.04	3.82	0.62	0.21	0.06	0.28	1.55	195.3	2.02	208.4	35.6	11.9	3.23	16.6	80.8
2.6	0.75	33.8	3.77	0.79	0.23	0.32	36.68	84.3	7.76	474.6	42.5	13.4	3.85	9.1	552.5
2.413	0.137	10.4	1.63	0.303	0.1	0.4549	12.59	129	2.371	254.9	38.09	9.799	2.779	22.25	282.25

APPENDIX B RAINFALL RECORD OF DE BILT

Processing of rainfall record

The historical rainfall record was measured in De Bilt in the Netherlands with a time resolution of 15 minutes during a period of 25 years from 1955 to 1979. All the dry weather periods were included in the database in order to keep the record complete, because for continuous simulation the dry weather periods have to be taken into account so that the effects of succession of rainfall events are represented correctly.

The rainfall depth of De Bilt rainfall record each year is summarized in the following table,

Table B.1 The yearly rainfall depth (mm) calculated from the rainfall record of De Bilt

year	mm	year	mm	year	mm	year	mm	year	mm
1955	663	1960	929	**1965**	**1152**	1970	908	1975	635
1956	748	1961	925	1966	1148	1971	562	1976	536
1957	928	1962	750	1967	853	1972	656	1977	813
1958	828	1963	777	1968	858	1973	780	1978	644
1959	**536**	1964	760	1969	747	1974	993	1979	873

Table B.1 shows that 1959 and 1965 are the driest and wettest year of this period. The most intensive storm occurred on July 19, 1966 during which 19.2 mm of rain depth was measured within 15 minutes, or approximately 77 mm/h. The mean rain depth per year was 800 mm.

Most existing hydrodynamic models are not able to take the long rainfall record for continuous simulation due to the limit of computing capacity of the software and hardware. The rainfall record has to be separated into a series of independent rainfall events, taking into account the dry weather periods and the emptying time of the sewer system.

Identifying independent rainfall events has been an issue in the literature for many years. There is perhaps no best method, but the most widely accepted approach is to divide the continuous rainfall record into independent events by a mininum inter-event time. Any rainfall not preceded by this minimum value is not part of a new independent event. It is thus important to determine the minimum inter-event time. It is evident that the longer the minimum inter-event time is assumed, the less independent rainfall events are created, and the longer the simulation time is needed, because less small rainfall events can be removed for simulation. Normally, those small rainfall events with a depth less than the storage capacity of a sewer system need not to be simulated.

Each sewer system has an emptying time defined as the time needed for water level to drop back to the DWF level from above the overflow weir crest after the rainfall event ceases. In order to identify the independent rainfall events, the minimum inter-event time should be no shorter than the emptying time of the sewer systems. Because the total simulation time will increase when the minimum inter-event time is longer, so the minimum inter-event time should be equal to the emptying time of a sewer system. To calculate the emptying time using a hydrodynamic model, information about the specific sewer system is needed. A special rainfall event has been designed so that it ceases at the moment when the water level is (just) above the weir crest.

The following example shows in detail how to determine the empting time and the variable storage capacity of the sewer system of Loenen using HydroWorks. The rainfall is so designed that the rain ceases at the same time as the overflow also ceases (see Figure B.1). As the water level rose from DWF level at 20:30 to the beginning of overflow at 25:45, there was in total 9.76 mm effective rainfall. During this period the pumped volume is: (2700/2+16200)*0.038=666.9 m^3 or 666.9/15.8/10=4.22 mm (the detail not shown here). The DWF was 2050 ie*0.012 m^3/h/ie*5.25 h=129.2 m^3 or 129.2/15.8/10=0.82 mm. So, the total variable storage capacity of the sewer system (rising period) was: 9.76+0.82-4.22=6.36 mm.

