UNIVERSITATEA TECHNICAL UNIVERSITY OF CIVIL ENGINEERING BUCHAREST

Department of Hydraulics, Sanitary Engineering and Environmental Protection

PHD THESIS
(SUMMARY)

CONTRIBUTION TO THE DEVELOPMENT OF THE CAPACITY OF TAKING OVER THE URBAN RAINWATER CONSIDERING CLIMATE CHANGE

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Between January 2016 and June 2016, I had the opportunity to be accepted to study at the Danish Technical University of Denmark (Danish Technical University) where I was a PhD student in the DTU Environment Department, putting the pin on the map of DTU Environment PhD students for the first time.

I would like to express my gratitude to Mr. Prof. Univ. PhD. Eng. Anton Anton as scientific coordinator. I am deeply grateful for the trust given, for all the advice and for all the support provided throughout the elaboration and completion of this PhD Thesis.

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1. INTRODUCTION

1.1. The importance and necessity of the research

Due to climate change, in recent years, in many areas of the Earth, numerous natural disasters have caused disasters that have cost billions of euros and numerous losses of life. The scale and nature of the changes brought about by climate change vary across the globe. With the intensification of the torrential nature of rainwater that led to the emergence of urban floods, a special interest has emerged in studying changes due to climate change in daily and extreme precipitation events. In recent centuries, urban areas have developed a lot and surface permeability has decreased. Thus, the urban environment became less resistant to the problems associated with water *(Brown et al., 2009).* At the same time, climate change has also led to changes in temperatures, which has led to rising sea levels, as well as changes in water availability or quality.

The research theme of this PhD Thesis is the contribution to the development of the capacity to take over the city rainwater in the conditions of climate change. Over the next few decades, extreme weather events are expected to become increasingly frequent due to climate change (*Arnbjerg-Nielsen et al., 2015*). These phenomena are particularly distinguished by the increased frequency of extreme events and the increase in these events in terms of magnitude (*Arnbjerg-Nielsen, 2012*).

In recent years, more emphasis has been placed on exploiting existing water resources in urban areas in as intelligent and efficient a way as possible *(Zhou et al., 2013).* This is, of course, a positive development of cities that tend to have a positive impact on human health and society; these are the so-called 'green-blue' cities (green-water quality control; blue-flood control) (*Roy et al.,2008; Brown et al.,2009*). However, these improvements must be implemented by taking into account flood protection measures, such as changes in urban water routes depending on the event to which they are exposed (*Mitchell et al., 2007*). This requires local analysis that can be done by building mathematical models that are used to test the effectiveness of various rainwater management solutions designed to protect the urban environment from climate change. Denmark is one of the countries that is making great progress in developing new systems for taking over city rainwater. The weather forecast of the 21st century predicts an intensification of the torrential rains with which we are currently dealing. For example, extreme rainfall, with a probability of recovery of 100-years will increase by 45% (*Grum et al., 2006*). Currently, sewer systems in Denmark are designed to cope with an event with a probability of occurring every 20 years if the sewer system is divisive, i.e., to cope with an event with a probability of occurrence every 10-years if the sewer system is unitary. In conclusion, if nothing is done to prevent the takeover of rainwater entirely by the classical sewer system, urban areas will be flooded 3 times more often than they are currently flooded *(Grum et al., 2006).* The starting point of this research was an event that happened in July 2013, when Copenhagen was affected by floods due to an extremely precipitation event, 150 mm in 2 hours and which caused material damage of over 800 million euros *(Ioan, 2014).*

To mitigate the impact of urbanization, the solution could be to control the source and increase the storage capacity (*Semadeni-Davies et al., 2008*). The present PhD Thesis aims to present the combined effects of the development of cities and climate change, presenting the general positive effects of the installation of sustainable drainage systems in the urban environment.

1.2. The purpose of the research

Adapting sewer systems and the urban environment to climate change is one of the biggest, but also the most rewarding challenges of the present.

Traditionally, rainwater is managed by the city's sewer system itself. It consists of main pipes and secondary channels (Figure 1.1a). Alternative, surface-based solutions have gained increasing attention (Figure 1.1b). Throughout this thesis, the term sustainable urban drainage systems (SUDS) are used when referring to multifunctional systems on the surface.

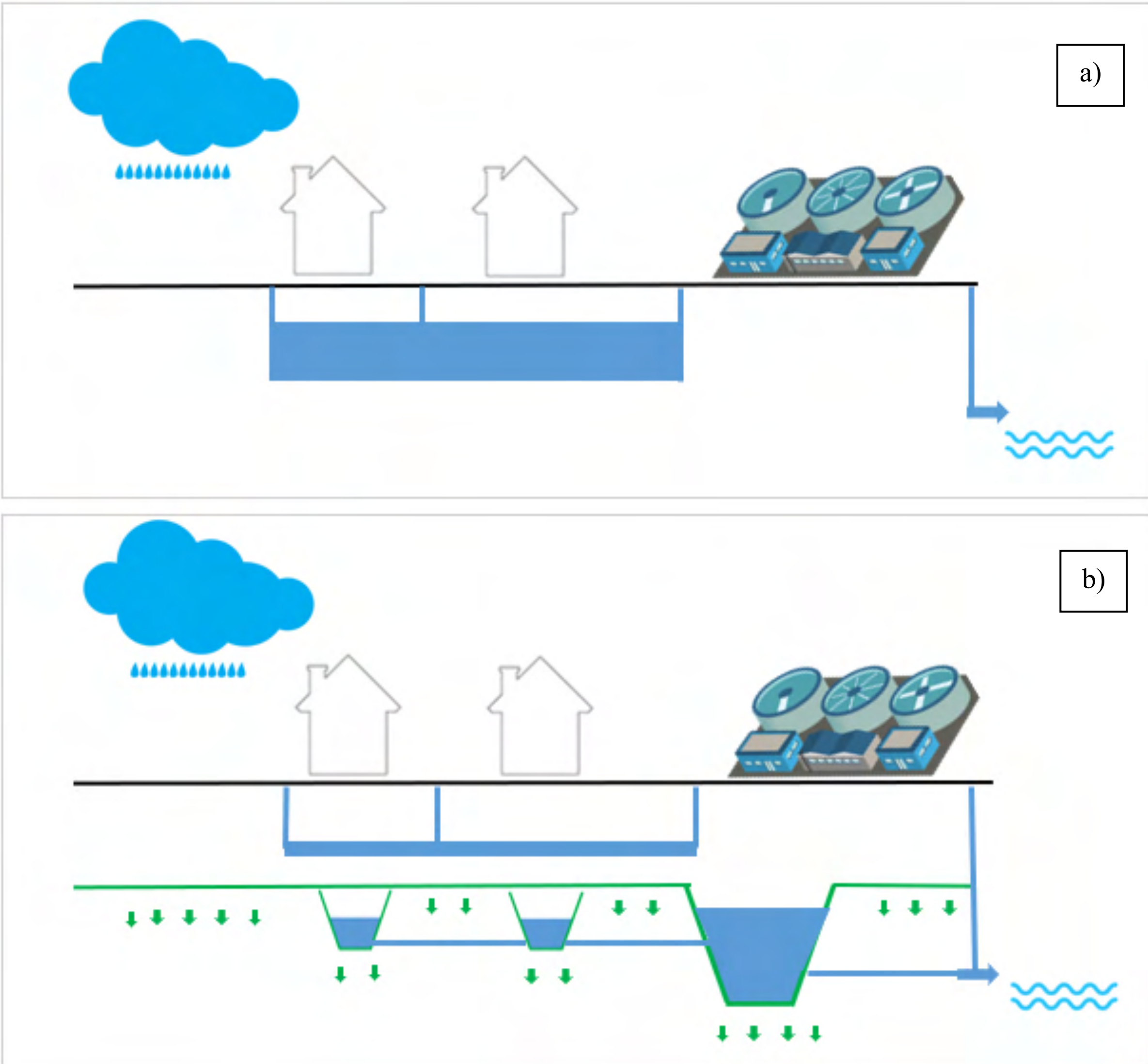


Figure 1.1 *Water flow to the recipient through a) underground systems and b) green infrastructure systems*

Sustainable urban drainage systems offer new possibilities for managing both small (daily) rainfall events and extreme (rare) rainfall events. Moreover, they provide additional social, environmental, and economic benefits by adding green and blue elements to the urban environment. Hydraulic modelling is an inherent part of urban water system (UWS) planning.

Sustainable urban drainage systems are usually assumed to be more environmentally sustainable. As such, the present PhD Thesis aimed at developing mathematical models (according to the different methodologies existing in the specialized literature at international level), thus adding an important tool in the SWM planning process of the decision-making process to study the adaptive capacity of the urban environment taking into account the effects of climate change.

1.3. The structure of the research PhD Thesis

The content of the research paper has a general framework organized on 7 main chapters, each of which is structured on several subchapters. These are preceded by the introduction section that will briefly expose the importance and necessity of the theme addressed in the chapter, but also the purpose and objectives pursued by the elaboration of the mathematical modelling that complete the work.

The first two chapters represent a detailed bibliographic synthesis on the subject addressed in this work, made by consulting the documentation available in the specialized literature, national and international, in the field of urban water management.

Chapter 1 is an introductory chapter, in which the context in which this research work was carried out is presented.

Chapter 2 presents urban flooding in terms of triggers and main elements. In this chapter, the sewer system is presented by first reviewing the main elements, their role, followed by a description of the sewer systems and processes, modelling principles, composition and shape of the sewer system. Emphasis is placed on the issue of the exploitation of water resources in the urban environment, detailing the three-point approach (3PA) presented by Fratini et al.,2012 as a tool to describe this problem, but also on the spatial and temporal distribution of precipitation events, being presented as a compromise between the typical response times of the sewer system and the times resulting from an analysis with the help of regional climate models (RCM). The last part of this chapter is dedicated to the calculation of statistical rains, referring to the way of calculating them.

In Chapter 3, the emphasis is on the evolution of precipitation over time. In this chapter, an analysis of the evolution of precipitation in the context of climate change in Europe is carried out, as well as a detail of future forecasts based on historical observations.

Chapter 4 details the theoretical bases of modelling the impact of climate change on rain and runoff. In this chapter, the focus is on the stages of modelling 1D and 2D modelling.

Chapter 5 assesses the impact of climate change and urbanisation on the rain that has elapsed, with the sewer system of the city of Ølsted in Denmark as a case study. This study provides a recommendation to model runoff in urban basins leading to functional models that can be used in simulating different precipitation events. In order to quantify the effects of increasing precipitation and urbanization (the emergence of new impermeable or very less permeable areas in the sewer basins) in the Ølsted area, a mathematically calibrated model of the sewer system was used. The regional climate model used in the Ølsted area to calculate statistical rainfall can describe extreme precipitation events over small areas, making it possible to describe the time-related extreme precipitation relevant to this study. The last part of chapter 5 aims to detail and take stock of the situation at international level and in Denmark of how cities adapt to climate change.

In Chapter 6, a complex analysis of the performance of four different approaches to two-dimensional modelling of sewer systems is carried out. The data underlying the mathematical models updated or realized in this work consist of the physical parameters of the sewer systems studied, data on the digital model of the land and GIS data on the use of areas.

Chapter 7 presents the general conclusions on the topic also by highlighting the original character and personal contributions.

The bibliography is presented both after each chapter and at the end of these works, in chapter 8.

The research paper ends with a list of articles, conferences, and posters where the research activity was presented.

1.4. Adaptation of urban areas to climate change in terms of rainwater management

Managing rainfall volumes of water is one of the biggest and most rewarding challenges of the present. Since the late 90s there has been an increase in the number of initiatives in terms of rainwater management in urban areas. It is desired to create an environment as natural as possible that is able to transport the flow of rainwater through a "green-blue" network (green = water quality control; blue = flood control) thus improving the appearance of cities, while turning them into safe places to live. There are many real-life constructed examples of how the "green-blue" network works. In the following, various research projects aimed at integrating the possibilities of rainwater management into urban design will be briefly presented.

Denmark is one of the countries that is making great progress in developing new rainwater takeover systems *(Cloudburst management plan 2012).* The event, which took place in July 2013, led to the development of new systems for taking over the city rainwater to adapt the city to climate change. They were based on measurements of all extreme weather events recorded in recent years, including the event in July 2013, thus making it possible to develop a projected climate change strategy.

The Danish Meteorological Institute (DMI) predicts a temperature increase of 2-3 degrees, there will be 25-55% more precipitation in winter by 2100, while precipitation in the summer months is expected to decrease by 0-40%. At the same time, precipitation will be more intense. The intensity of precipitation is expected to increase by 20-50%: 20% for frequent precipitation events and by 50% for very rare precipitation events. The intensity of the rain, which occurs statistically every 10-years, will increase by about 30% by 2100. Sewer systems in the future will have to cope with a volume of rainwater about 30% higher than at present. The intensity of the rain with a 100-year event is expected to increase by about 40% by 2100. The increase in intensity means that rain with a certain intensity will occur more frequently in the future. This means that, for example, the precipitation event that occurs today once every 50 years will occur in 2110 once every 10-years.

The plan for adaptation to climate change recommends starting work has in areas where it is necessary to do so and where there is local support. This will be mainly in areas where the city is being developed, modified and renewed, but also in areas where there is an increased risk of flooding. Adaptation to climate change involves considering rainwater collection and infiltration, biodiversity and the prevention of urban heat islands. The changes to the existing green spaces are designed to contribute to the city's climate adaptation, while providing the inhabitants of Copenhagen with spaces to relax and work.

2. URBAN FLOODING

2.1. Sewer systems

The sewer system is the set of engineering constructions, interconnected, which collects the sewer water, transports them to the treatment plant where the degree of treatment established according to the environmental conditions is ensured and then discharges them into natural receptors (rivers, lakes, seas, permeable soils with adequate facilities, etc.).

2.1.1. Sewer systems components and their role

The sewer system consists of pipes, channels, pumping stations and other auxiliary constructions located between the collection points and the treatment plant or mouths in the emissary. Pumping stations are built at the low points of the sewer territory, when – due to the configuration of the terrain – it is not possible for the sewer water to flow gravitationally or the flow rate is not sufficient. The auxiliary works on the network are drains that receive the rainwaters from the streets, connecting rooms, hill break manholes, washing manholes, spillways, retention basins, desanders, passages under the depressions and communication ways. The treatment plant consists of the complex of constructions and installations through which the quality parameters of the water are modified in such a way that the characteristics of the treated wastewater correspond to the norms in force specific to the receiver. Constructions for evacuation must ensure the safe discharge of water into the receptors for the sewer system and receiver.

