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By

Ole Mark

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Photo on Front Cover: Combined Sewer Overflow
at the Danube river, Prague 2019. Photo: Ole Mark

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Preface

The present write-up summarises part of the work carried out by the author during the last 25+ years within modelling of stormwater and sewer systems. The content of this dissertation is the present introduction and summary, plus 13 peer-reviewed journal papers, three conference papers and one book.

The author would like to thank my present and former colleagues: Johan Larsson, Karsten Havnø, Lars-Göran Gustafsson, Cecilia Wennberg, David Luketina, Sutat Weesakul, Anders Erichsen, Anders Lyngaard-Jensen, Arne Møller, Berislav Tomicic, Claus Jørgensen, Henrik Garsdal, Flemming Schlütter, Henrik S. Andersen, Kim Wium Olesen, Jeanne-Rose Renee, Justine Hénonin, Lars Yde, Morten Just Kjølby, Morten Rungø and Nina Sto. Domingo for many fruitful discussions on the topic. Special thanks go to Marianne Helwigh, Susanne Kallemose and Hanne Bertelsen for helping with the logistics of the manuscript and in particular to Sten Lindberg for always supporting me 100%. I would also like to sincerely thank Professor Torben Larsen for encouraging me to write this dissertation. Last but not least, I would like to express my thanks to Slobodan Djordjević and Henrik Madsen, who always give me inspiration for something new and interesting to research.

A special vote of thanks goes to DHI where I got the opportunity, through my work on numerous research projects, to produce many of the results reported in the research publications.

Finally, my sincerest thanks to my lovely wife, Birgitte, and my daughters, Sofie and Anna, for their support and belief in this project.

June 2017
Ole Mark

List of contents

Contents of the dissertation

The present dissertation builds on the 17 scientific publications listed below and focuses on the scientific contributions made by Dr. Ole Mark to the topic "Modelling of Urban Stormwater and Sewer Systems" during the past 25+ years. The line of research started in 1990 when the research focused on the physical behaviour of water in sewer systems, i.e. the head losses in manholes [1]. The research continued with a Ph.D. study on deterministic modelling of sediments and water quality in sewers. The results and the models are presented in the Ph.D. thesis "Numerical Modelling Approaches for Sediment Transport in Sewer Systems", 1995. The papers on sediments and water quality referred to in the present dissertation were not submitted as a part of the Ph.D. dissertation. Hence, those papers represent a scientific contribution, which goes beyond the Ph.D. These papers deal with research and analysis of the physics in sewers, e.g. the reduction of hydraulic capacity due to sediment deposits [2] and the sediment transport in sewers [3]. The interaction between sediments and hydraulics as well as the modelling of sediment transport in pipes were verified against laboratory measurements. The next step was to develop the theory and models for the transport of dissolved matter [7, 8 and 17] and water quality associated with sediments in sewers [4]. These models were originally used for the formulation of the master plan for Ljubljana, Slovenia [5, 6] in 1994. Here the models provided accurate results for predicting locations with sediment deposits and ammonia concentrations in the combined sewer overflow.

The physical processes (head losses and sediment deposits) in sewers have a significant impact on the hydraulic capacity of urban drainage and sewer systems. Hence, when serious cases of rainfall induced urban floods hit cities worldwide in the 1990s and the early 2000s (Mark et al., 2004), a natural expansion of the research was to address how to model urban floods, which was impossible at that point. A novel 1D-1D urban flood methodology was developed [10] and first applied in Dhaka City, Bangladesh, where it proved to be able to predict the extent of the floods. The 1D-1D flood modelling methodology has its limitations, since the assumption of the 1D modelling approach for the surface flow always must be verified after a simulation. The fast development of computational power triggered research into the feasibility of coupling the 1D pipe flow model with a 2D digital terrain model for the surface flow. The research into 1D-2D hydrodynamic flood modelling [14] was further fueled by the parallel research agenda addressing the impacts of climate change on society [12]. The research on urban drainage in the climate change context focused on impacts from climate changes in terms of urban flooding and physical mitigation measures to protect society costs efficiently, e.g. by using green areas as flood detention storage. A new research area was identified, since urban floodwater often originates from combined sewers, which means that floodwater may be a mixture of raw sewage and rain. One of the reasons for building sewer and water supply systems nearly two hundred years ago was to improve public health by eliminating human contact with wastewater in the streets. Therefore, a new modelling system was developed to provide a framework for the analysis of health risks associated with human contact with urban floodwater. This modelling system was set up and verified for cholera risks in Dhaka City during flooding. The research results were in agreement with reports from local hospitals [16]. However, structural measures can never stand alone as a flood proofing. Research was therefore initiated to improve urban real-time flood forecast systems and to quantify the residual risk that needs to be addressed when using real-time flood forecast and management systems [9, 15].

The priority of the presented research has been to test the general applicability of the developed models for cases with a high level of data availability and quality as well as for cases in the developing world with sparse and more uncertain data. Hence, efforts have also been made to document the applicability of the research result for developing countries [11, 13].

The dissertation is based on the 17 scientific publications below:

1. Pedersen, F.B. and Mark, O. (1990). “Head Losses in Storm Sewer Manholes: Submerged Jet Theory”. Journal of Hydraulic Engineering 116(11):pp 1317-1328.
2. Mark, O. (1992). “A Sediment Transport Model for Sewers”. Water Science and Technology 25(8):pp 141-149.
3. Mark, O., Appelgren, C. and Larsen, T. (1995). “Principles and Approaches for Numerical Modelling of Sediment Transport in Sewers”. Water Science and Technology 31(7):pp 107-115.
4. Garsdal, H., Mark, O., Dørge, J. and Jepsen, S.E. (1995). “MOUSETRAP: Modelling of water quality processes and interaction of sediments and pollutants in sewers”. Water Science and Technology 31(7):pp. 33-41.
5. Mark, O., Appelgren, C. and Kosir, M. (1996a). “Water quality modelling for the Ljubljana master plan”. 8th International Conference on Urban Storm Drainage, Hannover, Germany.
6. Mark, O., Cerar, U. and Perrusquía, G. (1996b). “Prediction of locations with sediment deposits in sewers”. Water Science and Technology 33(9):pp 147-154.
7. Mark, O., Wennberg, C., Kalken T. van, Rabbi, F. and Albinsson, B. (1998a). “Risk analyses for sewer systems based on a numerical modelling and GIS”. Journal of Safety Science 30:pp 99-106.
8. Mark, O., Hernebring, C. and Magnusson, P. (1998b). “Optimisation and control of the inflow to a wastewater treatment plant using integrated modelling tools”. Water Science and Technology 37(1):pp 347-354.
9. Mark, O., Boonya-Aroonnet, S., Hung, N. Q., Buranautama, V., Weesakul, U., Chaliraktraku, C. and Larsen, L. C. (2002a). “A Real-Time Hydrological Information System for Bangkok”. International Conference on Urban Hydrology for the 21st Century. Kuala Lumpur, Malaysia.

10. Mark, O., Weesakul, S., Apirumanekul, C., Boonya Aroonnet, S. and Djordjević. S. (2004). "Potential and limitations of 1-D modelling of urban flooding". Journal of Hydrology 299(3):pp 284-299.
11. Parkinson, J. and Mark, O. (2005). "Urban Stormwater Management in Developing Countries". A book – 225 pages published by The International Water Association. ISBN: 1843390574.
12. Mark, O., Svensson, G., König, A. and Linde, J. J., (2008). "Analyses and Adaptation of Climate Change Impacts on Urban Drainage Systems". 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK.
13. Mark, O., Lacoursiére, J. O., Vought, L. B-M., Amena, Z. and Babel, M. S., (2010). "The application of hydroinformatic tools for the water quality modelling and management in Vientiane, Lao P.D.R." Journal of Hydroinformatics 12(2):pp 161-171.
14. Domingo, N.D.S., Refsgaard, A., Mark, O. and Paludan, B. (2010a). "Flood analysis in mixed-urban areas reflecting interactions with the complete water cycle through coupled hydrologic-hydraulic modelling. Water Science and Technology 62(6):pp1386-1392.
15. Hénonin, J., Russo, B., Mark, O. and Gourbesville, P. (2013), "Real-time urban flood forecasting and modelling – a state of the art". Journal of Hydroinformatics 15(3):pp 717-736.
16. Mark, O., Jørgensen, C., Hammond, M., Khan, D., Tjener, R., Erichsen, A. and Helwigh, B. (2015). "A new methodology for modelling of health risk from urban flooding exemplified by cholera – Case Dhaka, Bangladesh". Journal of Flood Risk Management. DOI: 10.1111/jfr3.12182
17. Mark, O. and Ilesanmi-Jimoh, M., (2016). "An analytical model for solute mixing in surcharged manholes". Urban Water Journal 14(5):pp 443-451.

When one of these 17 publications is used as a reference in the dissertation, it is highlighted in the text by use of bold text font.

Sammenfatning

Computermodellering af afløbssystemer er en disciplin, som har udviklet sig eksplosivt igennem de sidste 50 år. Det anslås, at en stor del af alle byer i verden med mere end 100.000 indbyggere på en eller anden måde har anvendt computermodellering til design eller analyse af historikken i deres afløbssystemer.

Modellering af afløbssystemer anvendes ofte sammen med målinger af tilstanden i systemet, såsom vandstand, vandføring, vandhastighed, stofkoncentration mv. med henblik på design eller analyse. Målingerne anvendes typisk til kalibrering af computermodellerne i udvalgte punkter, og den kalibrerede model bruges derefter til analyse af årsager til problemer, sammenhænge i komplekse/store afløbssystemer, design, driftsoptimering m.m. For at designe afløbssystemer med et funktionskrav, som er forberedt for klimaændringer, er computermodellering en nødvendighed, da målinger normalt er kortvarige og ikke kan ekstrapoleres 50-100 år frem i tiden, hvilket typisk kan være levetiden af et nyt afløbssystem. Det stigende behov for analyser af klimaændringers påvirkninger af afløbssystemer vil således yderligere forøge efterspørgslen efter computermodellering.

Særligt har udviklingen af PC'en i de tidlige 1980'ere spillet en afgørende rolle for modellering af afløbssystemer, idet PC'en siden midt firserne er blevet ca. 1000 gange hurtigere, og den oprindelige begrænsende 640 KB hukommelse (som kunne håndtere omkring 250 afløbsledninger) er blevet erstattet af PC'er, som i dag, hvad angår hukommelse, overgår det behov, som selv de største beregninger kræver. Men ikke alene den rå computerkraft har bidraget til fremskridtet inden for computermodellering af afløbssystemer. Ud over forøgelsen af computerens kapacitet er der sket markante fremskridt inden for:

1. Beskrivelse af fysiske, biologiske/kemiske processer i afløbsledninger, f.eks. transport af opløst stof og sedimenter
2. Beskrivelse af fysiske processer i brønde i afløbssystemer, f.eks. energitab og opblanding

3. Delmodelsystemer, som beskriver årsagssammenhænge i afløbssystemerne, f.eks. kobling af sedimentaflejring med hydraulisk modstand
4. Koblede modeller, som sammenkæder eksisterende viden på nye måder:
   - kobling af 1D hydrodynamiske rørmodeller med GIS modeller af terræn og 2D hydrodynamiske modeller, som beskriver vandets strømning på terræn; sammenkobling af oversvømmelsesmodeller med modeller til beregning af skader fra oversvømmelser og sygdomsrisiko
   - kobling af output fra 1D hydrodynamiske rørmodeller, fx. kloakoverløb, for at analysere effekterne på recipienter
5. Nye anvendelser af modeller af afløbssystemer, f.eks. simulering af effekterne af klimaændringer

I herværende afhandling gennemgås udviklingen beskrevet ovenfor med fokus på forfatterens bidrag hertil inden for modellering af afløbssystemer.

Juni 2017
Ole Mark

Summary

Computer modelling of drainage systems is a discipline that has soared over the past 50 years. It is estimated that a large proportion of all cities in the world with more than 100,000 inhabitants have used computer modelling, in one way or another, for design or analysis of the performance of their drainage systems.

Modelling of drainage systems is often based on supported measurements of the condition of the system, such as water levels, flows, flow velocities, concentrations etc., for the purpose of design or analysis. The measurements are typically used to calibrate the computer models at selected locations, and the calibrated models can then be applied for the analysis of "the causes of problems", e.g. for complex/large drainage systems, design, operation etc. Computer modelling is very useful and recommended in order to design drainage systems and to provide a service level that is robust with respect to climate change. This is due to the fact that measurements cannot be extrapolated 50 to 100 years ahead, which will typically be the lifespan of a new drainage system. Climate changes and their effects on our urban water infrastructures will further advance the use of modelling.

The development and the introduction of the PC in the early 1980s played a decisive role in the modelling of drainage systems. Since the mid-eighties, the PC has become more than 1000 times faster, and the computer memory is now surpassing the needs of even the largest calculations compared to the early 1990s where the memory was limited to 640 KB (which could handle about 250 pipes). The increase of raw computer power and memory as well as the following advances has significantly contributed to the progress in computer modelling of drainage systems:

1. Description of physical, biological/chemical processes in the sewers, e.g. transportation of dissolved matter and sediments
2. Description of physical processes in manholes in drainage systems, e.g. energy losses and mixing
3. Development of models describing causal relationships in the sewer systems, e.g. coupling of sediment deposition with hydraulic resistance
4. Development of models and coupling of models, which link existing knowledge in new ways, i.e.:
    - coupling 1D hydrodynamic pipe flow models with GIS models of terrain and 2D hydrodynamic models describing the flow of water on the ground; linking flood models with models to calculate the damage from floods and the health risk
    - coupling output from pipe flow models, e.g. overflows, to analyse the impacts on receiving waters
5. New applications of models of drainage systems such as simulation of the effects of climate change

The present dissertation goes through the developments within modelling of urban drainage systems, with focus on the contributions made by the author.

June 2017
Ole Mark

1. Introduction

All over the world, cities have grown rapidly during the last century, and the local authorities have built new storm and wastewater drainage facilities. Many old cities have expanded according to their varying historical visions and needs. Hence, the design and form of the infrastructure have gradually developed into complex systems, and the authorities need tools to be able to achieve efficient design, operation and management. In addition to the urban developments the following essential drivers have historically pushed the construction and operation of urban stormwater and sewer systems:

- Improvement of public health by provision of water supply and sewers
- Protection of the aquatic environment by reducing the amount of wastewater discharged to recipients
- Prevention of flooding by provision of drainage systems and flood storage

An understanding of the physical system and its interaction with the environment is a prerequisite for effective planning and management of stormwater and sewer systems. In this respect, computer models provide the means for well-structured analysis of the performance and layout of the current system and the impact of possible changes on the system, thus providing a consistent scientific framework for coordinated management and planning. Apart from the assessment of different scenarios, the models also support improved process understanding. Urban drainage models are applied to understand the often quite complex interaction between rainfall, overflows and flooding. Once the current conditions have been analyzed and understood, alleviation schemes can be assessed and the optimal schemes implemented.