At 30:10 the rain and the overflow were both finished and at 37:50 the level dropped to the DWF level. So the empting time was 7:40 of 27600 sec. From 30:10 to 37:50 the pump operated at 0.038 m3/s, thus, the total pumped volume was: (27600)*0.038=1048.8 m3 /15.8/10=6.64 mm. The DWF during this time was: 7:40=7.67h*0.012*2050=188.7m3/15.8/10=1.19 mm. Thus, the total variable storage capacity during the dumping period was: 6.64-1.19=5.4 mm. This is almost the same as the static capacity of the sewer system (5.2 mm). Thus, the maximum empting time was 7.4 hours.

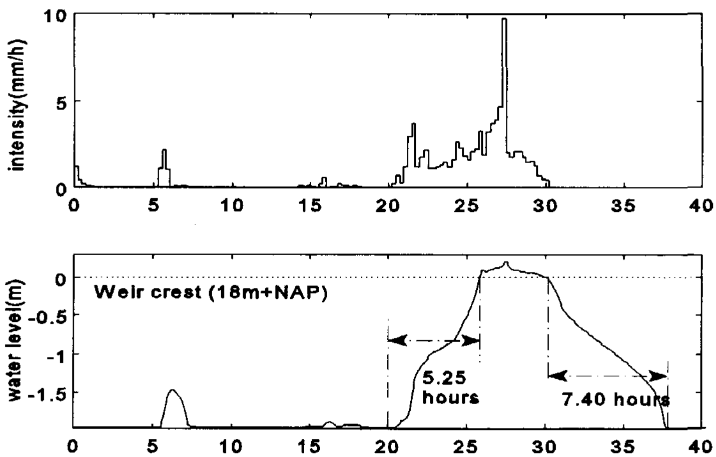


Figure B.1 Determining the maximum empting time of a sewer system

A simpler method of estimating the empting time of a sewer system with only one overflow weir is as follows,

1) Calculate the static storage capacity of the sewer system in m^3, 5.2 mm = 5.2 x 15.8 x 10 = 821.6 m^3
2) Calculate the pumping overcapacity in m^3/h, 0.038 m^3/s x 3600 s/h - 0.012 m^3/h/ie x 2050 ie = 112.2 m^3/h
3) Estimating the empting time by dividing the storage capacity by pumping overcapacity, 821.6 m^3/112.2 m^3/h = 7.3 hours

Since the sewer system of Loenen has only one overflow weir, the estimated empting time is approximately equal to the maximum empting time using HydroWorks. For sewer sytems with multiple overflow weirs and pumps, this simpler estimating method is not valid. However, sometimes in practice only the overflow weir with the lowest crest is taken into account when determining the maximum emptying time of a sewer system.

For the sewer system of Loenen, if the minimum inter-event time was assumed to be 8 hour or 480 minutes, in total 1235 rainfall events whose depth was larger than 5 mm were created from the rainfall record of De Bilt.

Standard rainfall events

Since in many cases local rainfall data are not available, ten standard rainfall events derived from the rainfall record of De Bilt have been created, which can be used to analyse the phenomena of surface flooding (Table B.2) and to calibrate detailed hydrodynamic models.

Table B.2 Standard rainfall events with the peak before (b) and after (a)

Rainfall intensity (l/s/ha)										
	Return period (year) and rainfall events No.									
time	b 0.25 a		b 0.50 a		b 1.0 a		b 2.0 a		5	10
(min)	1	2	3	4	5	6	7	8	9	10
0-5	10	5	10	5	10	5	20	10	50	60
5-10	20	5	20	10	20	10	40	20	90	120
10-15	30	5	30	15	50	15	70	30	160	210
15-20	40	10	50	20	90	20	110	40	160	210
20-25	50	15	70	25	90	25	110	50	140	190
25-30	50	20	70	30	70	30	90	70	110	160
0-35	35	25	50	35	50	35	70	90	90	120
35-40	30	30	40	40	40	40	50	110	70	80
40-45	25	35	35	50	35	50	40	110	50	40
45-50	20	50	30	70	30	70	30	70	30	0
50-55	15	50	25	70	25	90	20	40	20	0
55-60	10	40	20	50	20	90	10	20	10	0
60-65	5	30	15	30	15	50	0	0	0	0
65-70	5	20	10	20	10	20	0	0	0	0
70-75	5	10	5	10	5	10	0	0	0	0