2.1.2. Sewer systems processes

The collection and disposal of wastewater is done in one of the following procedures: the unitary process, the divisor process, and the mixed process. The unitary process collects and transports through the same sewer system all sewer waters: domestic, industrial, public, meteoric, surface and drainage. The unified process has the advantage that it requires a single channel network, lower operating costs, and the disadvantage of high upfront investment costs. The divisor process collects and transports through at least 2 different networks wastewater (domestic, industrial pre-treated and public) and meteoric. The flow of domestic wastewater is carried out through closed channels. The flow of pre-treated industrial wastewater is done through closed networks. The flow of rainwaters can be done either on the surface through street channels or open canals (ditches), or through a network of closed canals. The sewer in the divisor process is developed on the basis of the principle of retaining the water from the rains at the place of fall and the execution of infiltration basins - accumulation with/without reuse of these waters; reduction of impermeable surfaces in urban facilities; increasing the requirements for maintenance and cleaning of the urban spaces arranged and the increase of the specific areas (m^2/place) of green spaces.

2.1.3. Sewer system components

The sewer system consists of the pipes that ensure the transport of the collected water and the constructions that ensure the proper functioning of the network: connections, manholes, spillways, pumping stations, retention basins, water quality control systems and measurement of the flow of transported water. The water collected by the sewer system can come from various sources such as the interior installations of the dwellings, from inside the buildings with public destination (hospitals, schools, sports and leisure complexes), from the sanitary groups of the industrial units, from the waste water taken directly or from the pre-treatment plants when they meet the criteria of the required quality, from precipitation and melting of snow or from the infiltration of groundwater into the degraded pipes.

2.2. Main elements

Rain is an important part of the water circuit in nature, being a form of atmospheric precipitation. It is formed when various drops of water from the clouds fall on the surface of the Earth in liquid form. The rain consists of water droplets with dimensions ranging from 0.5 mm to 5mm in diameter and have a drop rate of 2.5 m/s.

2.2.1. Rainfall classification

The classification of rainfall can be made according to the volume of precipitation, as follows: very fine rain, when the precipitation rate is below 0.25 mm/hour; fine rain, when the rainfall rate is between 0.25 and 1 mm/hour; moderate rain, when the rate of precipitation is between 1 and 4 mm/hour; heavy rain, when the rainfall rate is between 4 and 16 mm/hour; very heavy rain, when the rainfall rate is between 16 and 50 mm/hour; heavy rain, when the precipitation rate is higher than 50 mm/h.

2.2.2. Rainwater flows

The problems of establishing the quantities of water from the rains and the melting of the snows taken over by the sewer system are very complex and are mainly due to the following: the knowledge about the rough rains is not directly exploitable, only partially the precipitation participates in the flow, numerous hydrological, meteorological, and geomorphological characteristics intervene in the system, imposed by the urban environment.

2.3. Rainfall measurement

The measurement of the quantities of rainwater is carried out with the rainwater meter. The measured values are expressed in mm thick water layer or l/m^2 (a 1 mm thick layer corresponds to a quantity of water of one litre evenly distributed over an area of 1 m^2). The continuous recording of the quantity of rainwater, its duration and intensity shall be measured with the rainwater. This shows the amount of rainwater fallen in a unit of time per unit of area ($1/m^2$/minute).

Precipitation is extremely difficult to measure, especially in strong wind conditions. Both because not all precipitation can be captured in the measuring device, and because the amount collected before the data collection could be lost. Only a part of the precipitation that falls in the form of snow will be able to be captured in the measuring device, the amount of precipitation collected could decrease with the intensification of the wind speed. To reduce strong wind conditions, in Denmark precipitation is measured with a Hellmann rainfall (200 cm^2 hole) placed 2.5 m above the ground surface to prevent accumulation from snow. In addition, a Nipher shield is positioned above the measuring stations in Greenland to cushion the influence of the wind.

In Denmark, there is more and more talk of the so-called 'guides'. These guides cannot be called standards because they are not required by law. It is a guide provided by the Danish National Wastewater Committee (SVK - Spildevandskomitteen) and which is used by all municipalities (counties/sectors) and private water companies. For this reason, these guides are very important. The first guide (Skrift 1) appeared in 1949 and used recorded data from 6 automatic measurement stations with a resolution of 5 min located in 1933. Later, other variants of the guide appeared (Skrift 2- Skrift 25), the intensity of the calculation rains being recalculated in each new variant of it. The intensities of the calculation rains were in the form of tables from which values were extracted. This data led to the creation of IDF curves: Intensity - Duration - Frequency (one curve for each exceedance period). In 1979, 145 new rain measuring stations were installed, which is the station system still in use today. Most of these stations were in the centre of major cities. The first guide that considered the data measured by the new rain measuring stations appeared in 1999 (Skrift 26). At the same time, the first regional model was created. This regional model has 2 advantages. With its help, the uncertainty (safety rate) is reduced, because at its base is a very large package of data. The second advantage is that the resulting information (the resulting parameters) can be obtained not only in the location where there is physically located a measurement station, but throughout the country. Thus, with the help of this regional model it is possible to calculate statistical rainfall throughout the country. Skrift 30 was used in this research, where average annual precipitation (the number of extreme events) and average daily extreme precipitation (magnitude of events) according to the regional climate model (1989-2010) are shown.

In Denmark, the statistical rainfall is calculated using a tabular model drawn up by the Danish Wastewater Committee. It is based on rain measurements from 1979 to the present and uses skrift recommendations as input data. The calculated rains are CDS (Chicago Design Storm) rainfall, synthetic rain events constructed using statistical calculations based on measured rainfall events. The calculation file is based on intensity-duration-frequency curves, adding a safety coefficient that takes into account the uncertainty of the model and the impact of climate change. This calculation file uses x (east) - y (north) coordinates to identify the location of the study area. Once the area is identified by reading the coordinates, the annual average precipitation and the average daily extreme precipitation are automatically identified from the database. Depending on the period of exceedance of the event to be calculated, the following parameter will be considered by the safety factor:

$$f_s = f_c \ x \ f_{sm} \ x \ f_{cs} \quad (2.4)$$

where:

f_s the safety factor;

f_c the climate factor;

f_{sm} the model safety factor;

f_{cs} the safety factor considering the runoff coefficient.

Version 30 of the guide (Skrift 30) takes climate change into account, thus providing recommendations for the use of climate factors for the purpose of sizing new sewer systems or for the rehabilitation of existing sewer systems. Two different sets of climate factors are recommended (Table 2-1). "Standard" climate factors are those factors that correspond to the best match in terms of the effects of climate change, and "high-grade" climate factors, are those factors that correspond to the best match in terms of the effects of climate change plus the standard deviation of the climate factor.

***Table 21** Recommended climate factors*

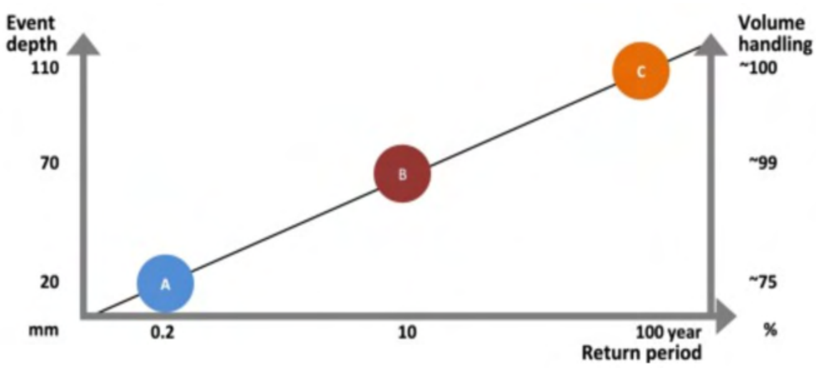
Probability of exceeding the event	100-year horizon		Horizon for 50 years	
	"Standard" climate factor	"High-grade" climate factors	"Standard" climate factor	"High-grade" climate factor
10-years	1,3	1,7	1,15	1,35

***Source:** Adapted from Skrift 30, 2014*

The safety factor of the model is a factor that introduces in the calculation of statistical rainfall the degree of safety (reliable) of the network model. This factor can only be considered 1 when the degree of confidence of the network model is very high, when the model used is a calibrated model, where calibration errors are less than 15%. When the model used is not a calibrated model, the safety factor of the model will be considered 1.1. The safety factor that considers the drainage coefficient is a factor that takes into account the appearance of new impermeable or very less permeable areas (houses, roads, parking lots, etc.) in the sewer basins. The safety factor considering the runoff coefficient shall be considered 1.1.

2.4. Rainwater management in urban areas

Different sectors of society were responsible for the exploitation of water resources and the protection of the urban environment from water-related problems. Today this leads to misunderstandings between urban planners, engineers, politicians, and citizens in that there is no common understanding of how the urban water system works, what are its important characteristics or how its needs are formulated (*Fratini et al., 2012*). The three-point approach (3PA) presented by Fratini et al. (2012) is a tool to describe this problem (Figure 2.1). It helps the stakeholders involved to form a common platform for urban water management.



Source: Fratini et al. (2012)

***Figure 2** Quantification of 3PA*

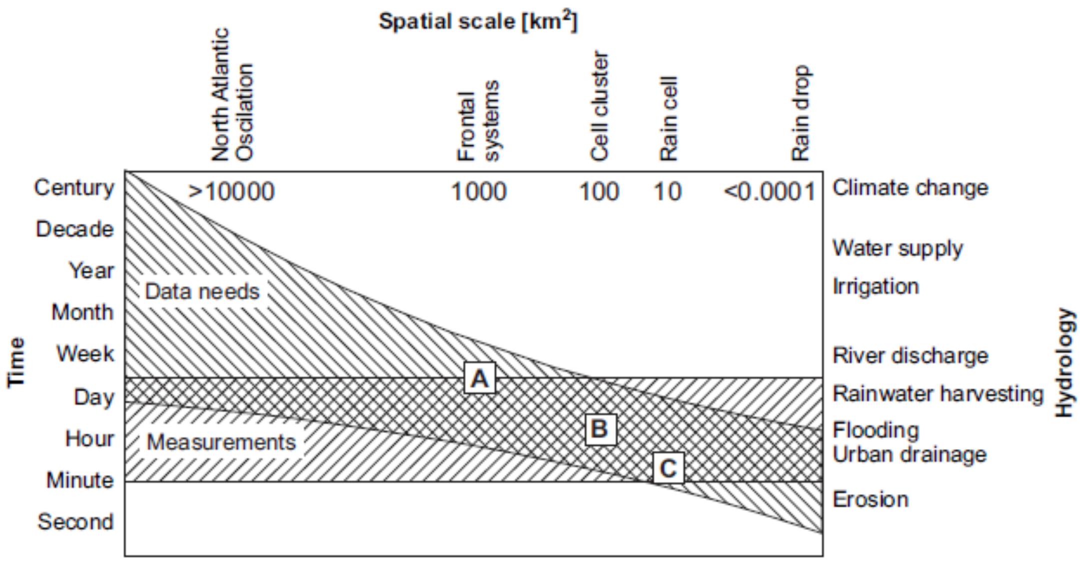
The three points symbolized in Figure 2.1 represent three different areas related to the precipitation analysed:

- 0.2 years - frequent precipitation with small return periods. All this together accounts for most of the total rainfall volume.
- 10-years - rare events with considerable magnitude and return periods of many years. They are the design standard for sewer systems.
- 100-years - extremely rare events with very long periods of recovery. These events cause significant flooding but are not considered in the design because the costs of flood prevention are higher than the costs of damage.

The quantification of 3PA leads to the conclusion that unitary sewer systems designed to control precipitation events with recovery periods of up to 10-years actually handle events up to 50 mm of volume and virtually all (99%) of annual rainfall.

2.5. Spatial and temporal distribution of the precipitations

The time scale must be a compromise between the typical response times of the sewer system and the times resulting from an analysis using regional climate models (RCM). As regards the 3PA approach the difference in scale between the different points can be highlighted below. As detailed time scales as possible (on the order of seconds) are required to model green systems that are designed to cope with frequent precipitation with small return periods. To analyse and understand severe precipitation it is necessary that the time scale is of the order of hours and ideally of the order of minutes (Figure 2.2 - points B and C). These fine scales are the resolution needed to shape and assess flood problems in urban areas.



Source: Hjalte Jomo Danielsen Sørup (2014)

Figure 2 *Spatial and temporal scales relevant for hydrology*

The performance of the system is not always based on individual precipitation events but on precipitation sequences (Mikkelsen et al., 2005), which represents the spatio-temporal resolution with which precipitation is measured (Bruni et al., 2014). The time series is a series of data describing the real dynamic behaviour of precipitation in time and space on the earth's surface (Thorndahl and Rasmussen, 2013).

Frontal precipitation occurs due to hot and cold fronts. They are generated by the forced ascensional movement of warm air. In the case of the cold front, there is short-term heavy rainfall over a distance of up to 60 km from the cold front. For the warm front, precipitation of low intensity occurs, but of great duration at a distance from the warm front of 300-700 km. CLUSTER cells are a group of cells moving as a single unit, with each cell at a different stage of the storm event cycle. This type of storms can produce moderate hail, flooding, and weak tornadoes. In the category of rain cells are classified rains that last on average 20-30 minutes that can produce torrential rains, hail, or weak tornadoes. The fact that events are not uniform in space and time is a real problem when discussing the issue of climate change. Climate change can be modelled using climate models (General Circulation Models (GCM) and/or Regional Climate Models (RCMs)). A changed climate will inevitably lead to changes in the weather and will result in problems for urban hydrology.

3. EVOLUTION OF PRECIPITATION IN THE CONTEXT OF CLIMATE CHANGE

3.1. Effects of climate change

To show the evolution of precipitation over time, the analysis presented by "WorldClim" version 1.4 was used, created globally covering all areas of land except Antarctica. The present, future and past precipitation conditions are presented as a raster of average monthly rainfall and are available in different resolutions, from 30 seconds (~1 km^2) to 10 minutes (~340km^2). They can be downloaded from the http://www.worldclim.org website.

Past precipitation conditions. "WorldClim" uses climate data from simulations of global climate models (GCM) presented in the fifth phase of the PROJECT OF CMIP (Coupled Model Intercomparison Project). These data were resized and calibrated according to the model of the present WorldClim 1.4 conditions (precipitation measurements recorded in the period 1960-1990). WorldClim presents the climate conditions of the Holocene (about 6000 years ago) in raster format with a spatial resolution of between 30 seconds (longitude/latitude) or about 900 m at the equator up to 10 minutes (18 km at the Equator).