Owing to the advances of computer performance during the past decades, many cities all over the world now use computer-based models of their sewers for several different purposes, e.g. reporting of overflows from sewers on an annual basis using a combination of measurements and modelling, managing local flooding problems using computer-based solutions and employing real-time warning models.

1.1. Brief history of urban drainage modelling

Deterministic modelling of urban stormwater and sewer systems dates back to the early 1960s when the British Road Research Laboratory developed and tested a method for computation of runoff from urban catchments in the United States (Terstriep and Stall, 1969). This model for runoff simulations was soon followed by the US Environmental Protection Agency (EPA), who financed the development of the first version of the EPA Stormwater Management Model (SWMM), which was released in 1971. Shortly after, the first comparative studies of urban drainage model surfaced, comparing models and demonstrating the benefit of model calibration (Marsalek et al., 1975). At the same time Wallingford, UK and the Danish Hydraulic Institute (DHI), DK developed their first 1-dimensional (1-D) flow models. Meanwhile, the Illinois Urban Drainage Area Simulator, ILLUDAS, was developed at the Illinois University (Terstriep and Stall, 1974). ILLUDAS was going beyond the rational method for design of urban drainage systems and was made available in the form of a 700-card FORTRAN IV deck. ILLUDAS was used worldwide, and local national guidelines were produced, e.g. in Sweden (Sjöberg, 1978). During 1982-86, the first commercial software packages for hydrodynamic modelling of sewers and urban drainage systems became available: MicroWASSP (Wallingford, 1982) by Wallingford, MOUSE by Danish Hydraulic Institute (Lindberg et al., 1986), and PCSWMM by Bill James (James and Robinson, 1984). Later came also SOBEK (WL Delft Hydraulics, 2009). The first modelling packages were released shortly after the first Personal Computers (PCs) became available, and since then, modelling software for urban drainage has closely tailed the PC and consumed its full capacity. As PCs became more powerful, the modelling software increased in complexity, and the maximum size of an urban drainage model has gone from approx. 250 pipes in the mid-eighties to the modelling of drainage systems in megacities with tens of thousands of pipes. E.g. it is possible to model urban flooding for a megacity of 1000 km^2 like Beijing (Hénonin et al., 2015).

Computer modelling of urban drainage has not added much new information to the pure basic theory and concepts concerning urban hydrology and hydraulics. However, it made hydrodynamic modelling feasible for practical purposes, and hence it brought fast and user-friendly computations, based on the St. Venant equations, to the broad engineering community. During the 1990s, computer modelling of urban drainage broke new grounds by developing both theoretical and numerical approaches to sediment transport and water quality in sewer systems (**Mark, 1992; Mark et al., 1995;** Blanc et al., 1995). These processes are still not fully understood. In the late 1990s, standardized national procedures were developed around the world for the implementation of urban sewer and drainage models, e.g. within urban pollution management (Foundation for Water Research, 1998), and the models were used for design, master planning and real-time control (**Mark et al., 1996a**; Metelka et al., 1998; **Mark et al., 1998b**). During the first decade of 2000, the leading modelling packages were fully embedded into the Geographical Information Systems (GIS). This was done in order to facilitate model building based on the digital records of the geometry of the urban drainage systems held by the local authorities in databases. The purpose was to process data about the terrain and surface features and to show model output in conjunction with the infrastructural data of the cities (Andrews, 2002; Andersen et al., 2004a). Subsequently, the integration of GIS (**Mark et al., 1998a;** Andersen et al., 2004a) linking 1-D models with 2-D free surface models was implemented (Alam, 2003), which enabled the simulation of pluvial urban flooding through the interaction between a 1-D flow model and a 2-D free surface flow model. This facilitated the analysis of flooding and flood risk rather than just modelling the flow of water in pipes and open channels. Lately, the development of deterministic modelling of sewer and urban drainage models has included:

- sustainable urban drainage elements (SUDS) such as soakaways (Roldin et al., 2012a), rainwater barrels and green roofs (Locatelli et al., 2014)
- flood simulation functionality (Djordejević et al., 2011) and flood damage economics (Hammond et al., 2015)
- analysis of health risk from human contact with floodwater (**Mark et al., 2015**)

Currently, water utilities worldwide design, manage and operate sewers and urban drainage systems by deterministic computer models using software such as InfoWorks (Andrews, 2002), MIKE URBAN (Andersen et al., 2004b), PCSWMM (James and Robinson, 1984) and SWMM (Huber and Dickinson, 1998). Hence, models for urban drainage and stormwater are predominantly deterministic models and thus the focal point of the present thesis.

1.1.3. The history of MOUSE – Modelling of Urban Sewers

MOUSE stands for "**Mo**delling of **U**rban **Se**wers". The first version of MOUSE was released in 1985 at the same time as the introduction of the first PC with an 8086 processor. The roots of MOUSE go back to the late 1960s when Professor Mike Abbott carried out some of the very first numerical water modelling initiatives at Danish Hydraulic Institute (DHI). Around 1964, Mike Abbott visited DHI, and together with DHI, he embarked on some of the first projects with serious commercial mathematical computer modelling of water (Mark and Hosner, 2003). In the early 1970s, the first in-house version of software for modelling of water surfaced, System 11. Here '11' refers to the 'physical' dimensions of the modelling system, since the System 11 model has '1' dimension in space and '1' layer of water. In 1978, it was decided to make a separate version of System 11 (programmed in PL1) for sewer systems. The name of the new “twin” to System 11 was System 11S, where ‘S’ stands for ‘Sewers’. Through a joint venture, System 11S was turned into a commercial software product by a group of companies (Krüger, PH-Consult, Emolet and Danish Hydraulic Institute). They successfully completed the first version of MOUSE 1.0 in 1985 for the IBM PC. After MOUSE was completed, System 11 was re-engineered from the mainframe computer to PCs and was renamed ‘MIKE 11’, with focus on river modelling.

Since 1985, the capabilities of MOUSE have been closely linked to the capabilities of the PCs on the market. New modules of MOUSE have always matched the speed of current PCs at the time of the first release. Examples are MOUSE PILOT in 1992 and MOUSE **TRAP** (**Tra**nsport of **P**ollution) in 1994 (Crabtree et al., 1994, **Garsdal et al., 1995**). Since its release, MOUSE PILOT has been used in projects applying true continuous hydrodynamic modelling incl. real-time control. In 2000, MOUSE PILOT was extended to include another two comprehensive tools, MOUSE RTC and MOUSE LTS. Just a few years before they were released, it would have been impossible to run neither TRAP nor PILOT due to the slow runtime. Today, however, the runtime is not that much of an issue. In 2004, MOUSE was embedded in GIS, and the new name of the software was MIKE URBAN (Andersen et al., 2004a). Shortly after the release of MIKE URBAN, the 1D modelling of sewers and drainage systems was expanded by links to a 2D hydrodynamic model. This new model computed the surface flow on terrain, and the full 1D-2D hydrodynamic modelling system was called MIKE FLOOD.

For a couple of years, the development of modelling software focused on the GIS user interface driven by asset management. At the same time, numerous experiences where drawn from the new applications which MIKE URBAN and MIKE FLOOD made possible. Simulations of the potential impacts of future climate changes, in particular, was a significant area for new research and model applications. The simulations of extreme rainfall events made it evident that there were shortcomings in the traditional way of simulating runoff from or in a city. The need for simulating the runoff from green areas and the interaction with groundwater resulted in new modules simulating green roofs and soakaways – even with links to the 3D groundwater model MIKE SHE. During urban flood events, diseases were spread to people who were exposed to floodwater. As a result it was concluded that floodwater consisting of both sewage and rainwater pose a health risk to the population. In order to understand and analyze this health risk in a consistent framework, a pollution transport model was added to MIKE FLOOD, which simulated the concentrations of pathogens in the floodwater. Afterwards the computed concentrations were translated into a health risk by quantitative microbial risk assessment (**Mark et al., 2015**).

At present, many practical problems within urban drainage and sewers still call for a deeper understanding and frameworks for consistent analysis. Examples are:

1. Need to handle increased flooding due to climate change in a robust, adaptive and cost efficient way
2. Integrated real-time optimal operation of the sewers and wastewater treatments plants
3. Corrosion of sewers due to hydrogen sulphide

The development of new models, software features and applications will most likely continue with equal speed and intensity in the future.

2. Deterministic modelling of sewers and urban drainage

Any model is a simplified mathematical representation of a physical system, e.g. coupled with biology and chemistry. A model is an abstraction of a system in the real world, and a model must never be expected to be an exact replication of reality. Even though the model is not equal to the real world, the model may still be perfectly fit for the purpose. The purpose of modelling is generally to understand how the full system behaves, e.g. to understand reasons for overflows/flooding, or to analyze how changes in one part of the system affect other parts of the system – or the system as a whole. This representation of a small part of the real world by a model may be based on a *deterministic* method (i.e. with a fixed relationship between physical disturbance and its impacts) or a *stochastic* approach, i.e. adding probability random component to the model inputs.

Hydrodynamics as well as sediments and water quality in sewers and urban drainage systems are still facing scientific challenges with respect to knowledge and modelling. To improve the understanding of the processes inside urban drainage and sewer systems, some of the main problems that yet need to be investigated are:

- Head losses in sewers
- Uncertain rainfall predictions, e.g. for real-time rainfall forecasts
- Sediment transport under conditions deviating from open channel flow
- Water quality processes and their interaction with sediments

The question is whether it is justifiable to apply deterministic modelling for everything in relation to the modelling of urban drainage and sewer systems. These main challenges and their importance for deterministic modelling of urban drainage and sewer systems are discussed in detail in the present dissertation.

Deterministic models used for urban drainage can be classified as *physically based models* or *conceptual models*. Assigning a model to one of these classes relies on the level of mathematical sophistication of the description of fundamental physical processes in the model. Basically, models are classified according to the significance of the models' equations' capability to describe the processes precisely. The dependence on empirical parameters classifies the model as conceptual and stresses the need for calibration against field measurements. In this context, many hydrological models would belong to the class of conceptual models, while the hydrodynamic network model is a case of a physically based deterministic model. Presently, researchers are continuously aiming at mapping and formulating more and more physical and biological processes in order to increase the level of knowledge and thus improve the physically based deterministic models. However, some of the processes still lack mathematical descriptions at the highest level of detail.

2.1. Head losses in sewers

The head losses in sewers consist of the friction losses in the pipes and the head losses in manholes. Historically the head loss in a pipe is well analyzed and described, e.g. by use of the roughness and the Manning equation, but the head loss in a manhole is still not well described for all manhole configurations. For modelling of a sewer system, an accurate description of the head loss across a manhole is essential, as this is the key parameter together with the hydraulic roughness of the pipes (the Manning number). Together, these factors govern the total energy losses in the sewer/drainage system and subsequently decide the quality of the modelling of:

1. The flow and velocity in the pipes
2. The water levels, e.g. causing surcharge or flooding
3. The temporal and special variation of concentrations

4. The overflows to recipients (flow and concentration)
5. The flood locations and extent

The friction coefficient of the pipes can be estimated based on the pipe material and the age of the pipes, whereas the local conditions of the manholes (geometry and flow) determine the head loss in the manholes. However, the head loss in the manhole is often the unknown factor because the flow pattern is hard to determine due to turbulence.

A number of researchers (Lindvall, 1986; **Pedersen and Mark, 1990**; Stovin et al., 2010) have investigated the impact of the head loss on flood and surcharge conditions when modelling sewers. Jacobsen and Harremoës (1984) found that simulations with System 11S (the early version of MOUSE) and EXTRAN (Roesner et al., 1988) showed satisfactory agreement between the results of simulation of surcharged conditions and observed data from a real sewer system in Denmark. However, they also noted that the head loss descriptions in the two programs are significantly different. By then, EXTRAN lumped the head loss in the manhole into the loss in the pipe, whereas MOUSE had individual descriptions of the losses in the manholes and the pipes. Both models were sensitive to the chosen head loss coefficient, and the head losses were recommended to be found based on calibration against measurement data.

Traditionally, the head loss in manholes is assessed by means of the Bernoulli equation by comparing flow conditions (energy levels) at two cross sections (upstream and downstream from the manhole) for varying geometries and flow rates. This approach is purely empirical and requires measurements for every possible combination of pipe/manhole shapes and diameters, angles and relative elevations. In order to reduce the uncertainties in the computations of the head losses at manholes, an analytic deterministic model of the head losses in manholes was developed by **Pedersen and Mark (1990)**. The model describes a case with only two pipes connected to the manhole, i.e. one inflow and one outflow pipe. The model fits remarkably well to experimental data from Marsalek (1984), Marsalek and Greck (1988), Johnston and Volker (1990) and Mark (1989), and thus the new model reduces the uncertainty in modelling of sewers. The benefit of this methodology is that it considers flow conditions within a manhole (via jet theory), which is a more physically sound approach. The applicability of jet theory was confirmed by Guymer and O'Brien (2000) and visualised by using planar laser induced fluorescence images (Figure 1). However, an open question remains: "Which head loss should be applied for the flow across the manhole that involves a change in pipe size, elevation or direction, or with more than one inlet or more than one outlet?" Today no general theory exists for these scenarios.

The flow conditions in the manhole do not only affect the head loss in the sewer/drainage system, but they also have a profound impact on the transport of dissolved pollutants in the case when variations occur in the concentration of pollutants within the sewers. The volume of water in a surcharged manhole is strongly correlated with the head loss in the manhole. Further, the water volume controls the transport and the mixing when pollution is transported through a manhole, i.e. there is a direct correlation between the head loss and the mixing of pollution across a manhole (Guymer et al., 1998). Traditionally, it is assumed that pollution entering a manhole is mixed instantaneously with the full volume of the manhole (**Garsdal et al., 1995**). This approach has been verified to work for modelling of ammonia in large combined sewer systems where the concentrations in the overflow can be simulated accurately (**Mark et al., 1996a**; Schlütter and Mark, 2003)). Such pollution transport models have proven to be very useful in defining the travel route and travel times for emergency planning in scenarios where unwanted substances are spilled into a sewer system (Larsson et al., 1996 and **Mark et al., 1998a**). However, the assumption of full mixing in a manhole introduces both a time lag and an amplitude error when a pulse of dissolved pollution passes a manhole. This may be the case if a first flush of pollution is transported through a sewer system during the onset of a rain event (Figure 1).