Firstly, the independent rainfall events are defined using an inter-event time of 5 hours. Secondly, the extreme rainfall events are selected based on the maximum rainfall depth during 15 minutes. The first 25 extremest rainfall events are used to produce the ten standard rainfall events with a return period of 0.25, 0.5, 1.0, 2.0, 5.0 and 10.0 years. For a return period of between 0.25-2.0 years, two forms of rainfall distribution are distinguished, i.e. the rainfall intensity peak before and after the centre of the distribution.

APPENDIX C ACKERS-WHITE'S MODEL

Ackers-White's model

Ackers-White's model for total load was first established for sediment transport in alluvial channels. Subsequent modifications were made by Ackers (1984) in order to apply the model for predicting sediment transport in sewers. This model was widely accepted for the following reasons,

1) Normally, this model predicts total load. However, it can also predict "pure" suspended solids concentrations by "forcing " the transition exponent (*n*) to be one.

2) The model predicts suspended solids concentrations in the form of a pollutograph, i.e. concentrations versus time, which may be useful in the management of such structures as detention basins, storage tanks and combined sewer overflows.

The three main equations are as follows,

$$F_{gr}=\frac{u^{*n}}{\sqrt{gd_{35}(s-1)}}\left[\frac{U}{\sqrt{32}\log(\frac{12R}{d_{35}})}\right]^{1-n} \quad (C.1)$$

$$G_{gr}=C_{aw}\left[\frac{F_{gr}}{A_{aw}}-1\right]^{m} \quad (C.2)$$

$$q_t=G_{gr}sd_{35}\frac{1}{R}\left[\frac{U}{u^*}\right]^{n}\left[\frac{W_eR}{A}\right]^{1-n} \quad (C.3)$$

where:

- F_{gr}= dimensionless mobility particle number, -
- G_{gr}= dimentsionless solid flow number, -
- q_t = total solid flow (kg particles/kg water), or concentration, kg/l
- u^* = friction velocity (m/s) = $(g\ R\ S)^{1/2}$, S = hydraulic gradient
- U = mean flow velocity, m/s
- R = hydraulic radius, m
- s = specific gravity of particles, g/l
- d_{35} = particles diameter (35% of particles have a diameter of less than d_{35} in mass)
- W_e = $10d_{35}$, effective deposited sediments width, m
- A = flow section area, m^2
- A_{aw}, C_{aw}, n, m = numerical coefficients, =f(D_{gr}), D_{gr}=dimensionless particle diameter

The last term of Equation (C.3), $[W_e\ R/S]^{1-n}$, is the modification term to apply the equation to sewers. This modification has only effect for coarse sediments that generally transport in the bed load. For fine sediments that transport generally in the suspended load, n is forced to equal to 1, thus this term has no effect at all.

Calculation procedures

1)Total load

The calculation procedures of total load are shown as follows,

1. Determine D_{gr} from known values of d_{35}, s and υ (kinematic viscosity of the fluid)

$$D_{gr}=[\frac{g(s-1)}{v^2}]^{\frac{1}{3}}d_{35} \quad (C.4)$$

2. Determine A_{aw}, C_{aw}, n, m from D_{gr},

$$A_{aw}=0.14+\frac{0.23}{\sqrt{D_{gr}}} \quad (A_{aw}=0.17\ \textit{for coarse material}) \quad (C.5)$$

$$\log C_{aw}=2.86\log D_{gr}-(\log D_{gr})^2-3.53 \quad (C_{aw}=0.025\ \textit{for coarse material}) \quad (C.6)$$

$$n=1.00-0.56\log D_{gr} \quad (C.7)$$

$$m=1.34+\frac{9.66}{D_{gr}} \quad (m=1.50\ \textit{for coarse material}) \quad (C.8)$$