The present precipitation conditions, according to "WorldClim" are based on precipitation measurements recorded in the period 1960-1990 in 47554 weather stations. From all these stations there are records for at least 10-years. Due to the very good quality of the recorded data, the first stations used in this analysis were the data provided by GHCN (Global Historical Climatology Network). The following data used were recorded in additional stations such as: FAO (Food and Agriculture Organisation of the United Nations), WMO (World Meteorological Organization), CIAT (International Centre for Tropical Agriculture), R-Hydronet (a regional network of electronic hydrometeorological data recorded in South America, Central America and the Caribbean). To obtain the best possible spatial representation, precipitation measurements recorded in smaller weather stations in Australia, New Zealand, Denmark, Sweden, Norway, Peru, Bolivia, etc. were also used (Hijmans et al., 2005).

Future precipitation conditions according to "WorldClim" are based on the climate projections of the IPCC's fifth Intergovernmental Panel on Climate Change (IPCC) assessment report for global climate models (GCM). These are the latest GCM climate projections. The resulting future precipitation conditions were resized and calibrated using as basic data the present WorldClim 1.4 precipitation conditions (precipitation measurements recorded between 1960 and 1990). This made it possible to obtain high-resolution information. Global warming increases the water vapor content in the atmosphere, leading to changes in the frequency, intensity and duration of extreme weather events. Globally, according to the fifth IPCC (Intergovernmental Panel on Climate Change) report, the future climate is expected to involve higher temperatures, longer and warmer heat waves and more severe rainfall events. Several dry periods, as well as rising sea level, although the regional differences are large. Hurricanes may occur in the North Atlantic and North Pacific.

3.2. The evolution of precipitation in Europe

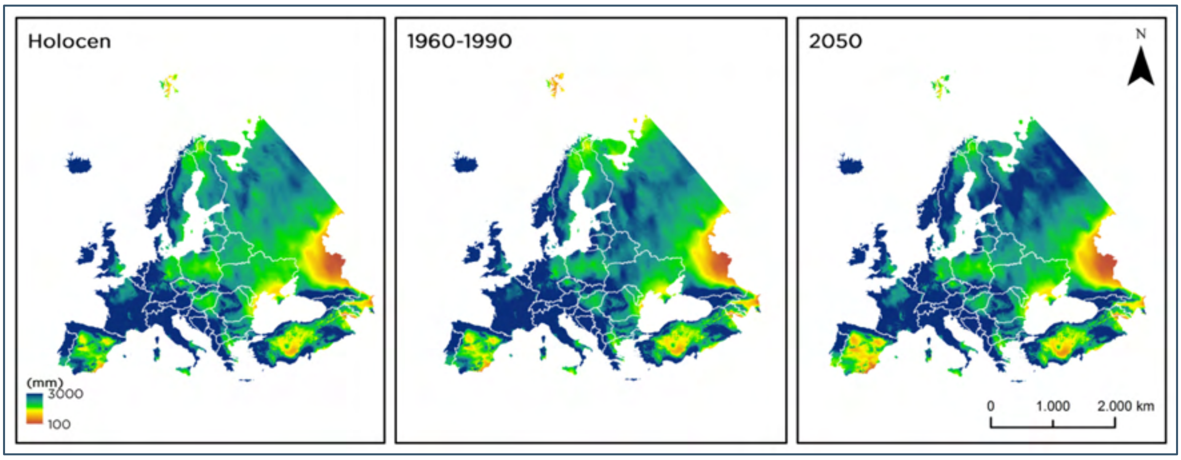
In Europe, according to the "WorldClim" the evolution of monthly precipitation over time is presented in table 3.1., according to the hadgem2-CC (Hadley Global Environment Model 2) Carbon Cycle) forecast model, a specific configuration of HadGEM2 used in the fifth phase of the PROJECT OF CMIP (Coupled Model Intercomparison Project). Areas where precipitation has a tendency to decline are in central, eastern and southern Europe. Changes in precipitation by 2050 are distributed differently in the four seasons (Table 3.1). The largest increase in precipitation is observed in winter, where the expected growth will continue until 2050. In contrast, a reduction in precipitation is expected in the summer season.

Table 31 *Evolution of monthly rainfall in Europe*

The evolution of monthly precipitation	Holocene		1960 - 1990		2050	
Moon	Minimum rainfall (mm)	Maximum precipitation (mm)	Minimum rainfall (mm)	Maximum precipitation (mm)	Minimum rainfall (mm)	Maximum precipitation (mm)
January	10	325	10	290	12	339
February	10	292	10	245	10	242
March	10	255	9	257	13	262
April	8	221	7	227	11	239
May	9	273	7	234	6	243
June	1	237	1	234	1	225
July	0	231	0	219	0	187
August	0	233	0	225	0	200
September	1	324	1	325	1	325
October	11	397	16	356	17	410
November	16	290	15	315	20	379
December	11	364	11	369	15	399

Source WorldClim 1.4

In the future, according to the HadGEM2-CC forecast model, a trend for more precipitation is generally observed in the northernmost parts of Europe (Figure 3.1). An increase in average annual rainfall in Europe is observed since the middle of the last century and is expected to continue throughout this century (Table 3.2).



Source: WorldClim 1.4

Figure 3 *Evolution of annual rainfall in Europe*

Table 3-2 *Evolution of annual rainfall in Europe*

Holocene		1960 - 1990		2050	
Minimum rainfall (mm)	Maximum precipitation (mm)	Minimum rainfall (mm)	Maximum precipitation (mm)	Minimum rainfall (mm)	Maximum precipitation (mm)
180	2888	161	2958	169	3065

Source: WorldClim 1.4

3.3. Evolution of precipitation in Denmark

Forecasts based on historical observations suggest that extreme precipitation events in the eastern part of Denmark should have been upward over the past two decades. However, growth continued longer than expected and with greater amplitude in the most recent years. This is most likely indicated by anthropogenic greenhouse gas emissions. Anthropogenic activity is expected to contribute further to a significant increase in the intensification of extreme rainfall and its occurrence in Denmark (Gregersen et al.,2014). The frequency of extreme events in the past has oscillated with a cycle of 25-35 years, a behavior that can be partly explained by differences in sea level (Gregersen et al.,2014). In Denmark, according to the "WorldClim" the evolution of monthly rainfall over time is shown in Table 3.3, according to the forecast model HadGEM2-CC (Hadley Global Environment Model 2 - Carbon Cycle), a specific configuration of HadGEM2 used in the fifth phase of the project of CMIP (Coupled Model Intercomparison Project).

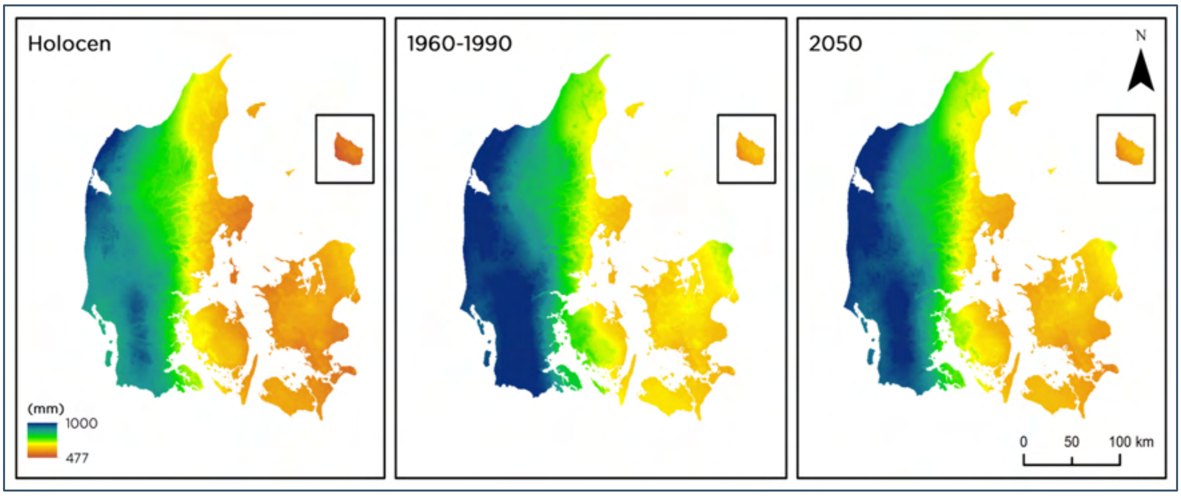
Table 3-3 *Evolution of monthly rainfall in Denmark*

The evolution of monthly precipitation	Holocene		1960 - 1990		2050	
Moon	Minimum rainfall (mm)	Maximum precipitation (mm)	Minimum rainfall (mm)	Maximum precipitation (mm)	Minimum rainfall (mm)	Maximum precipitatio n (mm)
January	40	79	41	76	50	96
February	25	47	27	50	29	57

The evolution of monthly precipitation	Holocene		1960 - 1990		2050	
Moon	Minimum rainfall (mm)	Maximum precipitation (mm)	Minimum rainfall (mm)	Maximum precipitation (mm)	Minimum rainfall (mm)	Maximum precipitatio n (mm)
March	25	50	30	60	30	64
April	25	50	31	50	32	48
May	33	54	37	56	42	60
June	32	60	40	68	38	64
July	50	72	55	81	40	59
August	39	76	49	90	32	56
September	45	94	52	100	51	106
October	45	113	47	108	51	116
November	53	114	53	108	49	123
December	44	87	45	89	45	97

Source WorldClim 1.4

At regional level, Denmark is experiencing increasingly prolonged heat waves (Figure 3.2). An increasing trend of precipitation is observed (Table 3.4). Summers in the future are expected to be characterized by longer periods of drought and events with more abundant rainfall, even though summers will be drier on large parts of the European continent. Winters are expected to be generally characterized by increased rainfall. There is an increase in average annual rainfall in Denmark since the middle of the last century and this is expected to continue throughout this century.



Source WorldClim 1.4

Figure 3 *Evolution of precipitation in Denmark*

Table 3-4 *Evolution of annual rainfall in Denmark*

Holocene		1960 - 1990		2050	
Minimum rainfall (mm)	Maximum precipitation (mm)	Minimum rainfall (mm)	Maximum precipitation (mm)	Minimum rainfall (mm)	Maximum precipitation (mm)
447	856	525	904	520	917

Source: WorldClim 1.4

According to the HadGEM2-CC forecast model, in the future, Denmark will be on the border between two areas, where the amount of summer precipitation in northern Scandinavia increases, while the amount of precipitation decreases in central, eastern, and southern Europe. Extreme precipitation events are expected to be even more severe, thus increasing both their frequency and intensity. According to the fifth phase of the CMIP project and implicitly WorldClim 1.4, Denmark will see in the future a warmer and wetter climate, and extreme weather events will occur more and more often.

4. RUNOFF MODELLING

Identifying the most effective rainwater collection and discharge systems can improve and over time even significantly diminish one of the major problems caused by severe disruption of environmental factors, flooding. To understand the challenges, we face today in terms of flooding and the risk of flooding occurring in the future, we use mathematical models that help us understand and analyse the impact of present and future precipitation. With the help of these mathematical models, different precipitation scenarios can be simulated and thus, one can observe the areas where flooding will be able to occur.

4.1. One-dimensional (1D) modelling

Numerous studies in the literature show that the use of one-dimensional modelling to determine urban flooding is a conventional approach that can provide an overview of potential flood-affected areas (Ole Mark et al., 2004). A one-dimensional model can be used in the simulation of present or future scenarios to assess the probabilities of failure of part of the drainage network (Thorndahl, Willems, 2008). In this research to perform the hydraulic and hydrological simulations, the MIKE URBAN modelling software package (DHI) was used, it uses the MOUSE (MOdel for Urban SEwers) program to build a rain-drain model. Mouse is used for planning, analysis and design related to rainwater drainage, combined and sanitary sewers and other drainage systems. It can be used to evaluate rainwater control strategies of gray infrastructure, such as rainwater pipes and drains, and is a useful tool for creating effective rainwater control solutions. Mouse was developed to support local, state and national rainwater management objectives to reduce infiltration and retention runoff and to help reduce discharges that cause damage to water bodies.

4.1.1. Hydraulic modelling

To describe the abstraction of rainwater as well as the movement of water in the sewer system, the mathematical modelling package MIKE URBAN simulates the flow in pipes using the Saint-Venant equations for free-surface flow in a finite space. The simulations are performed both for the subcritical flow conditions and for the critical flow conditions, while also including the effects given by the water in stationary mode. In the MIKE URBAN program, the manholes in the sewer system are called knots. They are represented in locations where there are manholes, pipes or where the dimensions of the collector change. Pipes are called links; they are defined between two nodes. The characteristics of pipes and manholes (nodes) in this study were imported and edited using the GIS tools integrated into the MIKE URBAN program. The pipes were defined by the following parameters: diameter (m), length (m), material, and the drains were defined by the elevation of the land (m), the elevation of the eraser (m), diameter (m).

4.1.2. Hydrological modelling

In the MIKE URBAN program, the hydrological process is described by the runoff conceptual model "Model A". The surface hydrological model uses the "Time-Time", considering a linear drain and a fixed permeable surface. This conceptual model describes a volume of rain leaking that is directly influenced by the size of the sewer basin. The "Area-Time" method includes major losses introduced (infiltrations, water retentions, etc.) in the model in the form of a hydrological reduction factor "RF". The initial loss is a singular loss that is recorded at the beginning of a rain event simulating the depth of rain necessary to be able to start the surface drain. Hydrological reduction factor (RF) – introduces in the surface hydrological model a reduction of the runoff generated from the sewer basins following the water losses caused by evapotranspiration, increased permeability of partially permeable areas, etc. The sinuousness of the drain hydrograph is controlled by the concentration time (TOC). This is the time required to allow water to flow from the farthest part of the basin to the entrance to the sewer system and the shape of the catchments used in the calculation. The drain process is a continuous process and is discretized over time by the Δt calculation step. It is assumed that the speed of the leak is constant. This implies the spatial discretization of the surface of capturing several cells in a form of concentric circles with a central point at the exit point.

4.1.3. One-dimensional modelling stages

The first stage is the creation of the models, hydraulically and hydrologically, thus shaping the MIKE URBAN 1D model. In this model is also included the contribution of wastewater to the sewer system. This is done using the 24-hour wastewater variation, information provided by the local water company.