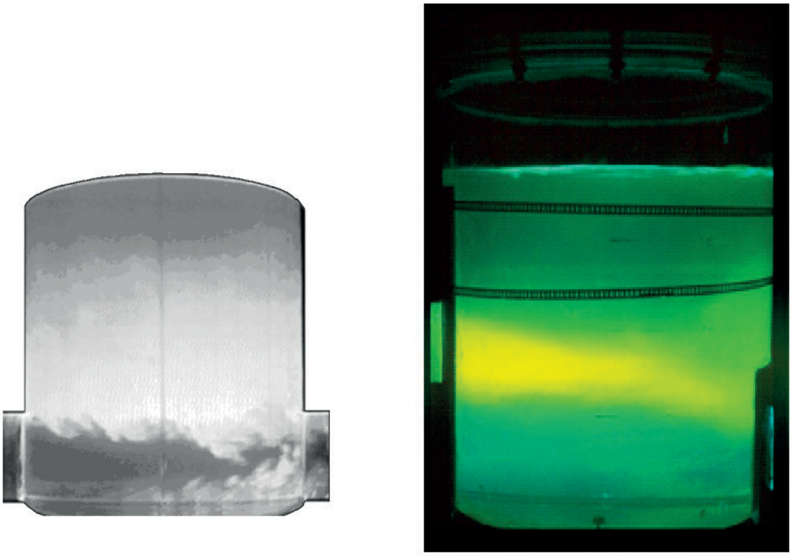

Figure 1. Planar laser induced fluorescence images showing the flow of dissolved material through a manhole. Flow direction left to right. The image to the left shows a straight flow through a manhole, while the image to the right shows a case where the outflow pipe (to the right) is a bit lower than the inlet (**Mark and Ilesanmi-Jimoh, 2016**)

An analytical model, which describes the mass conservative transport of dissolved pollution through manholes, has been developed and tested on experimental data (**Mark and Ilesanmi-Jimoh, 2016**). The new mathematical model for mixing in manholes improves the description of the transport of dissolved pollution across a manhole significantly. E.g., there is a much better agreement between simulated and observed peak concentrations and travel times across a manhole compared to what is obtained by assuming full instantaneous mixing in the entire manhole volume, denoted as 'full mixing' in Figure 2.

This description of the solute transport in a manhole has recently gained in importance with the development of models, which can simulate the transport of wastewater mixed with stormwater from overloaded drainage systems to the urban environment during flooding (**Mark et al., 2015**). The model developed by **Mark et al. (2015)** simulates pollution and health risk in floodwater by linking a 2D hydrodynamic urban flood and pollutant transport model with quantitative microbial risk assessment (QMRA). The outcome is an ability to understand the interaction between urban flooding and health risk caused by direct human contact with polluted floodwater. Such a model can be applied for analyses of options for decreasing the burden of disease on the population by use of intelligent urban flood risk management. The model was set up and demonstrated successfully for a flood event in Dhaka City in Bangladesh where waterborne diseases including cholera are endemic.

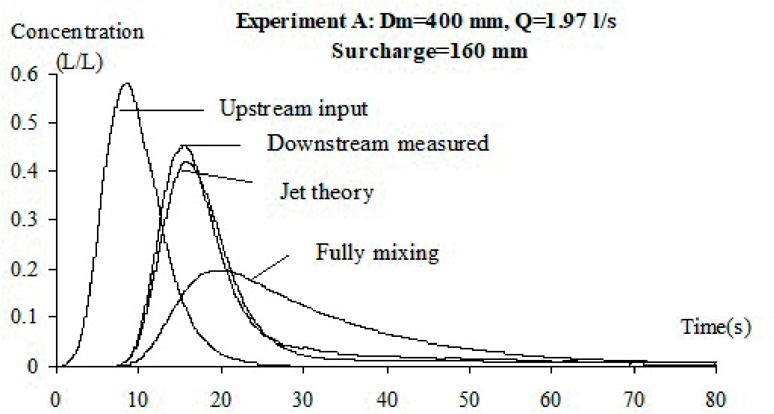

Figure 2. Comparison of simulated and measured downstream concentration profiles for a pulse of dissolved substance travelling through a manhole (Mark and Ilesanmi-Jimoh, 2016)

More accurate representations of the physics inside manholes provide the fundament for better practical applications for modelling of flooding, overflows, pollution, sediment transport and design of new systems. The impact of the head loss is decisive in particular with respect to modelling of urban flooding, which is one of the main applications of the modelling of sewers and urban drainage systems. The application of deterministic hydrodynamic models within urban flooding is further elaborated in Chapter 3.

2.2. Calibration and verification of models

Stormwater and sewer system models should reproduce the behaviour of the modelled system with a high degree of precision. This is typically ensured through the process of parameter calibration and verification of model results compared to the observed performance of the real system. Calibration includes fine-tuning of the model's key parameters with the objective of minimising the differences between the model results and the measured field data, e.g. water depths, discharges or concentrations.

All models should – if possible – be calibrated before their application. Conceptual models require more consideration in this respect than fully deterministic and physically based models, as the assumptions on which a conceptual model is based must be proven valid. Thus, in urban drainage modelling, focus of model calibration is usually on hydrological models (conceptual) which have an effect on the water balance and the routing times, while the deterministic hydrodynamic models of the drainage system mainly change the routing times and the onset of surcharging, which require adjustments to the Manning number and the head loss in the manhole for an accurate performance. In relation to the transport of pollutants, it is highly dependent on the flow velocity computed by the hydrodynamic model. The key parameter of the advection model itself is the dispersion coefficient, which is only significant when gradients exist in the concentration within the sewer system. Finally, the calibration of models with biological and chemical processes requires very special attention and care, which will be further elaborated in Chapter 4. Independently of the applied model type, a good modelling practice recommends proper model verification for any serious application.

For all the models mentioned above a continuous period or a group of measured intermittent events must be applied for calibration. The measurements must ideally include a full range of likely operational conditions in the system. The verification process is carried out by running measurements from a series of events that were not included in the calibration. The performance of the model for the verification period must show that the model reproduces the events within a satisfactory margin of error.

2.2.1. Sensitivity analysis and uncertainty

In relation to the application of models, uncertainty in the design and analysis of sewer and urban drainage systems is a serious issue, but still knowledge concerning uncertainties in urban drainage models is considered to be poor compared to river engineering (Deletic et al., 2012). Urban drainage modelling has many input parameters, e.g. degree of imperviousness, surface slopes, roughness, areal distribution of rainfall, which contribute to the uncertainties. Due to the variability in nature of these parameters, e.g. the hydrological reduction factor, some parameters will significantly influence: a) the occurrence of overflows, which may lead to significant environmental impacts; b) the rate of flooding, which leads to substantial financial losses in urban areas. The variability of the parameters may even be caused by changes over time, e.g. growth of cities, the increase of impervious areas, ageing network systems and/or climate change (**Mark et al., 2008**). Considering all these factors, precise estimations of all the modelling parameters is a difficult task. It is therefore necessary to determine the uncertainty of a parameter and its impacts on model results, and subsequently the applicability of the models, e.g. by use of the conceptual framework suggested by Deletic et al., 2012. For sewer and urban drainage models, the key parameters in the hydrological models are typically: areal distribution of rainfall, catchment area, imperviousness, hydrological reduction factor, routing time (e.g. expressed as time of concentration, Manning number or time constants) and initial loss (wetting of the surface); and in the hydrodynamic model: head loss at the manholes and Manning number. In order to determine the dominant parameters and their impacts, e.g. Monte Carlo simulations with Latin Hypercube, sampling can be applied in order to map the domain of the model results. Such simulations can increase the awareness of the uncertainty as demonstrated in the paper by Hansen et al. (2005).

One way to address the uncertainty in the application of real-time forecasts of urban flooding is to apply probabilistic methods for the estimation of the uncertainty in single-valued rainfall forecast from a numerical weather prediction model (Rene et al., 2013; Diez, 2016). Rene et al. (2013) apply a stochastic model to expresses the uncertainty conditioned on the rainfall in the form of the probability distribution functions. The rainfall input is subsequently applied in conjunction with a 1D/2D hydrodynamic urban flood model, and the resulting outputs are water levels/depths and flood maps computed for different percentiles, e.g. the maximum flood depths over the city area. Diez (2016) applied a combined hydrodynamic pluvial-storm surge model for deriving confidence intervals for probabilistic flood forecasts. These applications demonstrate how uncertainty can be addressed in a practical and informative way by combining deterministic and probabilistic approaches instead of seeing uncertainty as a limiting factor in urban drainage modelling.

2.2.2. Calibration support for urban drainage and stormwater systems

Important decisions concerning huge investments rely on the human perception of what a good calibration is and judging if the calibrated model is applicable for the specific practical purpose. The reliability of the modelling depends heavily on the adequacy of the calibration procedure employed and on the experience of the person performing the calibration. Today, urban drainage and stormwater models are nearly always manually calibrated to reproduce measurements of flow, water level, velocity and concentration. Automatic calibration support has been widely seen as a desirable replacement for the manual calibration procedure (Wan, B. and James, W. (2002), Wangwongwiroj et al., 2004), because it would be less subjective, less time-consuming than manual calibration and relatively easy to implement.

However, calibration cannot be 100% automated as a choice of objective functions must be made by an expert, depending on the key phenomenon, which will be analyzed by use of the measured data (e.g. combined sewer overflow volumes, pumping station activity, the onset of surcharging, surface flooding). Further, an automatic calibration procedure may stop at a local minimum of the objective function, or it may not converge sufficiently towards the chosen objective – e.g. due to errors in the measured data, which need to be screened by an expert/expert system.

So far only a small number of attempts have been made to produce robust and reliable automated calibration tools for hydraulic modelling of sewers and urban drainage systems (Wan, B. and James, W. 2002, Wangwongwiroj et al., 2004; Di Pierro at al., 2005; Khu et al., 2006). These researchers demonstrate that parameters of hydrologic and hydraulic models can be estimated by use of an automatic calibration procedure, where the statistical measures of the objective functions can be optimized fast and easily. However, calibration of urban drainage models is a multi-objective calibration problem, and the automatic calibration procedures will typically not produce a single unique set of parameters, but the output will be a Pareto set of solutions (non-dominated solutions), according to trade-offs between the objective functions. I.e. output can be a number of good calibration parameter sets without having identified the most optimal parameter set for the application (Wangwongwiroj et al., 2004; Di Pierro at al., 2005). For automatic calibration of water quality models for sewers systems, no work has been published yet. Analysis and automatic clean-up functions of the data applied for modelling (calibration) are important research topics, as shortcomings and faults in the datasets may result in a faulty automatic calibration answer. In short, automatic calibration support is still emerging and is not widely used within modelling of urban drainage systems, and more research is required in order to improve the automated calibration procedures to a level where they perform better than an experienced modeller does.

2.3. Application of sewer and urban drainage models

In addition to pure hydraulic problems and analysis a number of other problems (which often get less attention) exist. Currently, the water quality processes in sewers are poorly understood quantitatively, and data collection concerning the water quality processes in sewers is very limited compared to traditional water quality modelling in rivers and wastewater treatment plants (Rauch et al., 2002). An improved description of the transport of pollution through a manhole is one step in the right direction towards improving the applicability of water quality models for sewers. However, within some areas the limited knowledge currently available about water quality processes in sewers is sufficient for professional applications by use of deterministic modelling. The use of deterministic water quality models for sewers and urban drainage systems is elaborated in Chapter 3.

Sediment deposits in sewers reduce the hydraulic capacity, and pollution may be attached to the sediments. The impact of sediment deposits on the hydraulic capacity can be estimated, e.g. by using the Einstein Sidewall Elimination (Einstein, 1942; **Mark et al., 1996b**). Presently, a computation of the total sediment transport in a sewer system still lacks a general formulation. However, the sediment transport with the mean flow velocity of very, very fine suspended sediments without significant deposition can be modelled sufficiently accurately by using an advection-dispersion model (**Mark et al., 1995**). The transport of sediment depends strongly on the local hydraulic conditions together with sediment characteristics like size and density **(Mark, 1992)**. The application of deterministic models to compute sediment transport in sewers is elaborated in Chapter 3.

3. Pollution transport and water quality processes in sewers

Modelling of wastewater is essential for predicting inflow (quantity and quality) to wastewater treatment plants and for precise computations of overflows (quantity and quality) from sewer systems. Lately, a mathematical modelling system for the pollution transport in urban flooding has been developed (**Mark et al., 2015**).

Traditionally, modelling of volumes from combined sewer overflows is carried out by using a rainfall-runoff model as input to a hydrodynamic pipe flow model combined with a diurnal variation of the wastewater produced by the people living in the city. In many places worldwide, the performance of a sewer system is regulated by the Environmental Protection Agencies (EPAs), which in the past stipulated an acceptable number of "consented" overflow events per year. If a sewer system has less than five overflows per year, it may be considered to have a satisfactory performance. This is a performance measure, which is easy to implement and administrate, but it does not account for the actual volumes spilled, the quality of the overflow water or the impact on the receiving waters.

When computer modelling was introduced, it became possible to calculate volumes from all overflows in a drainage system. In the past, everything had to be measured in order to fully document the total overflow volumes. The relatively cheap and reliable implementation of models calculating overflow volumes and pollution emissions for an entire sewer system has changed the EPAs' focus from overflow frequency to annual overflow volumes and quality, when appropriate. For lakes, the accumulated overflows of nitrogen and phosphorus from the drainage system are more important than the number of spills. For small streams, the loads from extreme events causing high ammonia or low oxygen concentrations may be the main critical processes (**Mark et al., 2010**). As the water quality models have been improved, the philosophy behind sewer rehabilitation/optimization has changed from reducing the number of spills per year to decreasing the yearly overflow volumes as well as considering the load and impacts on the receiving waters.

In the early days of urban water modelling, the combined sewer overflow load to streams and rivers was typically computed based on a conceptual hydraulic model, e.g. the SAMBA model (Johansen et al., 1984). This kind of model is very simple and includes only computation of a time-area runoff hydrograph together with the most crucial elements of the pipe/drainage system, i.e. weirs, pumps, locations with divergent flow and outlets. The calculations are extremely fast and suitable for scanning a large number of possible layouts of drainage systems as a result of the simplification of the modelling elements. However, it only takes the quantity of the overflows into consideration.

The introduction of software for water quality modelling of urban drainage systems such as MOSQITO (Blanc et al., 1995) and MOUSE TRAP (**Garsdal et al., 1995**) in the middle of the 1990s made it possible to extend hydrodynamic modelling of water and include dynamic modelling of the transport of pollution and sediments in the sewer and drainage systems (Van Assel and Carrette, 2002; Schlütter and Mark, 2003). This advanced the description of the modelling of wastewater and the pollution loads to the receiving water even further. This kind of water quality modelling provides an accurate description of the dilution process, when the rainwater mixes with the sewage, together with an estimate of the water quality processes in the system. The outcome was more accurate computations of concentrations of conservative pollutants in the combined sewer overflow (Figure 3). Furthermore, it has demonstrated that in most cases, quasi-conservative pollution such as ammonia can be modelled very accurately (**Mark et al., 1996a**, **Mark et al., 1998b;** Andersen et al., 2015).