3. Calculate F_{gr}, G_{gr} and q_t using Equation (4.11)- (4.13) for known R, U, u^* (or S) and A.

2) Suspended-load

The calculation procedures of suspended-load are shown as follows,

1. Since n =1 for fine material transported in suspension, D_{gr} = 1 from Equation (C.7)

2. For known s and υ, using Equation (C.4), d_{35} can be calculated as,

$$d_{35}=[\frac{g(s-1)}{v^2}]^{-\frac{1}{3}} \quad (C.9)$$

3. Using Equation (C.5), (C.6) and (C.8), it is easy to calculate A_{aw}, C_{aw}, m as follows,

A_{aw} = 0.37, $C_{aw} = 2.95\text{x}10^{-4}$ and m = 11

4. Calculate F_{gr}, G_{gr} and q_t using Equation (C.1), (C.2) and (C.3) for known R, U, and u^* or S.

APPENDIX D SEWSIM IN SIMULINK DIAGRAMS

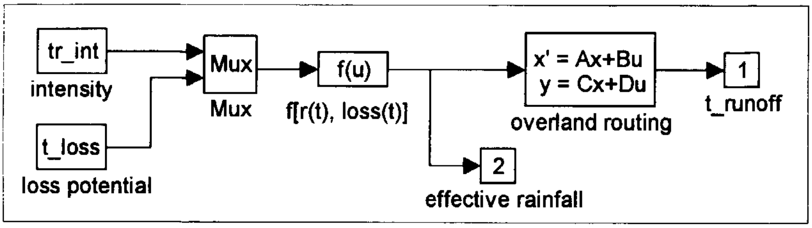
MATLAB/SIMULINK

"MATLAB is a technical computing environment or high-performance numeric computation and visualization. MATLAB integrates numerical analysis, matrix computation, signal processing, and graphics in an easy-to-use environment where problems and solutions are pressed just as they are written mathematically without traditional programming. ... MATLAB is an interactive system whose basic data element is a matrix that does not require dimensioning. It enables you to solve many numerical problems in a fraction of the time that it would take to write a program in a language such as Fortran, Basic, or C. ... MATLAB also features a family of application-specific solutions that we call toolboxs. Very important to most users of MATLAB, toolboxs are comprehensive collections of MATLAB functions (M-files) that extend the MATLAB environment in order to solve particular classes of problems. Areas in which toolboxs are available include signal processing, control systems design, dynamic systems simulation, systems identification, neural networks, and others." (From "MATLAB User's Guide")

SIMULINK is a MATLAB toolbox for simulating all sorts of dynamic systems, such as membrane processes (drink water), waste water treatment processes and the processes involved in urban storm drainage etc.. Model definition and analysis are two phases of the use of SIMULINK. To facilitate model definition, the software provides a class window called "block diagram" window. Defining a system is much like drawing a block diagram. The blocks are copied from standard libraries supplied with the software or block libraries built by users. After the model is built, it can be used to analyse the proposed dynamic system using built-in tools such as *linmod*, a tool for extracting the linear state-space model of a dynamic system around an operating point; and *linsim*, an integration algorithm for ordinary differential equations.