The calibration process of the sewer system begins by starting the measurement campaign. For this it is necessary to place measurement sensors in the sewer system, sensors that will measure the level and speed of flow, calculating the instant flow rate. These sensors will remain placed on the network until the calibration phase is completed. Once the data is recorded, it must be validated. The validation process consists of excluding atypical points from the measured dataset. One of the reasons for the appearance of these atypical points may be the content of impurities/air inclusions in the fluid, but also disturbances of the measurement sensor. The optimal way of data processing is to use the method of the smallest squares. With the help of this method, a curve drawn among the measured points will be determined, quite accurately approximating the values of the points. The calibration of sewer systems is very difficult to achieve, requiring many months of measurements and actual work with the mathematical model. Usually, following the calibration it is desired to obtain calibration errors of up to 15%, and the correlation coefficient to be between 0.8 and 1. It is very important that all events will be calibrated separately to be able to observe in detail the conditions of saturation or non-saturation of the soil at the time of the start of a precipitation event. A sensitivity analysis shall be made whereby the coefficients used in calibration must be identical in at least 50 % of the calibrated events to consider the hydrological model calibrated.

4.2. Two-dimensional (2D) modelling

A one-dimensional model can be a statistical tool, used to assess the performance of part of the sewer system, or it can be combined with a two-dimensional model to obtain more detailed results (Thorndahl, Willems, 2008). Two-dimensional models have been developed for modelling areas with flooding potential. Mixed 1D/2D modelling is used to analyse flood behaviour and identify the causes and effects of floods. The use of the mixed approach of the 1D and 2D numerical models increases the quality of the results. In this study, both one-dimensional models and two-dimensional models were used to obtain a better representation of the connection between the sewer system and simulated floods at ground level. The two-dimensional model used in this research is the MIKE FLOOD model and represents a configuration of two (or more) software specifically designed to work together.

4.2.1. Two-dimensional modelling stages

MIKE 21 is a 2D module and is used in conjunction with MIKE URBAN (1D module) to calculate flooding from the entry of the pressure sewer system. By combining the two models, the 2D MIKE FLOOD model is generated. For the construction of the MIKE FLOOD model, a routine of running in MIKE FLOOD was generated from the mike urban software, and the adjustment of the calculation parameters was made through the MIKE ZERO software. In the first stage it is necessary to use a numerical terrain model (DTM) in the studied area to perform MIKE FLOOD simulations. The accuracy of the height measured in the DTM is essential for the MIKE FLOOD model to correctly simulate the flooding of areas. DTM resolution is also an important property in performing MIKE FLOOD simulations. If the simulation represents an urban area, the resolution of the raster cells recommended by DHI is 1mx1m or 2mx2m. It is necessary to follow this recommendation because in a DTM, where the cells are smaller than 1x1m, it tends to be unstable during simulations. If a resolution of 1 or 2 m is not available, then a resolution of 3mx3m or 4mx4m is acceptable. However, if raster cells exceed a resolution of 4mx4m, houses or roads can fictionally block flooding in certain areas. In this research, a DTM with a resolution of 1.6mx1.6m. MIKE FLOOD simulations are simulations that take a very long time and therefore it is important to consider how large the surface is that actually needs to be simulated and what cell size should be used. Of course, a 2D model is able to provide a realistic estimate of the flooded surface. It is not an ideal way to calculate whether the results are to be obtained in real time because it requires a longer calculation time compared to the 1D models. In Chapter 6, one of the parameters studied will be the running time.

5. IMPACT OF CLIMATE CHANGE AND URBANISATION

5.1. Introduction

To exemplify the impact of climate change and urbanization on the rain, the Ølsted catchment was studied, with an area of 101 ha. Ølsted is a town in the municipality of Halsnæs, Hovedstaden Region, with a population of 1,943 (2016) located 51 km northwest of Copenhagen.

5.2. Basic data

In Ølsted, the collection of rainwaters is carried out both by divisor and by unitary process. A small part of the rainwater collection system is private, rainwater is collected in rainwater retention tanks and is used for watering green spaces, etc. The sewer divisor system is dimensioned for an event that corresponds to a rain with the probability of overrun once every 5 years, and the unitary sewer system is sized for an event that corresponds to a rain with the probability of exceeding it once every 10-years.

The Ølsted catchment (Figure 5.1) has an area of 101 ha divided into 1673 sewer basins. The sewer system consists of 499 manholes, 502 circular pipes, 3 open basins (lakes), 2 pumping stations, 1 spill and a treatment plant. The quantities of domestic water introduced in the mathematical model are based on water consumption in 2016. They were introduced into the model with the help of allocation points. The mathematical model of the sewer system uses a 24-hour variation for domestic water, with a maximum value of 1.8.

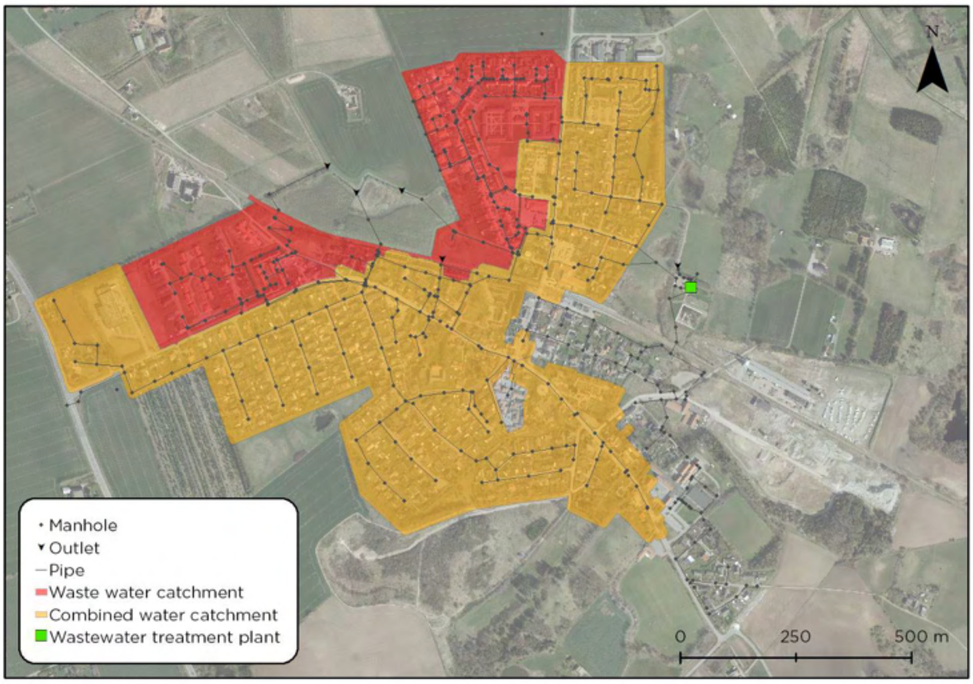


Figure 5 *Collection of rainwaters in unitary system and divisor*

5.3. Calculation hypotheses

The shape of the sewer basins is used in the rain-drain model is rectangular (TACurve1), where the length of the basin gives sewer is 4 times its width. The rain-drain concept model "Model A" calculates the runoff from the land surface resulting in a discontinuous hydrograph, with water runoff being generated only during a rain event. Depending on the type of area, the values of the drainage coefficients are as follows: houses 0.95, roads 0.90, parking lots 0.85, partially permeable areas 0.30 and green areas 0 (*Ioan et al., 2017*). After calibration, the hydrological model shall reproduce the flow rates and water levels measured at the two locations R24F028 and R24F504 during the measurement campaign. The purpose of this calibration is to obtain calibration errors of up to 10 % and the correlation coefficient to be between 0.8 and 1. All events will be calibrated separately. Following the sensitivity analysis, the coefficients used in calibration must be identical in at least 50% of the calibrated events to consider the hydrological model calibrated.

5.4. Measurement campaign

The location of the measurement points located is shown in Figure 5.5. The data obtained as a result of the sweeper campaign carried out between October 2016 and February 2017 both in dry and rainy periods were used to estimate the hydraulic performance of the sewer system. During this period, measurement sensors were placed in 2 different points of measurement: R24F028 and R24F504. For the measurement of flows and velocities in the measurement sections, flow meters with level sensor (Dual Wave Area/Velocity Sensor (AV150630417) were used, shown in Figure 5.6. This type of flow meter measures the average flow rate and level, calculating the instantaneous flow rate, and the counter showing the cumulative volume. They are composed of a submersed measurement sensor, ultrasound (mounted on the bottom of the manifold/channel) and a processing and display unit (flow monitor). The measurement by this method depends on the content of impurities/air inclusions in the fluid which must be at least 75ppm, having dimensions of at least 100 microns and a minimum speed of 0,03 m/s.

5.4.1. Rainfall measurement campaign

The location of the Ølsted Weather Station is shown in Figure 5.1. The measurements were also carried out between October 2016 and February 2017 in the Ølsted Weather Station with a BMI type pluviometer. The BMI-type pluviometer is equipped with a cylinder of internal diameter 5 cm graduated in 100 divisions and marked from 10 to 10 with digits. The interval between 2 consecutive digits represents 1mm of the height of the cumulative precipitation column, the one in reality corresponds to 1 l/m^2 of precipitation that has fallen in the unit of time. The measured rainfall has a resolution of 0.2 mm. The total volume measured has been converted to millimetres, and the time resolution is 2 minutes. The measured rain was divided into precipitation events as follows: a minimum of 60 min of dry period between measurements results in two different precipitation events. The only events used in the calibration are rain events over 3 mm (3 l/m^2).

5.4.2. Sewer system measurements campaign

The campaign to measure flows and depths in the two collection points was recorded without interruption throughout the 6 months (October 2016 – February 2017). There were located 2 points of measurement of flows and depths: the metering point R24F028 (Figure 5.2) and the measurement pointR24F504 (Figure 5.3).

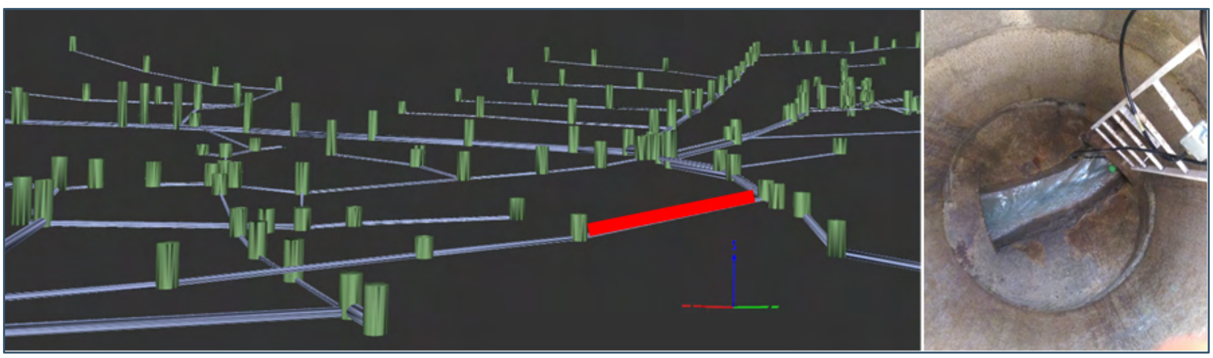


Figure 5 *Measuring point located in the spout R24F028*

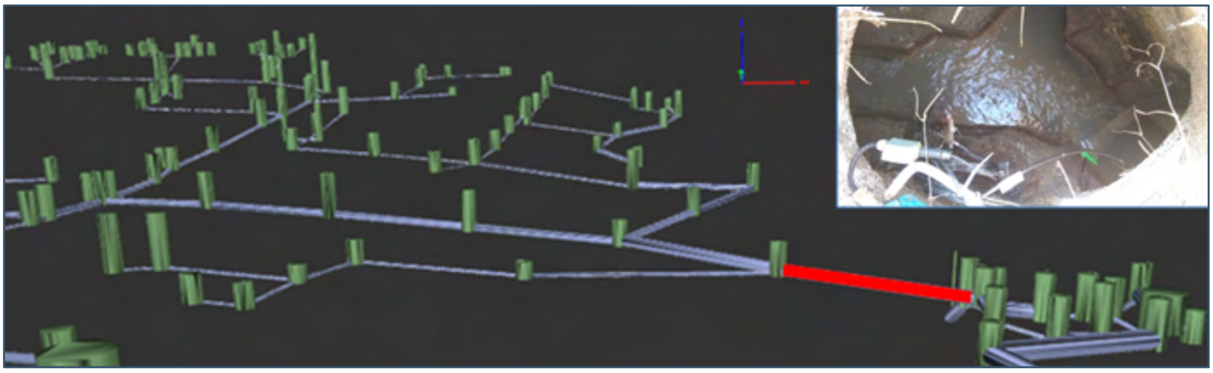


***Figure 5** Measuring point located in the spout R24F504*

Between October 2016 and February 2017, there were 16 events larger than 3 mm (3 l/m2). All these events were used in the calibration process Validation and data processing. The validation of the received data was made considering the identification of the measurement errors given by the measuring instruments used (+/- 1%). The measurement using flowmeters with a Dual Wave Area/Velocity Sensor (AV150630417) level sensor (ultrasonic) depends on the content of impurities/air inclusions in the fluid which must be at least 75ppm, with dimensions of at least 100 microns and a minimum speed of 0.03 m/s. This may be the cause of obtaining atypical experimental points. The exclusion of atypical points was made for each event as a first step in the process of validating the received data. Using the method of the smallest squares, a curve was determined among the measured points that approximate the path followed by these points. The curve is at the shortest distance from each point of the measured data set.

5.5. Network model calibration

The surface pattern results in a discontinuous hydrograph where runoff is generated only during a rain event. The 16 recorded precipitation events were used to calibrate the mathematical model by comparing the data measured in the network with the data obtained from mathematical modelling. The comparison of this data and the calculation of calibration errors was done in the Mike View program.

5.5.1. Measurement points calibration

5.5.1.1. Initial losses (IL)

The "time-area" method also includes losses, usually minor, introduced into the model as initial losses ("IL"). Initial loss – represents the depth of precipitation required to start the runoff. This loss occurs only once and represents the wetting of the catchment and the filling of small lowlands. The calculated calibration errors calculated at the R24F028 measurement point indicated the best overlapping match of the start of recorded precipitation events is 9×10^{-4} m initial loss. This has been validated as the most appropriate because the loss is the same in more than 50% of events. The calculated calibration errors calculated at the measurement point R24F504 indicated the best overlapping match of the start of recorded precipitation events is 4×10^{-4} m initial loss, being validated as the most appropriate because the loss is the same in more than 50% of events.