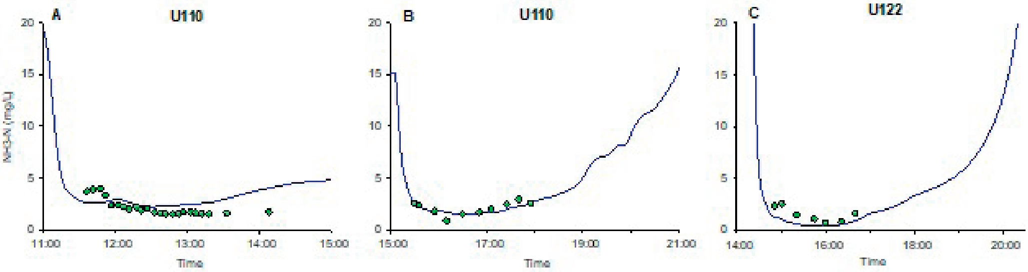

Figure 3. Simulated and measured ammonia concentrations at two combined sewer overflow structures (U110 and U122). A: 29th June 2012; B: 13th October 2012, and C: 13th October 2013 (Andersen et al., 2015)

During the 1990s, long-term continuous simulations of drainage system hydraulics and the transport of pollution gradually became a standard application practice, facilitating simulation of historical time series of rain and their impact in terms of overflow or load on the wastewater treatment plant. The long-term simulations combined wet weather condition simulations using a dynamic pipe flow model and simulation of wastewater flow during dry weather by means of a hydrological model (Gustafsson et al., 1999; Jakobsen et al., 2001). This model constellation made it possible to simulate many years (>25 years), while the feasible length of continuous simulations of the time series still depended on model size, computer speed and rainfall data period. Results were presented based on the statistical occurrence of impacts, e.g. in terms of overflow volume.

The understanding of the behaviour of the sewer system and its interaction with the environment gained from the long-term simulation is superior to the simulation of selected individual rain events, as the uncertainty of selecting only a few representative rain events is significantly reduced (Gamerith et al., 2011). Furthermore, based on a long-term simulation, the statistics are made on the computed output (the actual impact of rain) instead of statistics based on the input, e.g. the rainfall statistics. As the hydrodynamics in a sewer system is non-linear and highly complex, the statistics in terms of combined sewer overflow, stormwater overflow or flooding are by far more relevant and accurate than the statistics on the rainfall itself.

3.1. Self-cleansing sewers

The main purpose of sewers is to transport the wastewater safely from households to a safe wastewater disposal place, e.g. a wastewater treatment plant. Wastewater contains particles that must be taken into consideration when designing sewer systems. Therefore, it is of utmost importance that the sewer systems are designed in such a way that both water and particles are transported smoothly, thus avoiding sediment deposits (Crabtree, 1989; Butler et al., 2003; Ashley et al., 2004).

Today, many sewer systems around the world are facing problems with sediment deposits because water saving toilets have been introduced. The water saving toilet uses a significantly smaller amount of water (2-4l) than a traditional toilet (9-12l). As a result of replacing old toilets with new water saving toilets, the dry weather flow in sewers is reduced, and hence the sediment transport capacity is reduced. It is good to save water and the use of natural resources, but the reduced dry weather flow (with the same amount of sediments) increases the risk of sediment deposits. This may eventually cause increased flood risk and ultimately blocked pipes.

A basic definition of a self-cleansing sewer was put forward by May (1993), "*One having a sediment-transporting capacity that is sufficient to maintain a balance between the amounts of deposition and erosion, with a time-averaged depth of sediment deposit that minimizes the combined costs of construction, operation, and maintenance.*" Here, it is interesting to see that the self-cleansing criterion proposed by May (1993) does not prescribe that sediment never will deposit in a pipe. Sediments may deposit over time in a pipe, as long as the overall costs are smaller than the construction costs for a pipe with no sediment deposits. However, at present, worldwide sewers are still designed based on local experience. Typically the design is based on simple hydraulic parameters such as flow velocity and flow depth. A universal design criterion for self-cleansing sewers do not exist yet, but a formulation of a framework for self-cleansing sewers should soon be possible.

3.2. A consistent procedure for identifying locations with sediment deposits

A consistent procedure for identifying locations potentially having sediment deposits is outlined below. Each step in the modelling procedure addresses the likelihood of developing sediment deposits (**Mark et al., 1996b**), and each step must be completed and verified before continuing to the next step. The modelling procedure is based on simulation of various sediment parameters and sediment transport modes (**Mark et al., 1995**) during dry weather flow:

- Computation of the bed shear stress
- Computation of the dimensionless bed shear stress
- Computation of time above the critical bed shear stress, compared to time of travel for a particle in a pipe
- Computation of local mass balances for sediments
- Computation sedimentation pattern with a fully dynamic movable bed (morphological) model

The advantages and shortcomings of the above modelling approaches are briefly described below.

3.2.1. The bed shear stress

Worldwide, the self-cleaning conditions for a sewer/drainage system are frequently set based on a computation of the minimum average velocity for a pipe during a day. The bed shear stress is the relevant parameter to estimate if sediment moves, as the velocity is just one of the parameters that go into the computation of the forces acting on a sediment particle.

3.2.2. The dimensionless bed shear stress

A computation of the dimensionless bed shear stress takes the properties (density and particle size) of the sediment into account. The locations where the dimensionless bed shear stress falls under the critical bed shear stress are equivalent to locations where sediment definitely deposit during a day of dry weather flow.

3.2.3. The time above the critical bed shear stress

The time span, where the dimensionless bed shear stress is above the critical bed shear stress, should be long enough to make sure that the particles are transported to the wastewater treatment plant. It is difficult to predict the exact period, during which the dimensionless bed shear stress must be above the critical bed shears stress, but a first order estimate is the travel time for a particle to pass from upstream to downstream of the sewer system during dry weather flow.

3.2.4. The local mass balance for sediments

A computation of the local sediment continuity balance will reveal if the downstream capacity of the sediment transport is smaller than the upstream sediment transport capacity (**Mark 1992**). This may be the case due to local backwater. If the downstream sediment transport capacity is smaller than the upstream input, the sediment will deposit locally until the upstream input falls below the downstream sediment transport capacity.

3.2.5. A fully dynamic morphological model simulation

A fully dynamic morphological model simulation combines all the items mentioned above. Nevertheless, it has shortcomings. The initial conditions for sediment deposits are unknown, and the loads in terms of sediment input at the upstream boundary conditions are unknown. One way to get around this is to start a morphological sediment transport simulation with a thin layer of sediments (e.g. 0.5 cm) in all pipes (**Mark 1992; Mark et al., 1996b**). A simulation should run for 1 week in order to see where sediments deposit and build up. However, as the sediment input to the model is unknown and therefore set to zero, the results of such a simulation are still only indicative of where sediment deposits will be found in a sewer/drainage system.

Bertrand-Krajewski et al. (2006) proposed an alternative approach to modelling of sediment accumulation in sewers, where they reproduce asymptotic sediment volume accumulation by means of a three parameter conceptual model. For all morphological models, it should be noted that they are very sensitive to a very accurate description of the geometry of the sewers and model parameters. One way to understand sediment deposits and morphological modelling better is to model flushing operations, aiming at flushing away sediment deposits. Such modelling has been carried out by Creaco and Bertrand-Krajewski (2009), who tested four different sediment transport formula. They found good correlations between the modelled and measured sediment depths during flushing in real life in the Lacassagne trunk sewer in Lyon, France.

More research on how to keep sewers self-cleansing in the future is required. It would be desirable to have some globally valid models, which describe the conditions for self-cleansing pipes as a function of pipe geometry, flow/depth/bed shear stress and sediment characteristics. From a research point of view, a global applicable model for “non-deposit”/self-cleansing sewers is within reach.

3.3. The sewer as a physical, biological and chemical reactor

In order to model water quality in sewers it is necessary to acknowledge the different types of sewers and their individual water quality characteristics. Generally, all sewers can be divided into three categories:

1. *Storm sewers* – dominated by transport of rainwater, i.e. mainly runoff during rain events from the urban areas. Typically, stormwater runoff has low concentrations of pollution[1], and the transport time for the storm sewer system is often fairly short from a few minutes up to a few hours. If the transport time is short, and the concentrations are low, the aerobic conditions will govern, and there will be a low level of transformation and biological activity in the storm sewer.
2. *Sanitary sewers* – transport the wastewater from residential, commercial and industrial areas. Depending on the local layout of the sewer system, the wastewater may be carried by gravity or pumped (in areas with insufficient slope). The time of concentration for sanitary sewers may be from a few hours up to 1-2 days. Typically, the wastewater has high concentrations of pollution and biodegradable material, and therefore sanitary wastewater sewers may have high biological activity. If the transport time is long (more than approx. 4-6 hours), then anaerobic conditions can occur, with subsequent development of hydrogen sulphide.
3. *Combined sewers* – transport wastewater during dry weather and transport a mixture of wastewater and runoff from the urban areas during rain events. The transport time in a combined sewer system varies depending on the conditions. During dry weather flow, the combined sewers act like the sanitary sewers and may have a transport time from a few hours up to 1-2 days. However, during rain events, rainwater with lower concentration enters the sewers, and the transport time of water to the wastewater treatment plant is significantly shortened. When a combined sewer system is overloaded, the excess water is discharged into the receiving waters, e.g. a river, lake or a coastal area, and the combined sewer overflow may cause a serious deterioration of the water quality in the receiving waters.

Even though sometimes a first flush with wash-off from streets may exist.

The impacts of combined sewer overflow from sewer systems on recipients can be split into four distinct problems:

1. Hydraulic overload potentially causing erosion and flooding
2. Toxic impact due to un-ionized ammonia
3. Oxygen depletion
4. Hygienic problems caused by pathogens

In addition to the impacts from overflows, issues and challenges may exist in relation to the sewer system, such as:

1. Corrosion due to the generation of hydrogen sulphide
2. Odor problems outside the sewer system, also due to hydrogen sulphide
3. Reduced performance of the wastewater treatment plant due to large variations of the concentrations in the inflow to the treatment plant

The selection of an appropriate modelling approach for water quality in sewers depends on the type of sewer system and the nature of the problem of the recipient. Modelling of un-ionized ammonia in a combined sewer system may be accurately computed for a known load in the sewer system by applying an advection-dispersion model, which considers ammonia to be a conservative substance (**Mark et al., 1996a**). Nevertheless, it is necessary to include biological and chemical processes to model hydrogen sulfide in a pumped wastewater pipe, e.g. with a retention time of more than 4-6 hours (Erichsen et al., 1999; Vollertsen et al., 2013; Hvitved-Jacobsen et al., 2013; Vollertsen et al., 2014). The following sections focus on the applicability of different modelling approaches to different types of water quality problems in sewers.

3.4. Modelling of water quality

Modelling of water quality in sewers is a challenging task, which assumes that *both* the hydrodynamic and the water quality models are built and verified systematically. The calibration of the hydrodynamic model is of utmost importance as an error in the hydrodynamic model is carried on to the water quality model, e.g. a volume error of 10% too much water in the hydrodynamic model will directly imply that the concentration of pollution in the water quality model will be approx. 10% too small.

A strength of deterministic models within modelling of water quality in sewers lies in an increased understanding of the individual processes and their interaction. Deterministic modelling of water quality in sewers and urban drainage can be divided into two groups:

1. Quasi-conservative pollution
2. Non-conservative pollution

3.5. Modelling of "Quasi-Conservative Pollution"

The term "*Quasi-Conservative Pollution*" covers contaminants that do not go through a significant transformation during the time they stay in the sewer system. Ammonia and phosphorus are water quality parameters which are certainly not 100% conservative, but in most cases they can be modelled with sufficient accuracy under the assumption of being conservative (**Mark et al., 1996a, Mark et al., 1998b**).

Dissolved quasi-conservative pollution can typically be modelled by assigning measured concentrations to the wastewater and to the rain. Typically, concentrations in rain are significantly lower than concentrations in wastewater. The resulting concentration in the sewers is then effectively wastewater diluted with rainwater. At this point, it is important that the model applied for the pollution modelling has a good representation of the transport of pollution inside each pipe – and that it has a good description of the mixing processes inside manholes. The water quality model must have computational grid points within each pipe; otherwise, there will be too much numerical dispersion in long pipes resulting in peak concentrations being reduced too much (Guymer et al., 1998).

At present, modelling of the dissolved pollutant transport (with slow transformation processes) can be simulated by using an advection-dispersion model like MOUSE TRAP (**Mark et al., 1995; Garsdal et al., 1995**). Models transporting pollution with pure advection (no dispersion) are InfoWorks (Bouteligier et al., 2001) and the SWMM models (EPA SWMM, XP SWMM and MIKE SWMM) (Huber and Dickinson, 1998).

Basically, the advection-dispersion model has only one calibration parameter, as the computation of the advection of the pollution depends entirely on the water levels, flows and velocities computed by the hydrodynamic model (**Mark et al., 1998a**). The calibration parameter is the dispersion coefficient (**Mark et al., 2010**). In order to determine the dispersion coefficient, a tracer measurement can be carried out with salt, rhodamine, uranine or a similar substance. The model can also be calibrated based on measurements during a rainfall of a quasi-conservative pollutant like ammonia. However, it is highly recommended to perform a tracer study, which will verify whether the model is able to accurately describe the transport of a conservative substance under known and "controlled" flow conditions. In addition to determining the dispersion coefficient, tracer measurements serve several other purposes:

1. Verification of the assumptions concerning the infiltration of groundwater into the sewer system
2. Fine-tuning the roughness (Manning numbers) of the sewers included in the tracer measurement
3. Validation of the capability of the model to describe the transport of the dissolved pollutants
4. General verification of the hydrodynamic model

If an advection-dispersion model cannot be calibrated to a level where it reproduces the results from a tracer study, there is no reason to continue modelling anything related to water quality. Results from a tracer study and the corresponding advection-dispersion modelling of the city of Sundsvall, Sweden is shown in Figure 4 (Mark et al., 1998c). The results in Figure 4 point to the fact that the hydrodynamic model needs to be slightly recalibrated. The measured tracer has a minor delay of approx. 15 minutes, which suggests that the roughness in the pipes should be increased.