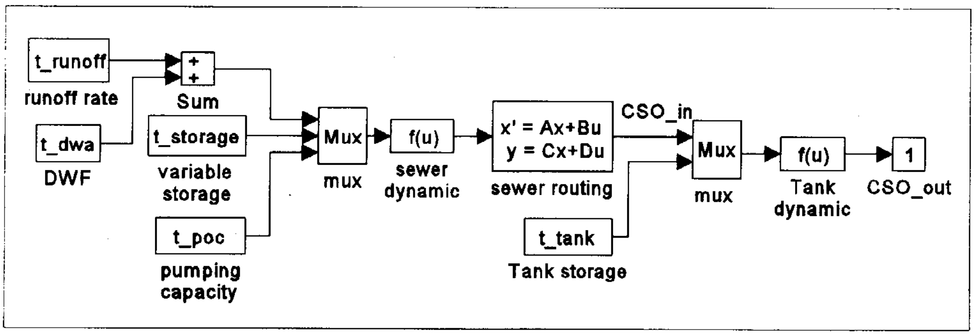
The conceptual CSO emission model SewSim is developed in MATLAB/SIMULINK environment. MATLAB is used to prepare input data processing, to create interface and menu, to control SIMULINK diagram and to present simulation results. SIMULINK is used to carry out the mathematically complicated and intensive simulations of the physical processes involved, for example, the state-space model representing the rainfall-runoff process. As stated above, SIMULINK model is diagram-driven, which implies that numerical models developed in such a way have a open, clear and straightforward structure which can be improved easily when new developments of the relevant field become available.

Rainfall-runoff module



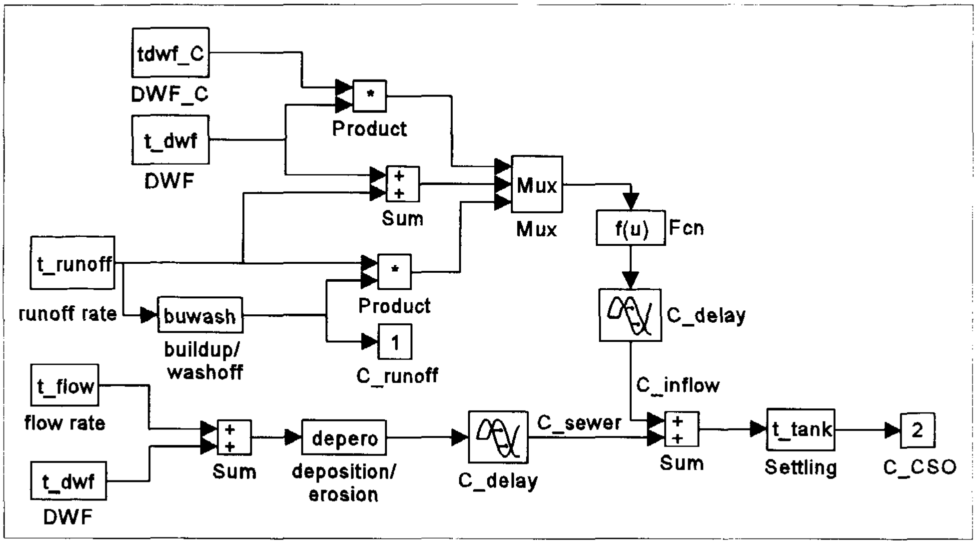
tr_int: vector containing values of rainfall intensity
t_loss: vector containing values of loss potential
Mux: combination of two vectors
f(u): function
1, 2: number of outputs

Sewer routing module



t_runoff: vector containing values of runoff rate
t_dwa: vector containing values of DFW
Sum: sum of two vectors
t_storage: vector containing values of variable storage
t_poc: vector containing values of pumping capacity
Mux: combination of three vectors
f(u): function
t_tank: vector containing values of tank storage

Quality module



t_flow:	vector containing the flow rate in the sewer network
DWF_C:	vector containing the pollutant concentration of dry weather flow
Product:	multiplication of the input vectors
C_delay:	this block delays the input vector by a given amount of time
C_inflow:	the pollutant concentration of the mixture of runoff and dry weather flow
C_sewer:	the pollutant concentration caused by deposition/erosion of sewer sediment
C_CSO:	the pollutant concentration of the overflowing water from the storage tank
t_tank:	settling processes of the storage tank
buwash:	this block simulates the processes of sediment buildup and washoff on catchment
depero:	this block simulates the processes of sediment deposition/erosion in sewer network

Two S-functions of SIMULINK have been written for the blocks *buwash* and *depero* which are the most important parts of this module. The clear structure of the SIMULINK block diagram makes the programming work a bit easier than the traditional one. However, what much more important is that the model built using SIMULINK blocks can be easily improved when the relevant knowledge becomes available.