5.5.1.2. Hydrological reduction factor (RF)

Hydrological reduction factor (RF) – introduces in the surface hydrological model a reduction of the runoff generated from the sewer basins following the water losses caused by evapotranspiration, increased permeability of partially permeable areas, etc. Calculation of calibration errors taking into account the influence of the reduction factor on the flow rate calculated at the measurement point R24F028 indicates a good match when the hydrological reduction factor is 0,7. At the point of measure R24F504 the reduction of the leakage generated from the sewer basins resulted in 0.7 from the analysis. They were validated in more than 50% of the events studied.

5.5.1.3. Concentration time (TOC)

Concentration time (TOC) - represents the length of time during which rainwater fallen on the farthest surface of the catchments drains into the sewer and reaches the calculation section. Calculation of calibration errors that take into account the TOC on the flow rate calculated at the measurement point R24F028 indicates a good match when the concentration time is 9 minutes. At the point of measure R24F504 the length of time during which rainwater fallen on the farthest surface of the catchments drains into the sewer and reaches the calculation section is 9 minutes. This is true in over 50% of the events recorded between October 2016 and February 2017.

After calibration, the model is able to render a transported flow rate and a depth of water in the channel similar to the measured data. Once the mathematical model of the sewer system is calibrated, it can be used to analyse the effects of changes in precipitation events due to climate change. A graphical representation of the flow rates at the measurement points R24F028 (Figure 5.4 left) and R24F504 (Figure 5.4 right) before calibration and after calibration was made to further highlight the difference between an uncalibrated mathematical model, which takes into account only the parameters recommended in the literature, and a calibrated mathematical model.

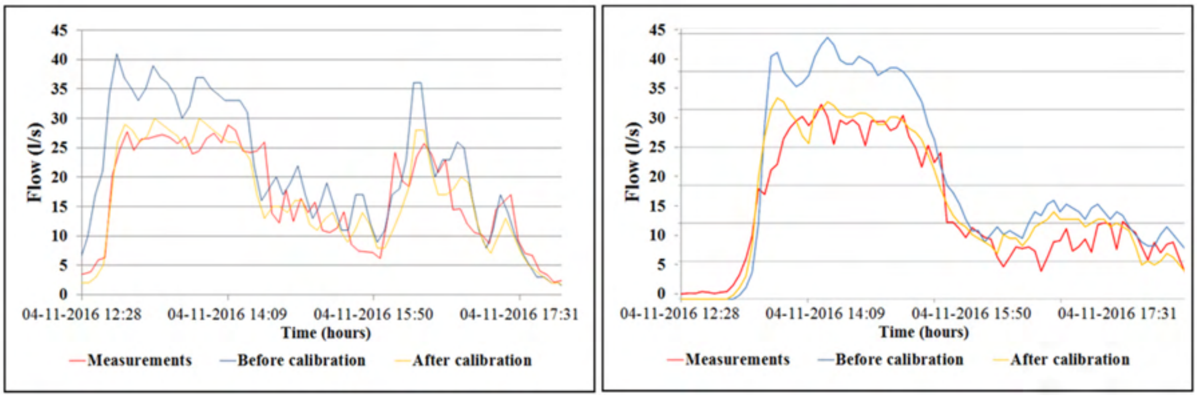


Figure 5 *Water flows carried by the sewer system before and after calibration at the point of measurement R24F028 (left) respectively at the measurement point R24F504 (right)*

5.6. The effects of climate change on sewer systems

Forecasts based on historical observations suggested that precipitation events in the Ølsted area over the past two decades will increase in terms of frequency and intensity. This increase resulted in a higher one than forecasts suggested. This is most likely indicated by anthropogenic greenhouse gas emissions (Arnbjerg-Nielsen, 2012).

5.6.1. Calculation of a 10-year event statistical rain

For the calculation of statistical rain with a a 10-year event, the latest version of the Skrift 30 guide was used. In this version are presented the average annual precipitation (the number of extreme events) and the average daily extreme precipitation (magnitude of events) according to the regional climate model (1989-2010). In the statistical calculation, the research area is identified on the basis of the coordinates x (east) - y (north) where the ETRS 1989 UTM ZONE 32N coordinate system is used. Once the area is identified, average annual rainfall and average daily rainfall are automatically identified from the database. Based on this calculation, the average annual rainfall in Ølsted is 668 mm and the average daily rainfall is 27.7 mm/day.

In the calculation of statistical rain with a 10-year event, the following factors were used: the safety factor of the model (f_{sm}), the climate factor (f_c), and the safety factor that takes into account the runoff coefficient (f_{cs}). The safety factor of the model is a factor that introduces in the calculation of statistical rainfall the degree of safety (reliable) of the network model. This factor can only be considered 1 when the degree of trust of the network model is very high. Taking into account that the model used in this research is a calibrated model, where calibration errors are less than 10%, the degree of safety of the network model is a very high one. That is why the safety factor of the Ølsted model will be considered 1. Version 30 of the guide (Skrift 30) takes climate change into account, thus providing recommendations for the use of climate factors for the purpose of sizing new sewer systems or for the rehabilitation of existing sewer systems. The safety factor that takes into account the drainage coefficient is a factor that takes into account the appearance of new impermeable or very less permeable areas (houses, roads, parking lots, etc.) in the sewer basins. In this research the safety factor that takes into account the runoff coefficient will be considered 1 only for the present situation in which climate change is not taken into account. In all 4 scenarios where climate change is included this factor will be considered 1.1.

The safety factors calculated using Equation (2.4) are shown in Table 5.1.

***Table 5.1** Safety factors used (Skrift 30, 2014)*

Period / Factors	Present	100-year horizon		Horizon for 50 years	
		"Standard"	"High Grade"	"Standard"	"High Grade"
f_c	-	1,3	1,7	1,15	1,35
f_{sm}	1	1	1	1	1
f_{cs}	1	1,1	1,1	1,1	1,1
f_s	1	1,43	1,87	1,265	1,485

The duration of the calculated events is 6 hours, and the time step is 10 minutes. Following the calculation of the statistical rains based on the calculated parameters, 5 statistical rain events presented in Table 5.12 resulted. These events represent the basis from which 5 scenarios were created and will be presented in what follows.

5.6.2. Mathematical modelling of the sewer system

The 1D mathematical model of the sewer system (Figure 5.2), calibrated in the previous chapter, has an area of 46 ha. This area is divided into 921 sewer basins. In this area, the sewer system is 80% unitary and 20% divisive. The calibrated mathematical model of the sewer system consists of 291 manholes, 292 circular pipes, 2 pumping stations, 1 spillway, a wastewater pumping station and a treatment plant:

5.6.2.1. Scenario 1

The first scenario is called S1 simulates the behaviour of the sewer system during event 1 with a probability of exceeding it every 10-years representing the present situation without taking into account climate change and without considering the emergence of new impermeable or very less permeable areas in the sewer basins. The event of precipitation with a probability of exceeding once every 10-years was created according to the increase in extreme precipitation events over the past two decades. In scenario 1, the hydrological rain-drain model uses the CDS 10 1.00 synthetic rain event where precipitation reaches 41.65 l/m2 in 6 hours. Following the modelling of Scenario 1, 23 of the 291 manholes were flooded due to the under sizing of the sewer system. The most affected area is located in the eastern, southeaster part of the model (Figure 5.5 Sc1).

5.6.2.2. Scenario 2

The second S2 scenario simulates the behaviour of the sewer system during event 2 with probability of overtaking every 10-years taking into account climate change over a 100-year horizon considering a standard climate factor of 1.3. At the same time, in this scenario, the emergence of new impermeable or very less permeable areas in the sewer basins was taken into account. In scenario 2, the hydrological rain-drain model uses the CDS 10 1.43 synthetic rain event where precipitation reaches 59.56 l/m2 in 6 hours. The results of the Scenario 2 modelling indicate 55 of the 291 manholes could be flooded due to the undersized sewer system. The affected areas are located in the centre and south-east of the Ølsted area (Figure 5.5 Sc2).

5.6.2.1. Scenario 3

The third S3 scenario simulates the behaviour of the sewer system during event 3 with a probability of overtaking every 10-years taking into account climate change over a 100-year horizon considering a high-grade climate factor of 1.7 that takes into account the emergence of new impermeable or very less permeable areas in sewer basins. In scenario 3, the hydrological rain-drain model uses the CDS 10 1.87 synthetic rain event where precipitation reaches 77.88 l/m2 in 6 hours. The results of scenario 3 modelling (Figure 5.32) indicate that 133 of the 291 manholes could be flooded due to undersized sewer system. According to this scenario, most of the Ølsted system becomes vulnerable (Figure 5.5 Sc3).

5.6.2.2. Scenario 4

The fourth S4 scenario simulates the behaviour of the sewer system during event 4 with a probability of overtaking every 10-years taking into account climate change over a 50-year horizon considering a standard climate factor of 1.15 that takes into account the emergence of new impermeable or very low-permeable areas in sewer basins. In scenario 4, the hydrological rain-drain model uses the CDS 10 1,265 synthetic rain event, where precipitation reaches 52.69 l/m2 in 6 hours. The results of the Scenario 4 modelling show that 37 of the 291 manholes could be flooded during event 4 due to the under sizing of the sewer system. The affected areas are located in the centre and south-east of the Ølsted area (Figure 5.5 Sc4).

5.6.2.3. Scenario 5

The fifth S5 scenario simulates the behaviour of the sewer system during event 5 with a probability of overtaking every 10-years taking into account climate change over a 50-year horizon considering a high-grade climate factor of 1.35 that takes into account the emergence of new impermeable or very sparingly permeable areas in sewer basins. In scenario 5, the rain-drain hydrological model uses the CDS 10 1,485 synthetic rain event, where precipitation reaches 61.85 l/m^2 in 6 hours. The results of scenario 5 modelling indicate that 63 of the 291 manholes could be flooded due to undersized sewer system. According to this scenario, the affected areas are located in the centre and south-east of the Ølsted area (Figure 5.5 Sc5).

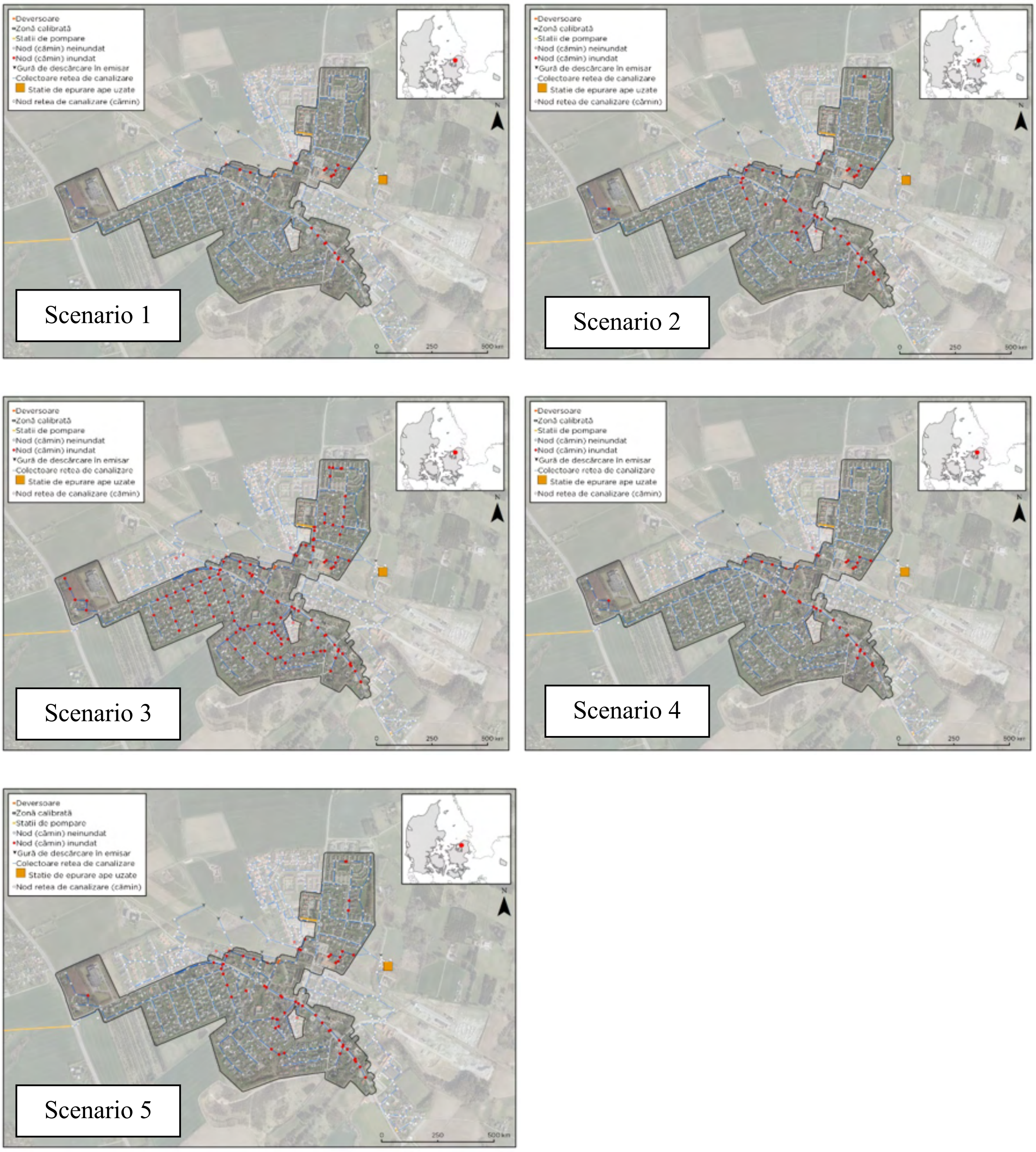


Figure 5 *Scenarios studied to show the effects of climate change on the sewer system Ølsted - Representation of vulnerable areas*

5.6.3. Results

The 5 scenarios created study the impact of climate change and urbanization on the sewer system in Ølsted. Three sections of the sewer system were chosen to analyse the quantities of water transported by the sewer system in relation to the transport capacities of the pipes. The first location chosen (Figure 5.6, location 1) is a concrete pipe with a diameter of 490 mm and a slope of 0.0222. The carrying capacity of the collector is 589 l/s, and when this capacity is exceeded, the collector comes under pressure. Thus, in this location, the results of scenario 3 modelling show that the inclusion of urbanization and climate change over a 100-year time horizon makes this section of the sewer system come under pressure due to its under sizing. The second location chosen (Figure 5.6, location 2) is a concrete pipe with a diameter of 400 mm and slope of 0.0111. The carrying capacity of the collector is 242 l/s, and when this capacity is exceeded the collector comes under pressure. The results of mathematical modelling have shown that this section cannot carry rainfall flows in any scenario that includes climate change, regardless of the climate horizon and the emergence of new impermeable or very poorly permeable areas in sewer basins. The third location chosen (Figure 5.6, location 3) is a concrete pipe with a diameter of 500 mm and a slope of 0.0046. The carrying capacity of the collector is 283 l/s. The results of mathematical modelling have shown that this section can carry rainfall flows in all scenarios that include climate change regardless of the climate horizon and urbanization.