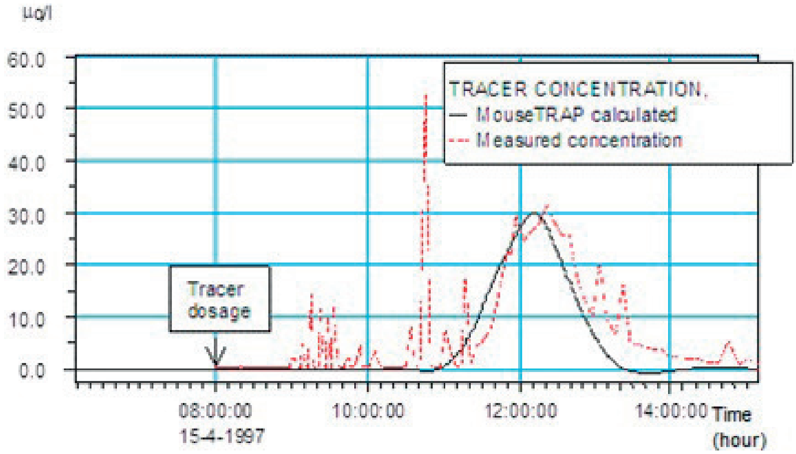

Figure 4. Tracer study results compared to initial advection-dispersion modelling results for Sundsvall, Sweden (Mark et al., 1998c). Based on these results, the model was recalibrated

3.5.1. Long-term simulation of pollution in sewers

During the 1990s, the fast increase in computational speed made it possible to carry out hydrodynamic and water quality simulations by applying deterministic models. These models allow for the computation of annual loads of pollutants to the wastewater treatment plant or annual loads of pollution discharged from combined sewer overflows. In addition, modelling extreme events can show how the rise of combined sewer overflow discharges of water and pollutants may potentially kill fish. Long-term simulations typically require data spanning from three to five times the return period of interest. Simulation results for a three-month period after applying an advection-dispersion model for modelling of various water quality parameters can be seen in Figure 5 for the Helsingborg sewer system in Sweden (Magnusson et al., 1998).

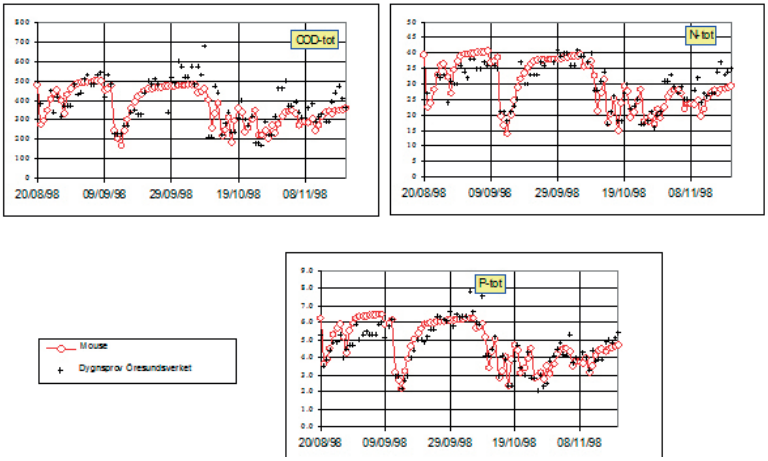

Figure 5. Measured wastewater quality compared to simulated advection-dispersion results for a long-term (three months) simulation of wet weather conditions (analyzed 24 hourly values) for Helsingborg, Sweden, (Magnusson et al., 1998)

3.6. Modelling of "Non-Conservative Pollution"

The term "*Non-Conservative Pollution*" covers situations where biological and chemical processes play a significant role during the time when the water passes through the sewer/drainage system. In this case, modelling of pollution by using an advection-dispersion model alone will be inadequate and give misleading results. Some examples of *Non-Conservative Pollution* are Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), hydrogen sulfide and some bacteria. However, if the sewer system has a short transport time, BOD and COD may be modelled, ignoring the water quality processes. Further, if the transport time is short, less than 4-6 hours, then hydrogen sulfide may not be formed, as the biological conditions in the sewer must become anaerobic first. However, if there is a contribution to BOD and COD from erosion of sediment deposits in the sewers, modelling of sediments must be included. Pollution, especially BOD, COD and phosphorous, may be attached to sediments (Crabtree, 1989; IWA, 2003). When suspended sediment or sediment deposits occur in sewers, it is of utmost importance to apply a model that can simulate the sediment transport processes, including erosion and deposition of sediments. Principles for modelling of sediment transport in sewers can be found in **Mark et al. (1995)** and IWA (2003).

Modelling non-conservative pollution in sewers must be carried out by computing the water quality processes based on the outcome of an advection-dispersion model (**Garsdal et al., 1995**). Modelling the transformation of pollution in a sewer/drainage system may be carried out by applying a model based on decay rates (**Mark et al., 2010**), by using models based on the physical, biological and chemical processes (**Garsdal et al., 1995**) or by using a detailed description of ALL the water quality processes involved as it is seen in the WATS hydrogen sulphide model (Vollertsen et al., 2013, Hvitved-Jacobsen et al., 2013). The SWMM models (EPA SWMM, XP SWMM and MIKE SWMM) and the InfoWorks model only have the capability to simulate the advection transport of pollution in a sewer system.

In order to calibrate a water quality process model it is required to have a minimum of two stations measuring both hydraulic and water quality parameters in each pipeline of interest. This is because the water quality parameters which determine the transformation/process rate can only be found by comparing the measurements from two or more measurement stations lying in a sequence. Some typical water quality processes under aerobic conditions are shown in Figure 6. At present, all the water quality processes in Figure 6 can be modelled, but detailed measurements for calibration of each individual process are not available for practical purposes. Hence, standard parameters e.g. from laboratory experiments must be used, introducing some uncertainty, which must be overcome by use of sensitivity analyses.

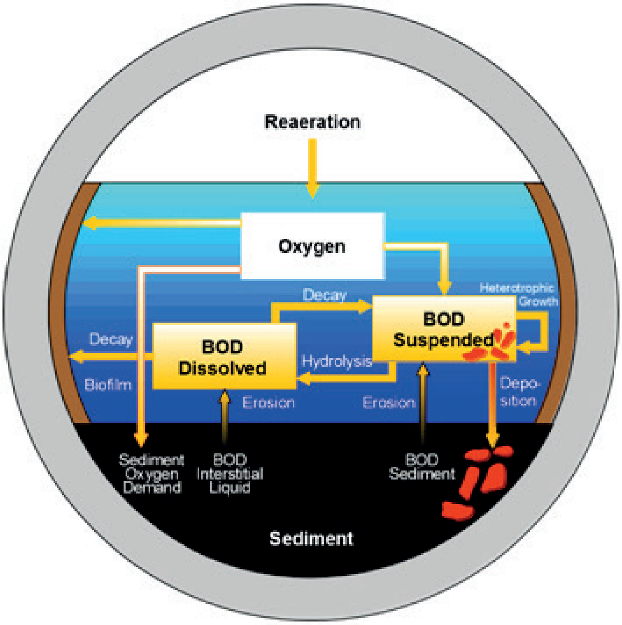

Figure 6. Water quality processes as can be modelled for wastewater under aerobic conditions (**Garsdal et al., 1995**)

3.6.1. Modelling of hydrogen sulfide and related corrosion of sewers

Understanding and modelling hydrogen sulfide (H_2S) is important as it introduces problems like odor and corrosion of pipes and metal constructions in sewers. When a sewer pipe collapses due to corrosion from hydrogen sulfide, it imposes huge costs to replace the damaged pipe. Furthermore, hydrogen sulfide is a toxic gas that poses a serious health risk to the sewer maintenance personnel and releases noxious odors to the city environment. Finally, hydrogen sulfide may cause inhibition of sewage treatment processes (Bentzen et al., 1995).

A high content of sulfide may be toxic to fish in streams affected by sewer overflow (Nielsen et al., 1992). Therefore, it is of high importance to understand and manage the phenomenon of hydrogen sulfide formation, and the development of modelling tools for the H_2S problems makes it possible to assess causes and alleviation measures.

Development of hydrogen sulfide occurs under anaerobic conditions in the sewers (Tanaka et al., 1998). In the early days (1970s), modelling of hydrogen sulfide was carried out with empirical equations (Thistlethwayte, 1972; Boon and Lister, 1975; Pomeroy and Parkhurst, 1976; Nielsen and Hvitved-Jacobsen, 1988). More hydrogen sulphide models have been developed, and they include almost all water quality processes seen from a theoretical point of view (Vollertsen et al., 2013; Hvitved-Jacobsen et al., 2013; Kjølby, 2015). Care should be taken when using the four empirical models mentioned above, as they have been developed using data from pressure mains and are therefore not generally applicable to all sewer systems. At present, the state-of-the-art model within H_2S modelling is the WATS model (Hvitved-Jacobsen et al., 2013). The WATS model applies an integrated aerobic and anaerobic concept for the transformation of organic matter and sulfur in wastewater (Hvitved-Jacobsen et al., 2013). An example of successful application of this rather complex model was modelling wastewater in the Estoril sewers in Portugal (Mourato et al., 2002).

In the laboratory, many of the individual processes have been described and measured. Based on laboratory experiments a number of models have been formulated, and the process parameters have been identified and measured. In real life it is almost impossible to measure the thickness of biofilm and sediment deposits along a considerable stretch of the sewer, as the composition of the sewerage varies during the day, week and even throughout the year. It might be possible to carry out measurements to get close to a snapshot of the biofilm conditions. This means that the present H_2S models cannot be calibrated to the traditional understanding as it is done for hydraulic models. However, Vollertsen et al. (2014) have recently calibrated and demonstrated the applicability of the WATTS model for the Bayside drainage area in San Francisco, US. The WATTS model was calibrated based on measured data from 12 measurement stations, and it was found that the model reproduced the general levels of wastewater H_2S concentrations, wastewater pH values and sewer H_2S gas levels, at levels suitable for practical applications.

Further research is required in order to identify/narrow the ranges of the H_2S model parameters and hence to reduce the number of calibration parameters. Finally, it would be a step forward if international standard laboratory procedures are developed so that wastewater samples can be analyzed and profiled, and the main H_2S model parameters are achieved easily. Albeit being difficult, H_2S modelling is still extremely useful for identification of locations with H_2S problems and for analyses of the impacts of mitigation measures.

3.6.2. A consistent procedure for modelling of water quality in sewers

In most cases, sediment affects the pollution significantly. In cases where the transport time of the sewer system is long (more than 4-6 hours) the interaction of BOD/COD and dissolved oxygen (DO) must be simulated in the model in order to produce reliable results. In the case where the oxygen level plays a significant role, a water quality process model is necessary, i.e. modelling of hydrogen sulfide. A consistent procedure for water quality modelling is outlined below. Each step in the modelling procedure must be completed and verified before continuing to the next step. If the model result is unsatisfactory at one of the steps, it is not possible to continue, as the result of each step depends on the success of the previous steps. The modelling procedure is as follows (Mark, 2005):

1. Carry out a tracer verification of the hydrodynamic model and use a pure advection or/and advection-dispersion model

2. Model a real quasi-conservative pollutant, e.g. ammonia, both for dry weather flow and for rain storms and verify whether the model reproduces the measurements
3. Analyze the ratio of dissolved and particulate COD/BOD and check if a first flush exists
4. If the water quality parameters in the study are attached to sediment, then include sediment transport modelling of the suspended solids
5. In order to determine the water quality process rates, obtain measurements of flow and pollution for relevant periods at an upstream and a downstream location in the sewer system
6. Model dissolved COD/BOD using the process rates from step 5
7. Model total COD/BOD as the outcome of the modelling of the dissolved COD/BOD and the sediment transport of particulate COD/BOD. Integrate modelling of sewers and urban drainage

3.7. Integrated modelling of urban drainage systems, the receiving waters and wastewater treatment plants

"Integrated modelling" in urban drainage is a term describing the modelling of the interaction between urban sewer/drainage systems, the receiving waters[2] and wastewater treatment plants. Most cities have these three components, and most people involved in the management of these systems will agree with the statement: "*It is logical and beneficial to plan, design and operate these components in an integrated manner*" (Rauch et al., 2002). But, in most parts of the world there have been fragmented planning, management and operation of sewer systems, wastewater treatment plants and the receiving waters. Furthermore, there is a general lack of methodology and technology for integrated planning and management and finally

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[2] Receiving waters are defined as groundwater, streams, rivers, lakes and the sea.

also a lack of regulatory frameworks for "Integrated Thinking". An exception to this rule is the procedure outlined in the Urban Pollution Management Manual in the UK (Foundation for Water Research, 1998).

The reasoning behind integrated management is old, and a number of different tools exist. The advent of computer models has perhaps been the biggest single factor in the development of integrated analysis. Historically, technological limitations have removed reality from integration, and independent pragmatic criteria for each component have been the norm (Rauch et al., 2002) as follows:

1. Sewers are typically designed to contain storm events of a particular return frequency without surcharging rather than to protect against flooding
2. Combined sewer overflows are engineered to pass forward flow dictated by downstream sewer or wastewater treatment plant capacity rather than to enable the receiving water to accept the overflows
3. Wastewater treatment plants are often designed to cope with an arbitrary multiple of dry weather flow rather than to treat all flows from the sewer system

As such, integrated modelling is a complex job – not only due to the sheer size of the system but also due to the different modelling approaches for each sub-system that have been developed. The hydrodynamics, in terms of flow and water levels, can be directly transferred between the sub-systems, but presently the frameworks for water quality modelling is handled differently in channels/rivers and at the wastewater treatment plant. This causes problems in the interface and data transfer between the sub-systems, which influences the precision of modelling the water quality processes. Here, it must be stressed that the water quality processes and the transformation of wastewater in sewers are not identical to the water quality processes in activated sludge and biofilm systems. Hence, modelling of water quality in sewers and in wastewater treatment plants is different, and it is not straightforward to link all water quality parameters and processes between these two systems (Rauch et al., 2002). During the past decades, modelling of water quality in sewers has been seen as a unique discipline even though similarities exist between processes in sewer systems and processes in wastewater treatment plants. Preferably, the modelling and analysis of sewers and wastewater treatment plants should be built on the same general equations and principles, so the modelling interface between the sewer system and the wastewater treatment plant is well defined and consistent. Similarly, the modelling carried out by using integrated models should pursue an integrated understanding and management of the sewers, the wastewater treatment plant and the receiving waters (**Mark et al., 1998b;** Clifforde et al., 1999; **Mark et al., 1999**; Williams and Mark, 2000; Tomicic et al., 2001; Rauch et al., 2002).

As more and more authorities want to embrace integrated analyses and modelling, the importance of water quality modelling has increased. Research focus is right now on both the amount of water and the water quality in sewers as design parameters for wastewater treatment plants and for integrated real-time operation (**Mark et al., 1998b,** Møller et al., 2015). At present, the models of wastewater treatment plant send set points and control information back to the operational model of the sewer system without considering the water quality. Even without using information about the water quality, the integrated hydrodynamic real-time systems have in real-life cases proven to be 30% more cost-efficient than traditional structural measures like building basins, bigger pipes and pumps (Møller et al., 2015).