ACKNOWLEDGEMENTS

The research work has been carried out in the Division Water Management, Environmental and Sanitary Engineering, of the Faculty Civil Engineering, Delft University of Technology in the period of 1995 to 1999.

First of all, I wish to thank Prof. ir. J.B.M. Wiggers who has been the supervisor of this research. His rich practical experience related to urban storm drainage was of great help to the whole work. In particular his critical but optimistic attitude towards scientific research in general has been a must of the success of this difficult research topic.

I am also grateful to Prof. dr. R. Price from IHE Delft, who has given me excellent ideas, valuable suggestions and encouragements, including the improvements of the English used in this thesis.

I thank Dr. Bertrand-Krajewski from France for his fruitful discussion on modelling techniques. Many thanks also go to ir. F. Clemens from Witveen+Bos, who has guided me how to apply the model to practical situations.

I wish to express my appreciations to the direct or indirect support for this research work from all the young colleagues of the Division and other friends, especially to ir. R.G. Veldkamp, ir. J. Kluck, ir. J. Langveld, ir. J.L. Korving and Dr. ir. J. de Koning.

Finally, I would like to thank my parents and my wife, drs. H. Zhang for their patience and support.

CURRICULUM VITAE

Name: Mingchuan Ruan, male
Birthday: 31 July, 1965, born in Wenzhou, Zhejiang provine, China

Sept. 1984 - July 1989 Bachelor of science (BSc)
"The Man-machine Dialogue System of One-dimensional Estuary Model"

Dept. of Environmental Engineering at Tsinghua University, Beijing, China

April 1990 - Aug. 1990
Intensive Course "Software Engineering", Wenzhou, Zhejiang Province, China

Aug. 1991 - April 1992
Intensive Course "Dutch for foreigners" at Delft University of Technology, The Netherlands

Sept. 1992 - Aug. 1993 Master of Science (Msc)
"Application of the Multiquadric-biharmonic Interpolation Method in Hydrology"

Sept. 1993 - Aug. 1995
Post-MSc course "Integral Water Management"
"Preliminary Research of Sediment Behaviour in Sewer Systems"

Sept. 1995 - Sept. 1999 Doctor of Philosophy
"Computational Modelling of Emission from Combined Sewer Overflows"

Dept.of Water management, Environmental and Sanitary Engineering,
Faculty of Civil Engineering at Delft University of Technology, The Netherlands

Publications

"Stochastic models for predicting sewer sediment load", 7th Int. Con. on Urban Storm Drainage, Hannover, Germany, 9-13 Setp., 1996
"Time-series models for CSO prediction", 2nd Int. Con. 'The Sewer as a Physical and Biological Reactor', Aalborg, Denmark, 26-28 May, 1997
"Modelling Sewer Emission Using Simulink", *Wat. Sci. Tech.* Vol. 36, No. 5, pp. 185-192, 1997
"Applications of time-series analysis to urban storm drainage", *Wat. Sci. Tech.* Vol. 36, No. 5, pp. 125-131, 1997
"A conceptual CSO emission model SewSim", *Wat. Sci. Tech.* Vol. 37, No. 1, pp. 259-267, 1998
"A new approach to CSO volume analysis", 3rd Int. Con. on innovative technologies in urban storm drainage, Lyon, France, 4-6 May, 1998
"Continuous simulation of CSO emission", UDM'98: Developments in Urban Drainage Modelling, London, UK, 21-24 Sept., 1998
"Application of a conceptual CSO emission model", Int. Con ."Application of models in water management", Sept. 24-25, 1998, Amsterdam, the Netherlands
"Application of SewSim for Continuous simulation of CSO emission", *Urban Water* (in press).

SBN 90 9013023-3