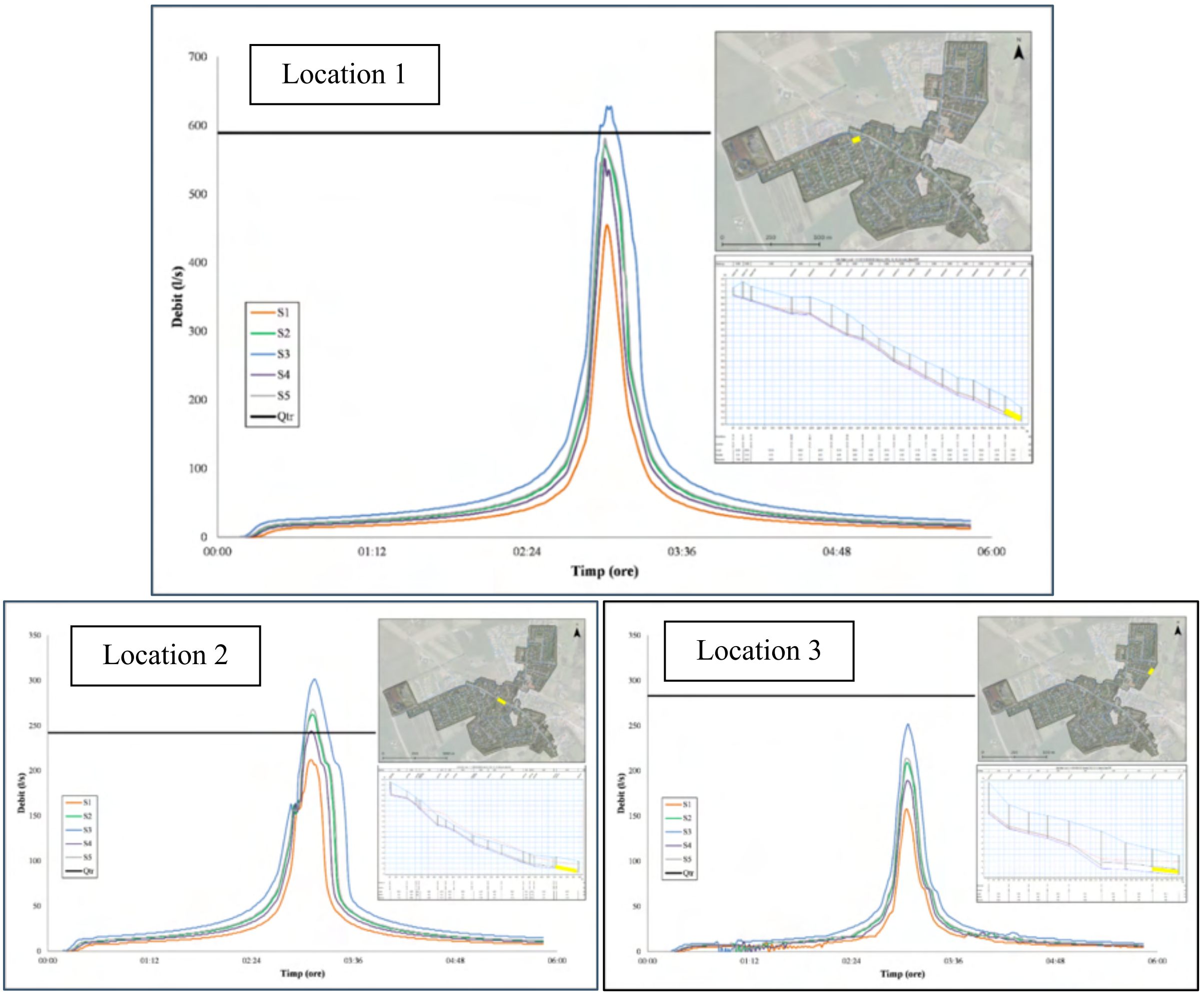


Figure 5.6 *Analysis of the quantities of water reached in the sewer system in relation to the transport capacities of the pipes*

6. RUNOFF MODELLING IN URBAN AREAS TAKING INTO ACCOUNT CLIMATE CHANGE

6.1. Introduction

In the last 30 years, changes in precipitation have been observed in Denmark, visible changes mainly in the frequency of extreme events, but also in their scale (Arnbjerg-Nielsen, 2012). There are different approaches to adapting cities to these extreme events. One approach is conventional adaptation in which the sewer system is expanded, but this is not always possible due to the very high implementation costs. Another approach is the adaptation of the urban landscape for rainwater management, which is often called low-impact development (LID) or sustainable urban drainage systems (SUDS) and involves elements of green infrastructure (GI) (Fletcher et al., 2014). Sustainable urban drainage systems offer many possibilities to "rebuild" cities taking into account the space needed for rainwater. This will allow cities to redirect rainwater to areas designed and suitable for flooding, inside or outside cities, during extreme rain events. This approach has become increasingly popular in Denmark in recent years (The City of Copenhagen, 2015). In this context, the precise modelling of storm runoff in urban basins is very important, but it is difficult to achieve due to the complexity of modelling green areas (DHI, 2015). Depending on local practice, available software, data availability, the possibility of data processing, calculation time and even the modeler experience, storm drains from urban basins can be analysed using different modelling approaches. The choice of modelling approach, precipitation loads on the model and model parameters are very important steps that must be carried out with caution, and therefore it is necessary to establish more accurate guidelines to help modelers choose the most suitable modelling approach.

This chapter focuses on the complexity of modelling rainwater movements in urban basins during extreme events, with a focus on taking into account green areas and SUDS. Four different flood modelling approaches are developed, tested and compared using the MIKE FLOOD (DHI) software package. Runoff in urban basins is modelled by taking into account green areas by an initial loss of the model or by using the Horton equation, with a high infiltration capacity at the beginning of the event. Surface drainage from green areas is either included in the drain pattern as a drain that loads the drainage system, or by loading on the 2D surface model without previous interaction with the sewer system.

6.2. Basic data

Between January 2016 and June 2016, I had the opportunity to be accepted to study at the Danish Technical University of Denmark where I was a PhD student in the DTU Environment Department. There, under the guidance of Prof. Univ. Dr. Ing. Peter Steen Mikkelsen studied runoff modelling in urban areas taking into account climate change. The results of this research were presented at the Conference "*The 4th Nordic Conference on Climate Change Adaptation - From Research to Action and Transformation*" in Bergen, Norway.

In this research, different approaches to runoff modelling have been studied taking into account climate change have been applied to the Nørrebro district (276 ha) in Copenhagen, Denmark, where a large number of SUDS measures have been implemented as part of the Copenhagen climate change management plan (The City of Copenhagen, 2015). In the hydraulic model of the existing sewer system, all 36 sub-projects (sustainable urban drainage systems) were included, which have the role of transporting most of the precipitation volumes. These durable urban drainage systems have been designed to completely protect the Nørrebro area in the event of a precipitation event with a 10-year event and partially in the event of a precipitation event with the probability of occurrence of once every 100-years.

The main conceptual hydrological model used in Denmark for modelling rainwater is 'MOUSE Model A'. This approach uses the "Time-Area" method taking into account a linear drain and a fixed permeable surface. This method includes usually minor losses in the form of initial loss and a hydrological reduction factor, which is usually a factor used to calibrate the hydraulic model. The "Time-Area" curve describes the area that contributes rainwater to the runoff calculated in the hydrological model and is defined according to the area of the sewer basin, the concentration time (TOC) and the shape of the catchment area. The conceptual model 'MOUSE Model A' can be replaced by the conceptual hydrological model 'MOUSE Model B'. This method of calculation is based on the calculation of a nonlinear reservoir that is described by the kinematic wave equation. This equation assumes uniform flow conditions on the surface and a uniform distribution of precipitation. The physical system included in the model consists of the following components: the runoff model (sewer basins), the sewer system and the 2D surface (land surface). The link between the main components is shown in Figure 6.1.

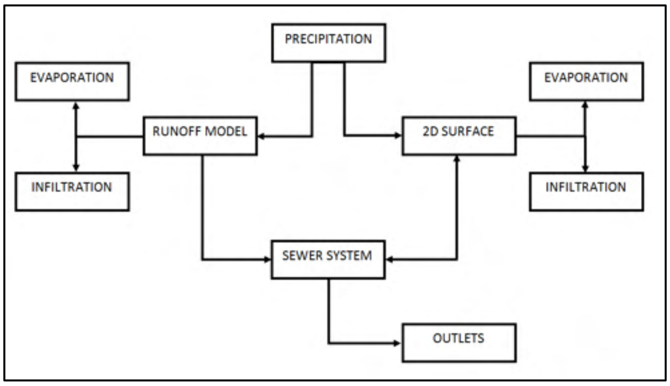


Figure 6.1 *The link between the main components of a flood calculation model*

6.3. Modelling hypotheses

The first modelling approach chosen for this study (M1) includes an initial loss in the calculation of the hydrological model, both for runoff from permeable surfaces and for runoff from non-perishable surfaces. The conceptual model used here is 'MOUSE Model A'. The runoff from permeable surfaces (green areas, parks,) and non-perishable (roofs, roads, parking lots) are reduced by initial losses. Their value is considered 0.0006 m. These losses are limited, which means that with the increase in the intensity of the rain event the importance of these losses decreases, and the runoff approach 100% in the case of extreme events (DHI, 2015). The representation of the surfaces that are included in the M1 modelling approach is shown in Figure 6.2. In this case the permeability of the areas contributing to the model will be included in the analysis. Leaks from Impermeable areas will be reduced as follows: roof drains will be reduced by 5%, road drains will be reduced by 10%, and leaks from the parking surface will be reduced by 15%. For this analysis the hydrological reduction factor used will be 1, which means that all losses will be included only in the initial losses. The runoff from permeable surfaces will primarily depend on the infiltration capacity of the soil.

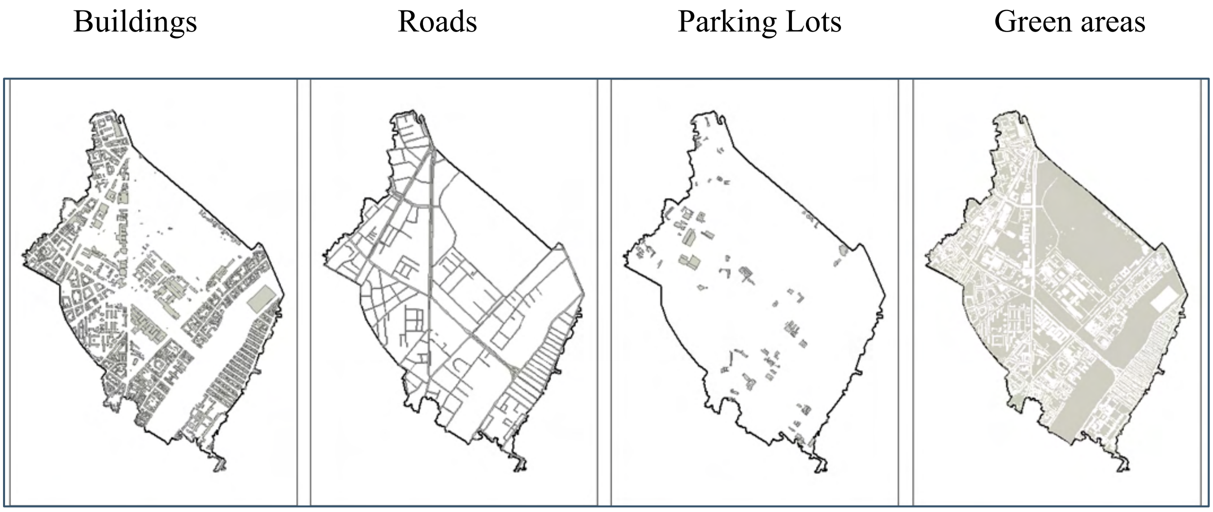


Figure 6.2 *Representation of surfaces that are included in the modelling approach M1*

The second modelling approach (M2) introduces in the calculation of the hydrological model only the runoffs coming from non-perishable areas, and in the hydraulic model they will directly contribute to the loading of the drainage system. The conceptual leakage model used here will be 'MOUSE Model A' which means that runoff from non-permitted areas will be calculated the same as with the M1 modelling approach. The difference between the M2 and M1 approach is that in the case of the M2 modelling approach, runoffs from permeable surfaces will be applied directly to the 2D land surface. Thus, part of these surface leaks will be transported on the ground to the depression areas where they will remain blocked, evaporate or inflate into the soil before turning into leaks that load the sewer system. The representation of the areas included in the M2 modelling approach is shown in Figure 6.3.