3.7.1. Forecast of water quality to wastewater treatment plants

Holistic analysis of the sewer system, the wastewater treatment plant and the receiving waters is an emerging area with potential for integrated analysis of the overall performance (**Mark et al., 1998b**). The sewer system and the water quality processes in the sewers play a fundamental role in this analysis. More information and solutions concerning modelling of water quality in sewers become available, and as a result, better and more sustainable solutions may hopefully be developed for management of wastewater in the sewer systems.

Currently, the integrated real-time operation of the sewer system and the wastewater treatment plant takes place based on analysis of the hydraulics only. It is estimated that there is an unlocked potential for an even better optimisation; if, for example, ammonia concentrations can be forecasted 3-4 hours ahead during rain, this will result in operational gains at the wastewater treatment plant. Today, the mathematical models are capable of carrying out such simulations in an off-line environment, but so far, the models have not been applied in real time (Hassan, 2017). Here, tracer measurements are required under different flow conditions in order to validate the modelling framework. Finally, real-time data assimilation will be desirable for simulation of ammonia concentrations in order to correct for unforeseen industrial loadings to the sewers.

3.7.2. Modelling of the impacts of combined sewer overflows on bathing water quality

Today, modelling of the water quality in overflows has become increasingly important in order to understand and manage bathing water information systems in real time (Andersen et al., 2013) as well as to apply real-time control for reduction of the impacts of sewer overflows.

Pathogens in sewers are not problematic as long as they stay inside the sewer system. However, when pathogens leave the sewer system, either in reduced numbers after wastewater treatment, through an overflow or during an urban flood event, they may pose a health risk to the people in contact with the contaminated water. These will typically be people bathing in a recipient that has been exposed to combined sewer overflow or people wading in urban floodwater (Mark et al., 2002b; Mark et al., 2002c). Experiences from modelling of faecal Coliform bacteria in receiving waters have shown that Coliform bacteria cannot be considered conservative or without natural decay (Evison, 1986), e.g. in the sea where the main controlling parameters for bacterial decay are salinity, temperature and light intensity (Tomicic et al., 2001).

Little information is currently available concerning the transport of pathogens in sewers, and it is therefore recommended to model pathogens in sewers as a conservative substance until further research is carried out on this topic. Preliminary research results have shown that for sewer systems with a short transport time, accurate modelling results can be achieved by assuming the pathogens to be conservative, as shown in Figure 7 (Andersen et al., 2015), or by having a first order decay rate (Rauch et al., 2002).

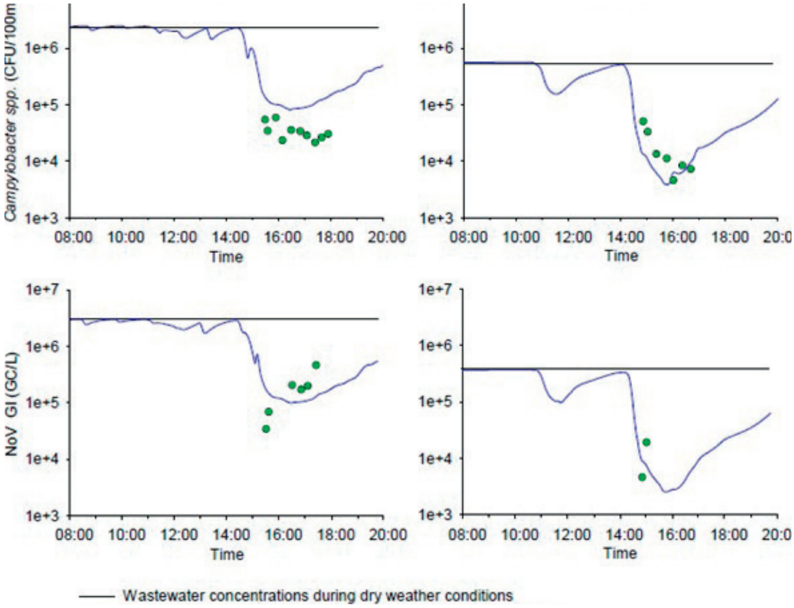

Figure 7. Campylobacter and Norovirus GI in wastewater during dry weather conditions, tailed by a rain event. Locations: two combined sewer overflow structures, U110 and U122 in Damhusåen catchment, Denmark (Andersen et al., 2015).

Modelling the health risk due to bathing in polluted water is typically based on modelling of *E. coli* followed by quantitative microbial risk assessment (QMRA). A hydrodynamic model in combination with a water quality model of the sewer system may compute the overflow etc. Transport, dilution and water quality processes in the recipient can then be computed e.g. with a 3D hydrodynamic model. This methodology has been validated for an overflow event in connection with an ironman competition (Andersen et al., 2013). Simulation using the hydrodynamic model of the recipient in conjunction with a water quality model showed that the contribution from the combined sewer overflow resulted in 0.13% of wastewater in the bathing water at the time of the ironman competition. The total estimated incidence rate from the quantitative microbial risk assessment of the pathogenic load of five reference pathogens was 42%, compared to 55% in an epidemiological research study covering the same case (Harder et al., 2010). This must be compared to the incidence rate from the same iron man competition the following year, which was around 2-6% at a time when the bathing water was not polluted (Andersen et al., 2013).

The quality of an integrated model for an urban drainage system depends strongly on the quality of the water quality sewer model, which today is the weakest link in the integrated modelling. Despite these uncertainties, integrated modelling is still very valuable, and this type of modelling will definitely dominate the future. Today, the main challenge for integrated management of urban water systems is to change the legislation from optimization of each individual sub-system to a performance evaluation of an integrated management of the wastewater system.

4. Modelling of urban flooding

When a city is flooded, it may be due to a number of individual causes such as flooding from a river (riverine flooding), local rain over the city (pluvial flooding) or high water levels at sea (coastal flooding)[3], or a combination of these causes.

Flooding in urban areas is an unavoidable problem for nearly all cities worldwide, and it causes immense costs to the society, both in terms of direct and indirect flood damages. Issues due to urban flooding range from minor problems, such as water entering the basements of a few houses, to critical incidents, where large parts of a country and its cities are inundated for several days, people are killed and huge values are lost; an example is the incident in Thailand in 2011 (HAII, 2012).

Cities in developed countries typically have small size flood problems, i.e. water logging due to insufficient sewer/drainage capacity. However, even developed cities can still be struck by unprecedented rainfall and taken by surprise, as it has happened to the city of Copenhagen on 2 July 2011. In Copenhagen, vast parts of the city were flooded with up to knee-high water levels in the streets. The damages from this flood event are estimated to be in the order of 1 billion USD. Other examples of cities experiencing serious urban flooding problems are Beijing, China; Dhaka, Bangladesh; Ho Chi Min City, Vietnam; Huston, Texas, US; Mumbai, India; Nice, France, and Phnom Penh, Cambodia (**Mark et al., 2004**).

The flood problems are further aggravated and the flood risk increased, as cities in China and other developing countries grow very fast (**Parkinson and Mark, 2005**), and planning methodology and funds are insufficient or unavailable to expand existing drainage systems. However, novel modelling methods are surfacing to study the full urban water cycle, where stormwater management and water resources management analysis are combined in order to achieve full understanding of

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[3] In the following, the term "urban flooding" is used with respect to pluvial flooding

the hydrological processes (stormwater infiltration, groundwater levels, water balance) of a catchment area, aiming at sustainable urban developments (Locatelli et al., 2017). Finally, climate change predictions foresee an increase in the extreme rainfall events in most parts of the world (**Mark et al., 2008**; Djordjević et al., 2011; Quevauviller et al., 2012), and this will further increase the urban flood problems significantly.

4.1. Physically based deterministic modelling of urban flooding

When the computer model for urban drainage and sewer systems surfaced in the 1980s, the computers were too slow, and they had insufficient memory to handle both the simulation of the flow in the pipes/drains and the surface flow on the terrain. Hence, the first urban flood simulations only simulated the location in the network with insufficient capacity, and they did not simulate the extent of the urban floods. Simulations of the extent and movement of the surface floods were not carried out until the middle of the 1990s. In the mid-1990s a new urban flood modelling approach was developed using hydrodynamic simulations for the pipes/drains below the surface coupled with simulations of the surface flow, which was carried out by pseudo-2D modelling based on 1D hydrodynamic modelling with flood storage (**Mark et al., 2004**). An accurate description of the terrain was made feasible as comprehensive, high-resolution urban digital terrain models became available, and these turned out to be some of the most important inputs to urban flood modelling. The high-resolution digital terrain data came from the new remote sensing technology (aerial photos, satellite data) and were converted into urban digital GIS maps. The GIS maps were used for computing flood storages (**Mark et al., 1997;** Mark et al., 1998c) and for identification of the street slopes and other features in the 1D model on the surface. In addition to the terrain models, the digital maps were used to identify impervious surface areas and catchment area boundaries. The concept of a 1D-1D urban flood model can be seen in Figure 8.

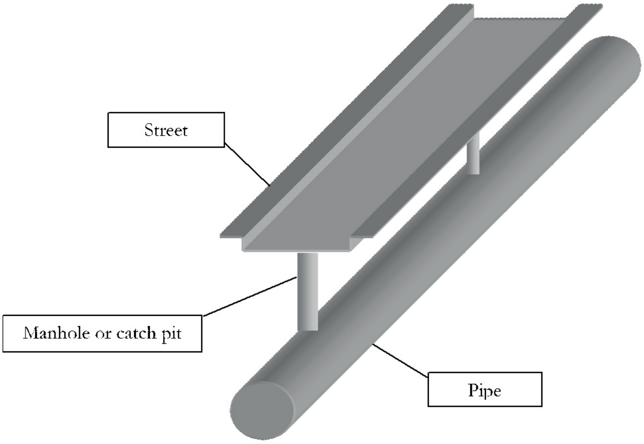

Figure 8. Sketch of the 1D-1D flood model. A pipe below ground connected to a street on the surface of the terrain (**Mark et al., 2004**)

This 1D-1D flood simulation method was applied worldwide for simulating urban floods, e.g. in Dhaka, Bangladesh (Djordjević et al., 1999; Mark et al., 2001), during the storm "Allison" in Texas, US (Holder et al., 2002) and in Bangkok, Thailand (Boonya-Aroonnet et al., 2002). The method has proven to be accurate and applicable to large, densely populated cities both in the industrialised as well as in the developing countries (Figure 9).

During the period 2003-2006, models were developed which simultaneously simulated the 1D sewer/drainage network model (**Mark et al., 2004**) and the 2D surface flow (Alam, 2003; Carr and Smith, 2006; Chen et al., 2005; Mark and Djordjević, 2006). The 1D-2D modelling approach provided easier and more accurate analysis of overland flow than the 1D/1D approach. Further, the 1D-2D flood modelling is easier to use, as there is no need to verify whether the 1D flow assumption in the streets and the surrounding areas is valid during the floods, which makes verification rather laborious for large flood extents. However, the 2D flood models require more computational time as the time steps can be up to one order of magnitude smaller than for the 1D-flood models, and the number of computational cells can be 2-3 magnitudes higher than for a 1D-flood model. The first 2D surface models were based on uniform Cartesian grids, meaning that the cell sizes were the same for the whole model area. Some physical features in a city need to be resolved with a resolution of approx. 2-2.5 m **(Mark et al., 2004)**, which means that the number of computational grid cells in an urban flood model becomes a limiting factor for the size of the model area, as common urban flood models typically cover an area of 20-100 km^2.

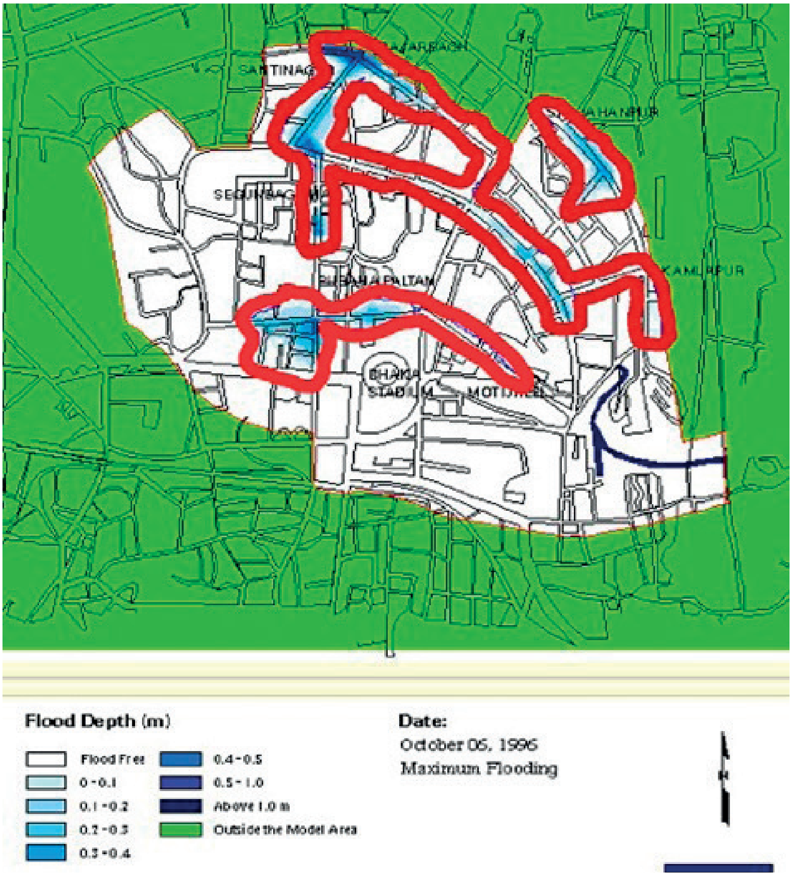

Figure 9. Comparison of simulated flood depths (blue) with observed flood extent (red lines) for the flood in Dhaka City 1996 (**Mark et al., 2004**)

As a response to the problem of the required high number of grid cells, alternative modelling approaches were developed to speed up the simulations by means of multiple nested computational meshes, which made it possible to model whole cities such as Beijing, China, which covers 1000 km^2 (Hénonin et al., 2015). A different modelling approach is to apply pure GIS analysis without any time dimension in the modelling. Such an approach is excellent for screening of locations for potential flood problems. However, it is a limiting factor that the flood modelling approaches do not include the true physics of the sewer/drainage system below ground and that backwater cannot be described. Hence, this type of flood modelling is only suited for problem identification and fast screening of alternative mitigation measures on the terrain, where detailed 1D-2D flood simulations are still required for the detailed design of mitigation measures.