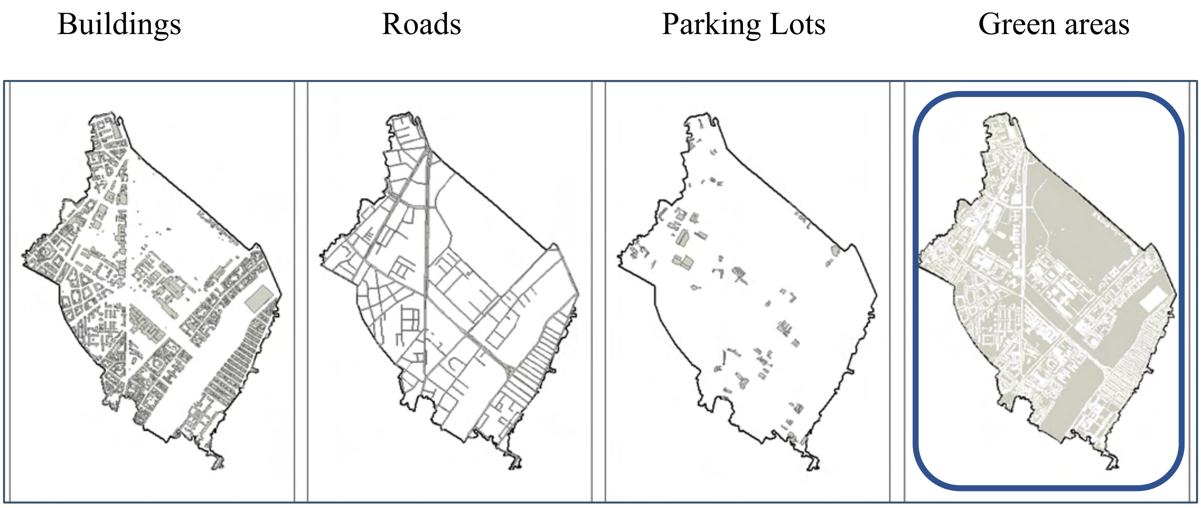


Figure 6.3 *Representation of surfaces included in the M2 modelling approach*

The third modelling approach (M3) is to divide the percentage of sewer basins into non-perishable surfaces and permeable surfaces, thus considering that all sewer sub-basins are identical. The conceptual model of the leak used here is the "MOUSE Model B", a model that applies the Horton equation:

$$I_H(t) = I_{Imin} + (I_{Imax} - I_{Imin}).e^{-k_a.t} \tag{6.1}$$

where:

$I_{H(t)}$ Horton infiltration (m/s);

I_{Imin} initial (maximum) infiltration capacity (m/s);

I_{Imax} final (minimum) infiltration capacity (m/s);

K_a empirical constant (time factor) (s-1);

t time since the rainfall starts (s).

The Nørrebro basin is divided into 40% flat Impermeable areas and 60% permeable areas (Figure 6.4) with an average infiltration capacity. Impermeable areas such as roofs, roads and parking areas are reduced by the initial losses divided into: $5x10^{-5}$m initial losses in wetlands and $6x10^{-4}$m initial losses stored. The runoff from Impermeable areas is also reduced by initial losses: $5x10^{-5}$m initial losses in wetlands and $4x10^{-2}$ m initial losses stored.

Figure 6.4 *Representation of the surfaces included in the M3 modelling approach*

The soil type is clayey and based on the infiltration parameters in the literature, the maximum infiltration capacity has been established $5x10^{-5}$ m/s and will be reduced during the rain event to $1x10^{-6}$ m/s. Non-perishable surfaces are divided into steep surfaces (roofs) and flat surfaces (parking lots) while the permeable areas are divided into permissible areas where the infiltration capacity is high, medium and small. In this study for ease of calculation the assumption is that all non-perishable surfaces in the model are flat et all permeable areas have an average infiltration capacity. This method allows to take into account infiltrations for permeable areas where infiltrations decrease exponentially. A high infiltration capacity at the beginning of the precipitation event is also taken into account. For this conceptual model, the properties of the soil are represented by the input parameters.

The fourth modelling approach (M4) is to include only surface leaks from non-permitted areas calculated with the "MOUSE Model B" drain conceptual model as direct load on the sewer system. The runoff from non-permitted areas will be calculated the same as in the M1 modelling approach. Like the M2 modelling approach, in the M4 modelling the surface leaks from the permeable areas will be introduced directly into the 2D surface model. To make this possible, rainfall will be processed in advance in order to exclude losses and thus include only the runoff. The initial losses will be considered: $5x10^{-5}$ m initial losses in wetlands and $4x10^{-2}$

m initial losses stored. As for the infiltrations considered, these will be the maximum infiltration capacity $5x10^{-5}$ m/s to be reduced during the rain event to $1x10^{-6}$ m/s. The representation of the surfaces included in the M4 modelling approach is shown in Figure 6.5.

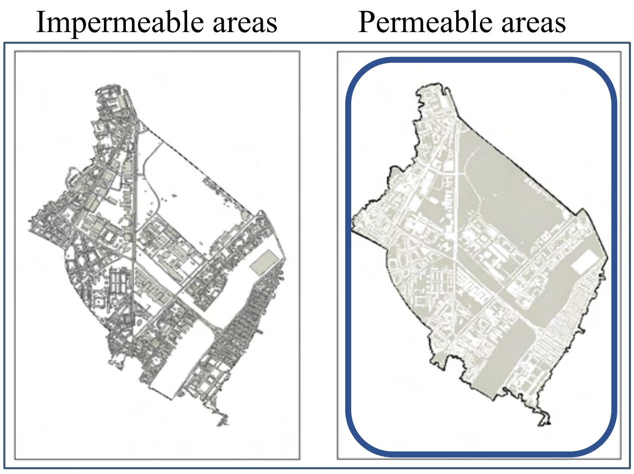


Figure 6.5 Representation of surfaces included in the M4 modelling approach

6.4. Runoff calibration

A calibration based on measured values will not be possible in this research, as flood observations are not available. However, a calibration of the models used in the 4 proposed modelling modes will be done by the method of comparing the models. This will allow the investigation of the various choices that must be made in the process of hydrological modelling in order to obtain a more real representation of the flooded surface. The use of different hydrological parameters or the modification of hydrological parameters could have a very big impact on the calculation of the runoff. In this study, the hydrological model used for calibration is the "MOUSE Model B" (also used in the M3 modelling method), since it is the most complex hydrological model. Following the running of the hydrological model used in the M3 modelling method for an event with a a 10-year event, it resulted that in the permeable areas the rains could not infiltrate completely.

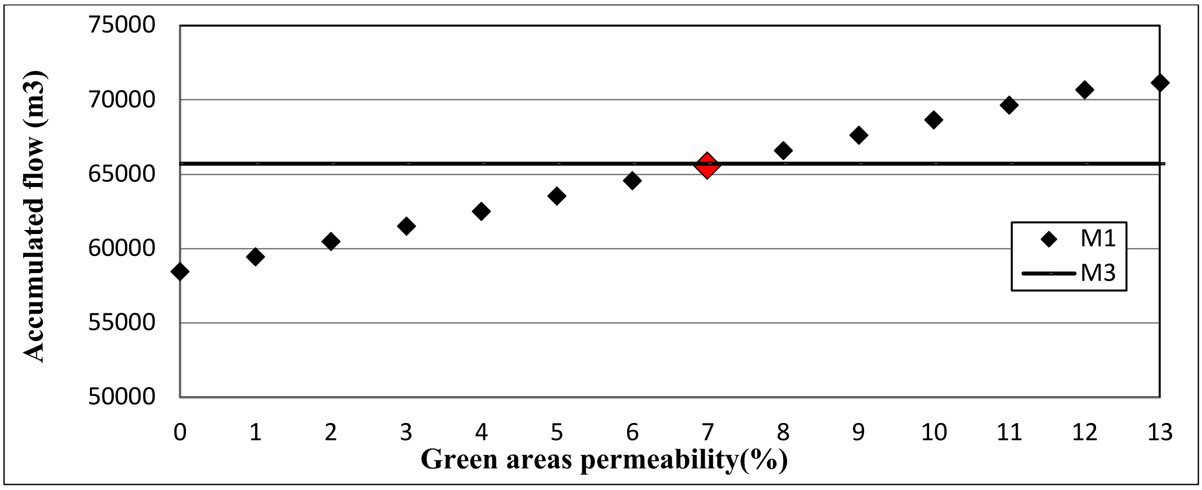


Figure 6.6 *Calibration of the hydrological model used in the modelling method M1 using the hydrological model used in the modelling method M3 for an event with a probability of occurrence every 10-years*

Thus, the calibration of the hydrological model (Figure 6.6) used in the M1 modelling method using the hydrological modelling model used in the M3 modelling method showed that 7% of the studied precipitation event can no longer infiltrate, thus contributing to the volumes transported by the sewer system.

According to the results obtained, the permeable surfaces in the Nørrebo catchment will generate a significant surface drain following an event with a a 100-year event. As shown in Figure 6.7, after the calibration of the hydrological model used in the M1 modelling method using the hydrological model used in the modelling method M3, 42% of the studied precipitation event will generate runoff, after excluding the initial losses and infiltrations, thus contributing to the volumes transported by the sewer system.

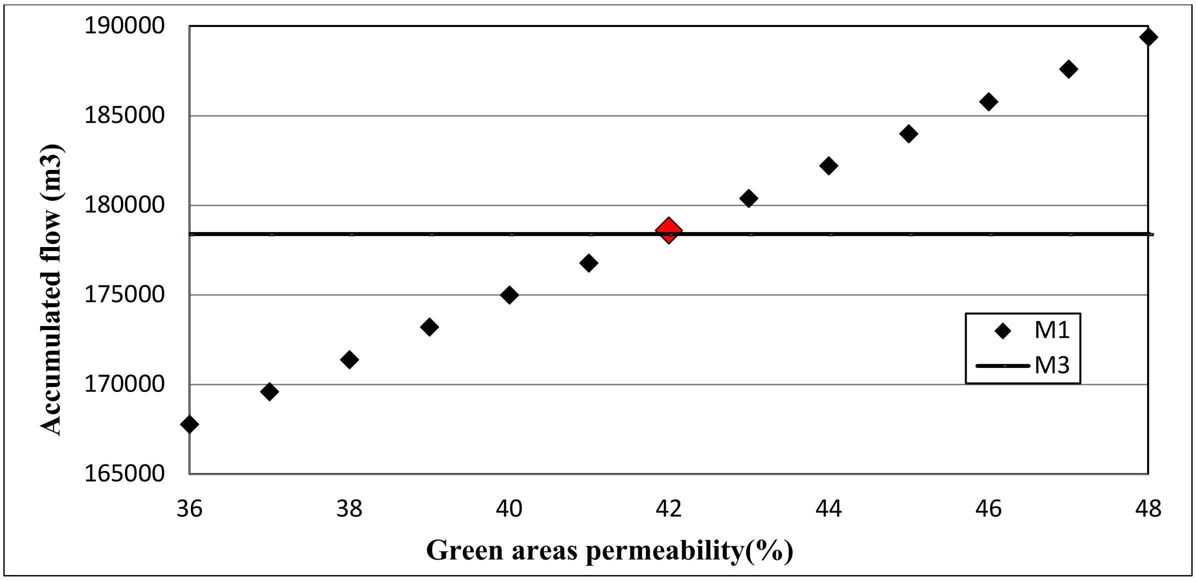


Figure 6.7 *Calibration of the hydrological model used in the modelling method M1 using the hydrological model used in the modelling method M3 for an event with a a 100-year event*

In the M2 and M4 approaches because runoff from permeable surfaces will be applied directly to the 2D land surface, part of these surface leaks will be transported on the ground to the depression areas where they will remain blocked, evaporate or infiltrate the soil before turning into leaks that load the sewer system. In order to be able to reproduce this, given that the physical representation of the sewer sub-basins does not change, it is necessary to make adjustments to the drainage parameters. In the case of the M2 modelling approach, the permeability of the green areas was set at "0%" and in the case of the M4 modelling approach the minimum infiltration capacity was set at 1m/s. In this way, leaks from green areas directly connected to the sewer system will be excluded, and runoff volumes that may overlap will be avoided. The results of running the hydrological model used in the modelling method M3 for an event with a probability of occurrence of once every 10-years, showed that rain-permeable areas cannot infiltrate completely. The calibration of the hydrological model (Figure 6.8) used in the modelling methods M2 and M4 was made using the hydrological model used in the modelling method M3.

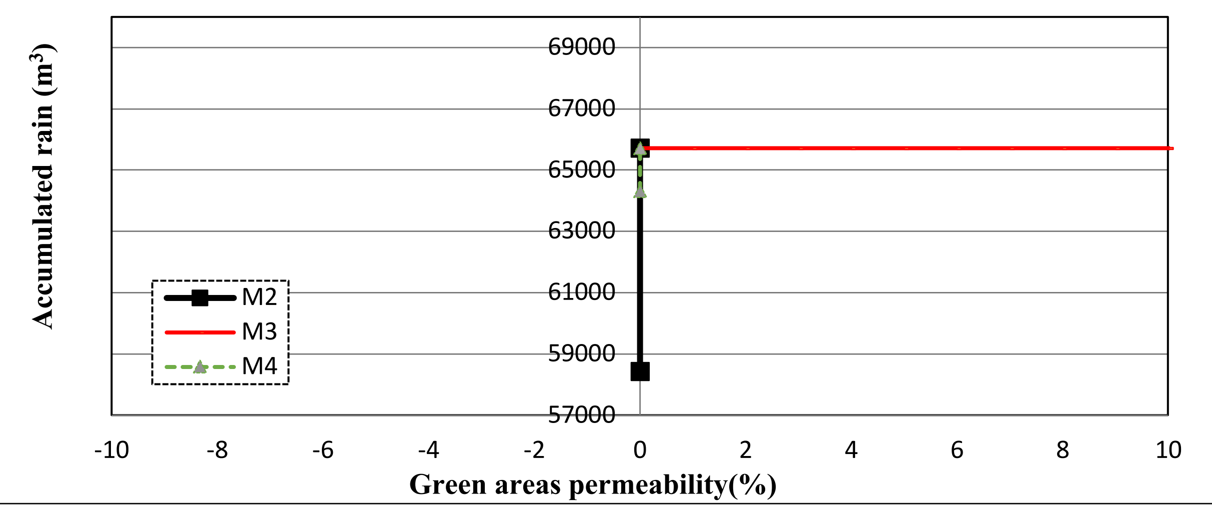


Figure 6.8 *Calibration of the hydrological model used in the modelling method M2 and M4 using the hydrological model used in the modelling method M3 for an event with a a 10-year event*

Also, the results of the run of the hydrological model used in the M3 modelling method for an event with a probability of occurrence of once every 100-years will generate a significant runoff. The calibration of the hydrological model used in modelling methods M2 and M4 using the hydrological model used in the modelling method M3 is shown in Figure 6.9.