4.2. Modelling of the impacts of climate change

In spite of the computational limitations, the 1D-2D Cartesian models still opened for a completely new suite of analysis, e.g. analysis of today's flood risks and analysis of the impacts of climate change. Analyses of the impacts of climate change were timely supported by methods for prediction of future design rains, e.g. in the year 2100 (Spildevandskomiteen, 2008). At the same time, a consistent framework was outlined for modelling the impacts of climate change in cities (**Mark et al., 2008**; Paludan et al., 2010). The framework outlined data requirements, model limitations and applicability for different analyses and applications.

One outcome of the new technological progress, supplemented with a concise modelling framework, was a local Danish directive (The Danish Nature Agency, 2013; Spildevandskomiteen, 2017). The directive stated that all Danish municipalities had to map today's flood risk together with the flood risk under the future climate conditions. After the flood risk mapping exercise, the municipalities had to out-line climate mitigation measures at an appropriate level (The Danish Nature Agency, 2013). The development of the novel flood risk modelling framework facilitated knowledge-based decisions for protecting the Danish society from the impacts of extreme rainfall under future climate changes. In addition to simulations of the future climate conditions, simulations of today's climate conditions were carried out in order to "pick the low hanging fruits", aiming at a fast implementation to reduce the worst flood damages for today's climate. An example is shown in Figure 10, where the flood risk can be seen for a Danish city in the year 2100 for rain with a 10-year return period for climate scenario A2. Further, Figure 11 shows conditions for the same rainfall, but here a climate adaptation measure has been implemented in the form of a football field, which is used actively as flood storage.

Figure 10. Simulated flooding for climate scenario A2 for rain with a 10-year return period in 2100 (Paludan et al., 2010)

Figure 11. Simulated flooding for climate scenario A2 for the same rain as in Figure 10. The football field is used as flood storage (Paludan et al., 2010)

4.2.1. Flood damages

The main objective of simulating the flood hazard for a future climate is to protect the society in a cost efficient way. One way to compute the cost related to flooding in urban areas is to compute the flood risk by collecting information about historical flood incidents from insurance companies, e.g. as done in Norway (König et al., 2002) or Brazil (Nascimento et al., 2005). An alternative technique is to quantify the damage by using "Flood Damage Curves" describing the extent of the damage as a function of land use and water level (Nascimento et al., 2005). Hammond et al. (2015) present state-of-the-art in urban flood impact assessment and apply it as part of the Drivers-Pressures-States-Impacts-Response (DPSIR) framework on several urban flood cases on the CORFU project (Djordjević et al., 2011). Currently, such "Flood Damage Curves" are only available for few places around the world, but they can easily be developed. When dealing with flood damages, the following issues should be included in an assessment of damage related to flooding (Paludan et al., 2010):

1. Prevent that the population is brought into contact with a mixture of sewage water and rainwater due to overloading of the drainage systems
2. Vital community functions, such as electricity supply, water supply, heat supply, communication points and hospitals are not out of operation due to flooding
3. The number of affected basements and buildings is minimized
4. The number of flooded electrical power cabinets and equipment is minimized
5. The impact of flooding on traffic is minimized

4.2.2. Modelling of climate adaptation measures

Climate adaptation measures consist of the traditional measures to increase the capacity of a pipe/drainage system (pipes, basins, pumps etc.) and elements of green infrastructure, nicknamed LIDS or SUDS. The prediction of future climate conditions forecasts that extreme rainfalls will increase by 20-30% demanding the implementation of climate adaptation measures in order to maintain today's flood service levels for the public (**Mark et al., 2008**). In many places, the cities are heavily built-up, and it is rather expensive to dig into the ground and expand the pipe system. Research has therefore been directed towards reducing the inflow to the drainage/sewer systems by means of green roofs (Villarreal and Bengtsson, 2005; Locatelli et al., 2017) or by infiltrating part of the rainwater into the ground , e.g. through soakaways (Bergman et al., 2011; Roldin et al., 2012b; Roldin et al., 2013). Here, it should be noted that green roofs may have a side effect when used for reduction of runoff, i.e. a green roof may generate a first flush of pollution (Berndtsson et al., 2008), and research shows that green roofs are a source of contaminants (Berndtsson et al., 2006); a phenomenon that is mostly ignored. Further, green roofs must be used with care for climate adaptation, as they may reduce the runoff by 50-60% on an annual basis, whereas the reduction in runoff during extreme rain events may only be in the order of 10-15% of the rainfall (Locatelli et al., 2017).

The traditional 1D-2D urban flood models only simulate the flow in the pipes/drainage system with an impervious 2D surface flow model (**Hénonin et al., 2013**). In order to simulate infiltration from pervious surfaces, new concepts of modelling urban floodwater interaction with groundwater were developed replacing the 2D impervious flow model by a 3D groundwater model (MIKE SHE) (**Domingo et al., 2010a**) (Figure 12). **Domingo et al. (2010a)** demonstrated that for a highly urbanized area built on moraine soils, the infiltration from the surface is insignificant during the actual flood event (Figure 13). The reasoning and the analysis behind this finding were that they wanted to explore the impact from an increase of the soil moisture content to 100% during the onset of the rain, meaning that no infiltration could take place. The findings by **Domingo et al. (2010a)** cannot be generalized since sandy soils have much higher infiltration rates, implying that it is necessary to use a model that simulates infiltration, when sandy soils are dominant in the catchment area.

Furthermore, the modelling of the interaction between surface water and groundwater must be included in rural areas in order to obtain correct flood maps (Domingo et al., 2010b). Roldin et al. (2012a) extended their modelling concept with detailed mathematical formulations of the interaction between a partly full soakaway and the groundwater. They demonstrated that the interaction between the groundwater level and the infiltration capacity of soakaways strongly limits the use of soakaways as a climate adaptation measure in areas with high groundwater levels or soils with low permeability.

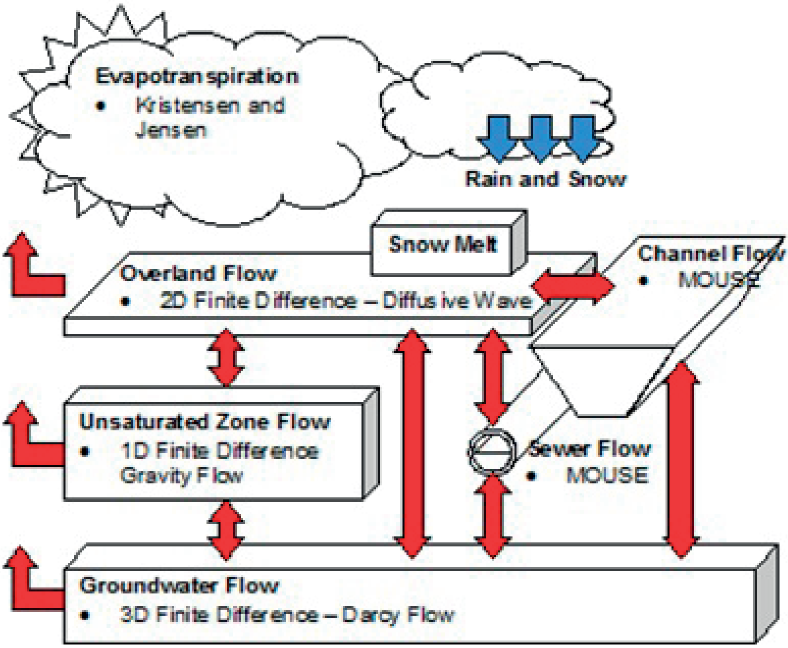

Figure 12. The modelling concept, adding the interaction between the overland flow and the 1D hydrodynamic pipe flow model with the groundwater. From (**Domingo et al., 2010a**)

Figure 13. Comparison of a traditional 1D-2D flood map from MIKE FLOOD (left) and MOUSE-SHE incl. ground water interaction (right). Case: Greve, Denmark, moraine soil. (**Domingo et al., 2010b**)

4.3. Real-time modelling

A real-time data stream provides information about the inputs and status of the system in the past and now. Adding a model to the real-time data collection system provides the means for adding value to the real-time data (**Mark et al., 2002a**). A model can be used to compute the status of the system between the locations of the real-time sensors (interpolation in space). The model can also be applied to forecast the future status of the system based on the real-time information and forecasted boundary conditions in the form of rainfall and water levels when relevant (extrapolation in time). The different levels of information depending on the availability of data and models can be seen in Figure 14.

Using a model together with real-time data provides an option for improving the information at that point in time and for forecasting the future status of the system, e.g. inflow to wastewater treatment plants, overflows and flooded areas (**Mark et al., 2002a**). The use of real-time forecasted information in combination with controlled devices (weirs, gates and pumps) and/or real-time management procedures can reduce problems significantly, and thus reduce the operational costs, environmental impacts and flood damages. The flow and water level data generated by a real-time information system can be useful as historical data for design and maintenance of the hydrological system. A real-time system can also be used to train operators.

A simple real-time forecast and mapping of the flooded areas and their flood risk provide the first level of information when the design capacity is exceeded. Such maps can be used in the pre-flood phase to prepare the emergency response from the authorities (**Parkinson and Mark, 2005**). The provision of real-time urban flood forecast requires both a reliable real-time data communication system (**Mark, et al., 2002a**) and some kind of model to forecast the flood hazard and risk.

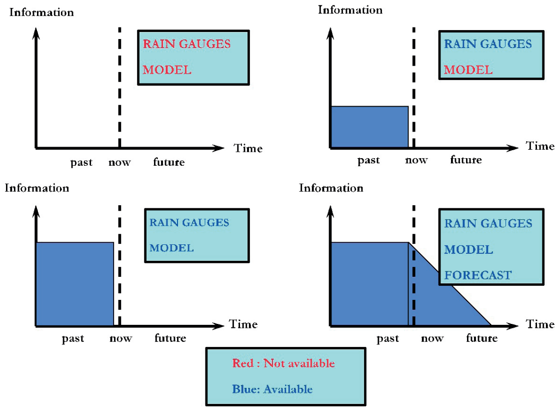

Figure 14. The level of information as a function of the application of: 1) No rain gauges and no model available. 2) Only rain gauges available. 3) Rain gauges and a model available. 4) Rain gauges, a model and a forecast available (**Mark et al., 2002a**)

Real-time flood forecasting for cities is an area, which is still emerging. However, it is surprising that only very few real-time urban flood forecast systems have been implemented, considering that all sewer and urban drainage systems are designed for a given return period. Meaning that the systems are designed to fail/flood when the rain exceeds the return period of the design, and flooding can more or less be expected with the same frequency as the return period of the design rainfall. Here a real-time flood warning is a cost efficient way to forecast overloads of sewer/drainage systems, as such a system extends the time to prepare a flood response before a flood occurs.

A worldwide survey with 176 participants investigated the use of real-time data for urban flood management together with the perceived challenges in getting hold of the necessary basic data to build a real-time urban flood information system (Rene et al., 2014). The research hypothesis was that the lack of real-time urban flood forecasting systems was related to the lack of relevant modelling data and real-time data. The conclusion of the research was that most of the people in the survey actually had the means and resources to perform real-time urban flood forecasts, but many were not aware of the fact that they actually already have what it takes to make a real-time urban flood forecast (Rene et al., 2014).

A real-time flood forecast system can be built in a number of different ways (Weesakul et al., 2003; **Hénonin et al., 2013**). The urban flood forecast systems range from a single real-time rain gauge or a numerical weather prediction model to 1D-2D hydrodynamic flood models forecasting in real-time the interaction between storm surge and pluvial flooding (Weesakul et al., 2004; Hénonin et al., 2015; Diez, 2016) (Figure 15). The modelling system is driven by data such as rainfall, flow, water levels at sea as well as rainfall forecasts from numerical weather prediction models. Urban flood forecast models can become rather complex so it is important to choose the simplest modelling complexity. However, it is still important to provide a forecast, which is sufficiently accurate for the purpose of the modelling as the ultimate objective of flood forecasting system is to provide an accurate and timely flood prediction (**Hénonin et al, 2013**).

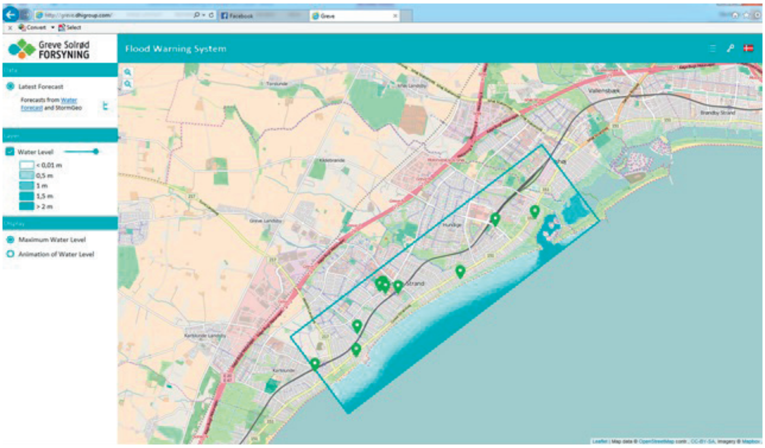

Figure 15. The MIKE FLOOD model for the coastal area of Greve in Denmark. The modelling system comprises the combination of a 2D hydrodynamic model for the sea, which continues inland as the 2D hydrodynamic surface model, and a 1D hydrodynamic model of the sewer system (Domingo et al., 2010b; Diez, 2016)

4.4. Urban flooding and health risk

Open sewer systems surfaced right after the epidemics in Europe during 1650-1670. However, many of the cities, like Copenhagen, were hit by Cholera in 1853 and the open sewers were abolished and replaced by new underground sewers. The sewers significantly reduced the human contact with wastewater and improved the health conditions. Since then, many thousands of kilometres of sewers have been constructed to transport human wastewater safely away from households. However, diseases are still spread, when sewage is mixed with floodwater and the population is exposed to the polluted floodwater.

At present, a number of cities have experienced severe flooding due to pluvial flooding, as the capacity of the sewers is too small, or they have been exposed to rainfall with a higher return period than what they are designed for. This results in situations where the population is wading in a mixture of rainwater and sewage during floods. Consequently, the population is exposed to sewage on the ground surface of the cities. The polluted floodwaters may reach and contaminate local drinking water wells or leaking water supply pipes. This unfortunate interaction between drinking water and floodwater may cause serious health problems and calls for an integrated water management policy (**Parkinson and Mark, 2005**).

Examples of diseases spread with urban floodwater mixed with sewage are cholera, diarrhea or leptospirosis, where leptospirosis is a bit special and difficult to model as it is spread by bacteria in the urine of rats. During the floods in the northeastern part of Thailand in September 2000, a total of 6 921 cases of leptospirosis were reported, of which 244 were fatal (Bangkok Post, 20 September 2000). During the flood in Copenhagen, Denmark on 2 July 2011, four cases of leptospirosis were reported, and one was fatal. Another health hazard is the risk of getting parasite infections from wading through or having other contacts with urban floodwater (Kolsky, 1998). Moreas (1996) studied parasite infections and found a correlation between flooding and parasite infections. He found that a decrease in the number of floods reduced the prevalence of hookworm alone by a factor of three and for roundworms and hookworms together by a factor of two. The best way to manage parasite problems is to break their life cycles. Here, intelligent flood management comes into play, as it removes the natural environment of the parasites, removes the transport and spreading of rat urine by flood water and hence reduces the number of infections and the health burden on the population.

Cholera outbreaks are not uncommon in Asia. The outbreaks are believed to follow two transmission routes. A primary transmission route of exposure is ingestion of polluted floodwater followed by a secondary direct or indirect person-to-person transmission. This situation triggered research into the link between infection risk and urban flooding (**Mark et al., 2015**). The research presented by **Mark et al., 2015** focused on the risk of getting cholera in Dhaka City during floods.

In order to simulate the health risk associated with urban flooding, Dhaka City was selected as the case area as this city is prone to urban floods (**Mark et al., 2004**). In Dhaka City the probability of contracting cholera from contact with urban floodwater can be high during flood events, when floodwater mixed with sewage is spread all over the city. In order to understand this health issue in more detail, a novel methodology research has added quantitative microbial risk assessment (QMRA) to urban flood models (**Mark et al., 2015**). To be able to simulate the health risk, the hydrodynamic flood models were expanded to include a simulation of floodwater transportation on the ground surface by use of an advection-dispersion model, which was then coupled to the advection-dispersion model in the 1D hydrodynamic drainage model (**Garsdal et al., 1995**).

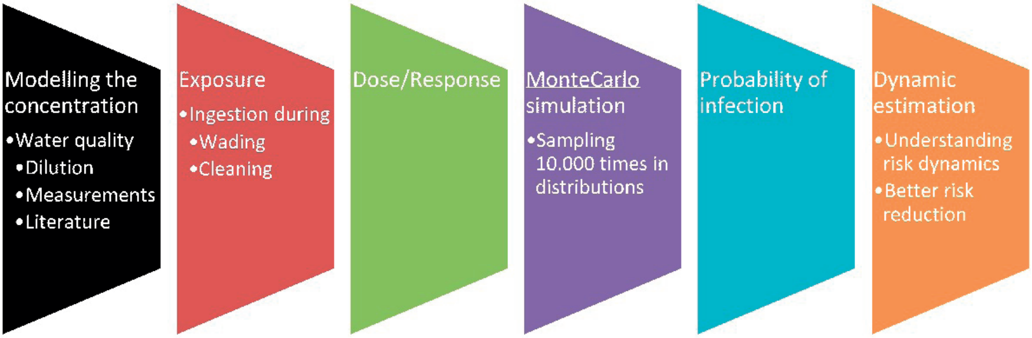

Figure 16. The full computational flow for estimation of the health risks from contact with urban floodwater in Dhaka City, Bangladesh (**Mark et al., 2015**)

In addition to the flow and concentration modelling results, the exposure (ingestion rates) was determined and a dose/response relation was developed. The health risk was then computed in connection with Enterococci, *E. coli*, *V. cholerae* and *V. cholerae* O1 El Tor for three flooded locations in Dhaka city. The results from the computations covering the health risk at three locations showed that direct environmental exposure during flooding results in an average cholera risk in the order of 5.2 × 10−5 to 2.2 × 10−3, where small children in slum areas have the highest risk (**Mark et al., 2015**). This computed health risk is in agreement with the overall incidence of severe cholera in Dhaka City, which was estimated in 2010 to be approximately 280 per 100000. Contact with polluted floodwater is therefore a plausible route of primary transmission of cholera and may partly explain the autumn cholera peak in Dhaka City.

The health risk assessment based on hydrodynamic modelling defines a consistent framework for the analysis of the health risks associated with direct urban floodwater contact (Figure 16). This framework offers a unique possibility for understanding the interaction between urban flooding and health risk caused by direct human contact with the floodwater and hence creating an opportunity for reducing the burden of disease in the population by intelligent urban flood risk management.

5. Current challenges in relation to deterministic modelling of urban drainage systems

In chapter 1-4, development and state-of-the-art deterministic modelling of urban sewer and drainage system during the past decades have been presented. The state-of-the-art modelling has some weak points and some knowledge gaps, which limit the possibility of achieving the full benefits of the developed models. These weak points are discussed in brief below.

5.1. Challenges in respect to modelling of water quality

Modelling of water quality in sewers is an emerging area as water quality and sediment transport processes are difficult to describe precisely by deterministic theories and models. However, it is at present feasible to model some water quality processes in sewers accurately, which provides very valuable information for practical purposes (**Mark et al., 1996a; Mark et al., 1998a; Mark et al., 1998b;** Mark et al., 2002b; Mark et al., 2002c; Mark and Erichsen, 2007; **Mark et al., 2010**). A basic modelling of the water quality provides a significantly higher level of knowledge and understanding compared to modelling water alone, e.g. when modelling combined sewer overflows. A number of practical operational problems in sewers push the research towards more robust urban drainage systems and practical solutions to handle significant problems. Some of the main drivers for modelling of water quality are:

1. Reduction of odor problem and corrosion of pipes due to formation of hydrogen sulphide
2. Optimization of wastewater treatment based on forecast of water quality to wastewater treatment plants
3. Health aspects in relation to urban floods

Water quality models exist to address the drivers mentioned above, but the full potential of the water quality models is not used. In the laboratory, many of the individual water quality processes have been identified and studied in detail (**Garsdal et al., 1995**, Hvitved-Jacobsen et al., 2013). The modelling of water quality in sewer and urban drainage systems has reached a point where the water quality models describe many individual water quality processes, such as oxygen update by biofilm, hydrolysis process between suspended as well as dissolved BOD and oxygen uptake from sediments (**Garsdal et al., 1995**; Hvitved-Jacobsen et al., 2013).

However, in real world sewers, very few water quality measurements have been carried out which means that many of the model parameters and their values originate from laboratory experiments. A number of the parameters in water quality models are "undetermined" when it comes to practical real life applications, and very few water quality modelling cases involving BOD/DO processes exist. Only very few of the possibilities for water quality modelling are used for practical applications at the moment. A way forward is to expand the water quality sampling programs in sewers and then to judge the value of the additional information versus the extra costs for the laboratory analysis. A quick fix within research and applications in relation to water quality modelling may be to combine the well-proved simulation of ammonia (for overflows) with real-time forecasts of flow into wastewater treatments plants, and to base a part of the wastewater treatment plant operation on the forecast. The first real-time forecasts of ammonia in a sewer system have shown promising results in terms of accuracy and robustness (Hassan, 2017). It is straightforward to establish and test a real life application of such a real-time system, which the operators of wastewater treatments plants can benefit from with respect to a more efficient operation.

More research on the link between urban floods and health risk is needed for other pathogens and for non-tropical conditions like the risk of getting a novovirus/*Campylobacter*/*Cryptosporidium* infection during floods in Europe. Presently, the projection for the future climate is that in many places around the world the number of extreme rainfall events will increase. In order to adapt to a future climate, cities worldwide consider directing floodwater into open green spaces instead of expanding the underground system of concrete pipes. From a financial point of view, there is often a lot of money to be saved by having a controlled flood in a green space compared to expanding the capacity of the sewer system. However, if a green space is flooded with a mixture of sewage and rainwater then there might be a health risk associated with using the green area some time (days) after it has been flooded with a mixture of sewage and rainwater. The question is how long does it take after the flood before it is safe to use the green area again for recreational purposes, such as for babies and children playing on the grass, picnics etc.,. Research into this area is currently taking place at DHI in association with the local authorities, and the outcome will be extremely valuable input to get cost-benefit computations of climate mitigations measures.

5.2. Challenges with respect to modelling of urban flooding

In the future, problems related to urban flooding are foreseen to expand as cities in the developing countries are growing rapidly (**Parkinson and Mark, 2005**), and climate change may increase the extreme rainfall events and violate with everyday service levels with respect to flooding. Urban flood problems will surface in places where they have not been experienced before. This poses a challenge for convincing people to carry out flood modelling events, even before they have experienced serious flood problems. The purpose of such flood modelling is to make people aware of the real flood risk so they can make a timely, informed decision about the flood protection of their cities.

In order to gain the full benefits of deterministic urban flood modelling there is a policy/communication challenge, which must be addressed. Flood maps should be part of the daily planning and not something, which is only carried out after a flood has occurred. Urban flood models are typically only calibrated against a few locations where only the max flood depth is recorded. This means that the flood component of an urban drainage model is often calibrated with fewer data than the 1-D pipe flow model. Hence, there is then a higher degree of uncertainty about the computed flood depth compared to the water depth in the pipes/drains. This uncertainty can be reduced by collecting more flood data during flood events so the validation of the flood model related to time and space is improved. This can be done e.g. by using drones or remote sensing data. At present, there are a number of places where the modelling of urban flooding can easily be extended to overcome some simple gaps as follows:

1. Citywide flood modelling
2. Modelling of runoff from green areas
3. Real-time urban flood forecast

5.2.1. Citywide flood modelling

During the past decade, urban flood modelling has focused on developing flood computations with a sufficiently high accuracy and resolution in order to describe the flood problem within an acceptable amount of computational time **(Mark et al., 2004)**. Challenges still exist when a city area is split into a number of sub-areas and models, where floodwater simulated in one sub-model needs to be transferred into the neighbouring sub-model in order to get a correct flood map of the city areas. It seems to be a tedious and slow process to split a city into a number of sub-models in order to identify locations with flood problems. Citywide flood modelling of mega-cities is a huge step forward, like it has been done in Beijing, China, which covers 1000 km^2 (Hénonin et al., 2015).

At present, however, the citywide modelling of urban flooding does not directly take the capacity of the sewer/drainage system into consideration. Presently, the citywide modelling can only be used for problem identification. After the problem has been identified, the problem must be analyzed in a sub-model (1D-2D) where care must be taken in order to get the correct definition of model boundaries etc. There is a need for significantly more computational power or new modelling approaches, which can describe mega cities in a very high resolution (Chen et al., 2012).

5.2.2. Modelling of runoff from green areas

Traditionally, many sewer systems around the world were designed assuming that the green areas (lawns, parks etc.) did not contribute to the runoff, or assuming that a fixed percentage of the green area generated runoff. This is a fair assumption for the design procedure of combined sewer systems and urban drainage systems as long as no significant overland flow occurs on/from the green areas[4]. At present, the modellers expose their computer model of the cities to design storms with a 100-year return period or even a future 100-year design storm in order to compute a "worst case" scenario today and under future climate conditions. This kind of analysis of the flood impact from a 100-year storm makes it vital to model the green areas and their runoff in details. The present modelling of the runoff from green areas creates a problem when the return period of the then rain becomes very high (more than 10-20 years). The infiltration capacity of the green areas is exceeded, and the green areas may then act as impervious areas.

A few modelling shortcuts exist to simulate the process by approximating the infiltration of the green area with an initial loss, or by letting the rain fall directly on the 2D terrain model of the flood model and then simulating the surface runoff only by using a 2D hydrodynamic model with a description of infiltration. This model gives problems with the impervious

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[4] Depending on local conditions, the assumption, that no overland flow occurs on/from the green areas, approximately corresponds to a rain with a 10 years return period in Denmark.

areas as the runoff is now overestimated due to the fact that the 2D terrain model does not include relevant hydrological processes such as “initial loss” and “hydrological reduction factor” etc. From a mathematical modelling point of view, it is a simple task to develop a consistent modelling framework with 2D surface models for green areas, as it has already been done for several lumped urban hydrological models (Terstriep and Stall, 1974; Lindberg, et al., 1986, 1989). Hence, a model for the infiltration and a set of equations to keep track of the soil moisture etc. must be included in the 2D hydrodynamic models, and when this has been completed the modelling framework must be tested and calibrated against measured runoff from green areas.

5.2.3. Real-time urban flood forecast

Sewers and drainage systems will never be designed in a way so that flooding does not occur. There will always be a residual flood risk. This flood risk can be handled efficiently with real-time flood forecast systems. At present, few real-time urban flood forecast systems have surfaced (Rene et al., 2014; Diez, 2016). The flood forecast systems operating in real-time are deterministic, and only a few probabilistic methods have been developed so far (Rene et al., 2013, 2015). The deterministic forecasts have serious limitations as both the uncertainty experienced in previous weather forecasts by using radar (Chumchean et al., 2005; Einfalt et al., 2005) and the uncertainty in the model structure should be taken into consideration (Ahmad et al., 2004). A forecasted flood map may show no flood risk as the deterministic forecasted water level is a few cm below an embankment level. However, the combined uncertainty of both the forecast and the model is larger than the distance from the deterministic forecasted water level to the top of the embankment level. Based on the uncertainty, the flood forecasted could have shown a forecasted overtopping of the embankment and a subsequent flood behind the embankment. This flaw can be removed by adding a probabilistic element to the forecast so the result from the flood forecast is a deterministic flood map plus an additional flood map, e.g. showing the 95% confidence level for the flood extent. Here the computation of the 95% confidence level can be based on the experienced and computed uncertainty in the weather forecast and the uncertainties from the model structure and model calibration.

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The thesis at a glance

Computer modelling of drainage systems is a discipline that has soared over the past 50 years. It is estimated that a large proportion of all cities in the world with more than 100,000 inhabitants have used computer modelling, in one way or another, for design or analysis of the performance of their drainage systems. The development and introduction of the PC in the early 1980s played a decisive role in the modelling of drainage systems. Since the mid-1980s, the PC has become more than 1000 times faster, and the computer memory surpassed the needs of even the largest calculations, which around 1990 was limited to 640 KB memory (which could handle about 250 pipes). The increase of raw computer power and memory as well as the following advances has significantly contributed to the progress in computer modelling of drainage systems:

1. Description of physical, biological/chemical processes in the sewers, e.g. transportation of dissolved matter and sediments
2. Description of physical processes in manholes in drainage systems, e.g. energy losses and mixing
3. Development of models describing causal relationships in the sewer systems, e.g. coupling of sediment deposition with hydraulic resistance
4. Development of models and coupling of models, which link existing knowledge in new ways, i.e.:
    - coupling 1D hydrodynamic pipe flow models with GIS models of terrain and 2D hydrodynamic models describing the flow of water on the ground; linking flood models with models to calculate the damage from floods and the health risk
    - coupling output from pipe flow models, e.g. overflows, to analyze the impacts on receiving waters
5. New applications of models of drainage systems such as simulation of the effects of climate change.