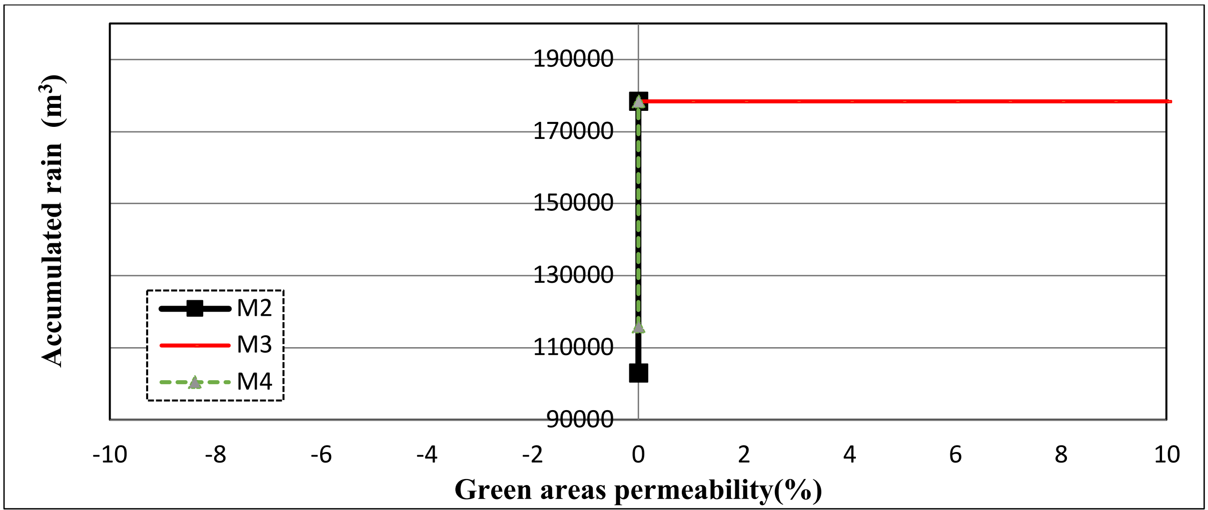


Figure 6.9 *Calibration of the hydrological model used in the modelling method M2 and M4 using the hydrological model used in the modelling method M3 for an event with a probability of occurrence every 100-years*

6.5. Results

Different methods for comparing the proposed modelling approaches and their performance are used in this study. The comparison will be made on the basis of common criteria: Both the surface flow from non-perishable surfaces and the surface flow from permeable surfaces is applied to the network model (M1 vs M3); Runoff from non-perishable surfaces is applied to the network model, and runoff from permeable surfaces is applied directly to the 2D surface (M2 vs M4); Runoff from non-perishable surfaces is calculated using the conceptual model A

(M1 vs M2); Runoff from non-permitted surfaces is calculated using the conceptual model B (M3 vs M4).

6.5.1. Hydrological modelling results

In this study the hydrological model used for calibration is the "MOUSE Model B" used in the M3 modelling method. Following the running of the hydrological model used in the M3 modelling method for an event with a a 10-year event, it resulted that in the permeable areas the rains cannot infiltrate completely. The calibration of the hydrological models used in the modelling methods M1, M2, M4 using the hydrological model used in the modelling method M3 showed that the runoff introduced in the hydraulic model are approximately equal. The volumes of accumulated rain entered in the hydraulic model for a 10-year event are shown in Figure 6.10.

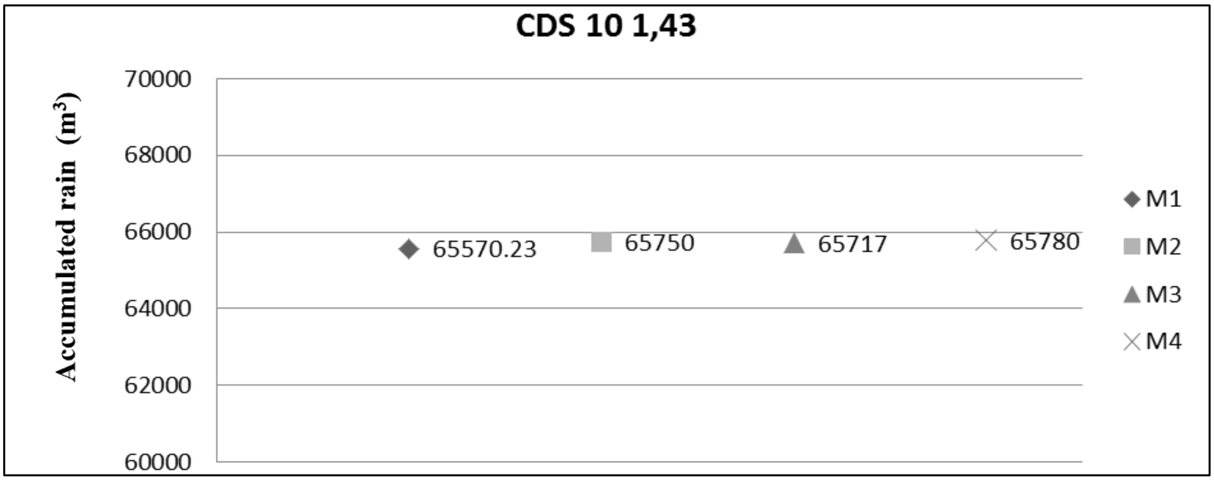


Figure 6 *Accumulated rain in case of a 10-year event*

Also, following the calibration of the hydrological models used in the modelling methods M1, M2, M4 with the help of the hydrological model used in the modelling method M3 for an event with a probability of occurrence of once every 100-years, the runoff introduced in the hydraulic model are approximately equal, so the accumulated rain volumes introduced into the hydraulic model for an event with the probability of occurrence of once every 100-years are shown in Figure 6.11.

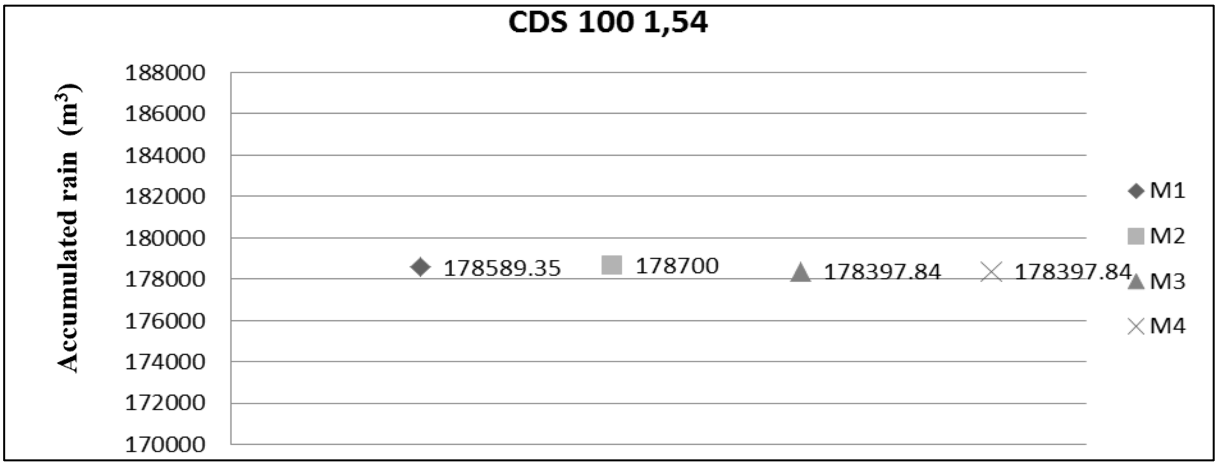


Figure 6 *Accumulated rain for in case of a 100-year event*

6.5.2. Hydraulic modelling results

6.5.2.1. Flood limit

Areas have been observed where due to the fact that the surface drainage has loaded the sewer system, an instability has been created in the hydraulic model, thus generating fictitious floods (M1 vs M3). It has been observed that in the case of modelling approaches where runoff from permeable surfaces was applied directly to the 2D land surface (M2 and M4), some of the runoff was transported on the ground to the depression areas where they remained blocked in the event of a precipitation event with a 10-year event, no significant loads of the sewer system were observed, the contribution of the green areas being very small. In Figure 6.12, the results obtained from the M1 modelling method are compared with the results obtained from the M2 modelling method.

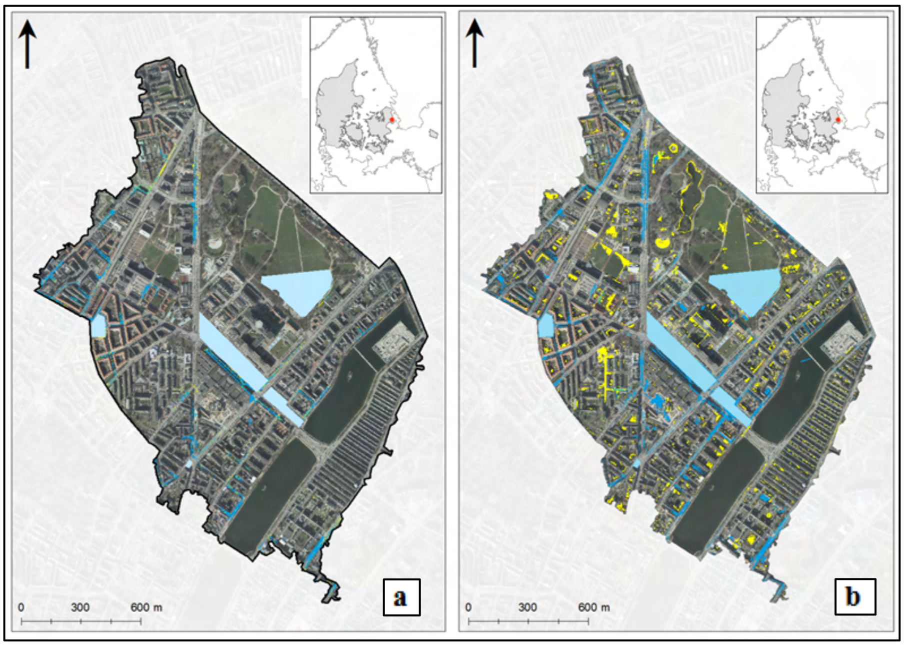


Figure 6- *Observed flood limit for a 10-year event; b- Observed flood limit for a 100-year event*

6.5.2.2. Flooding depth

In the case of a precipitation event with the probability of occurrence of once every 100-years the flooded areas and the depth of the flood differ depending on the chosen modelling method. If the sewer basins are directly connected to the system (M1, M3), the precipitation volumes will be transported by the existing system and after its transport capacity is overcome, the water will be transmitted by the green-blue solutions. In the case of a precipitation event with a 10-year event, no important loads of the sewer system were observed in all 4 modelling approaches studied, the contribution of the green areas being very small. In Figure 6.13 the depth of water (method M1) is represented on depth ranges, from 20 to 20 cm, in different shades of blue (dark blue for large depths and light blue for shallow depths).

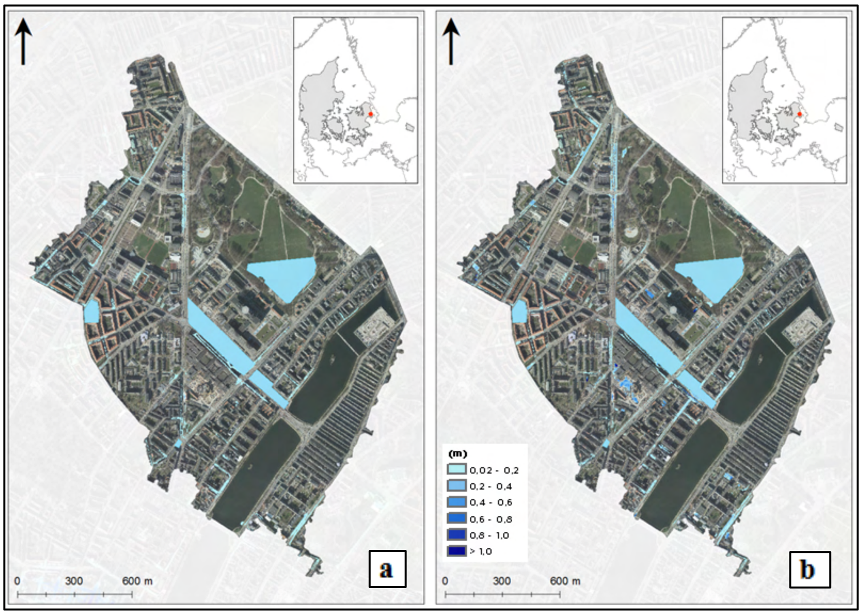


Figure 6 *Flood depth calculated for 10-year event; b-* *Running time in relation to the number of cells that actively participate in the calculation of flooding for a100-year event*

6.5.2.3. Running time and wet cells

The running time of a model is the length of time it takes to perform a calculation process and is proportional to the number of unit transformations performed. The resolution of the model directly influences the number of wet cells (cells that actively participate in flood calculation) and the number of dry cells (cells that do not actively participate in the flood calculation). The analysis of the running times of the models concluded that the running time increases in direct proportion to the number of wet cells, thus obtaining a rolling time of up to 36 hours in the case of a precipitation event with a 10-year event and a running time of 60 hours in the case of a precipitation event with a 100-year event. In the case of the introduction of runoff directly on the 2D surface, the number of active cells increases, which leads to longer running times: 43 hours in the case of a precipitation event with a 10-year event and a rolling time of 116 hours in the event of a precipitation event with a 100-year event.

6.5.2.4. Flooded area and flood volume

The analysis of the flooded areas in relation to the flood volume for each of the 4 modelling approaches showed that there is no direct connection between the flooded area and the flood volume. When precipitation events with a 10-year event are studied, most often even if the flooded area is very large, since the depth of the water does not exceed a few millimetres, the flood volumes do not increase significantly with the expansion of the flooded area. In the situation where both permeable and non-permeable surfaces are directly connected to the sewer system, both the flooded area and the calculated flood volume are smaller than if only the non-perishable surfaces are directly connected to the sewer system. This is because a large part of the runoff from the permeable surfaces was transported on the ground to the depression areas where they would remain stuck before reaching the sewer system. In cases where the events of extreme precipitation are studied (precipitation events with a 100-year event) then the flood volume is directly proportional to the flooded area, this time the depth of the flood exceeding 10 cm.

7. GENERAL CONCLUSIONS

The research theme of this PhD Thesis is the contribution to the development of the capacity to take over the city rainwater in the conditions of climate change. Urban flooding is one of the greatest natural hazards in the damage caused by them largely due to climate change. The impact of floods is devastating in terms of loss of life and material damage (infrastructure, property, etc.). The increasing level of damage caused by natural hazards has made urban flooding a fundamental problem for the continuous development of flood risk management plans. Over the past 30 years, Denmark has seen changes in the frequency and intensity of extreme rainfall events. The starting point of this research was an event that happened in July 2013, when Copenhagen was affected by floods due to an extreme rainfall event, 150 mm in 2 hours and which caused material damage of over 800 million euros.

With the intensification of the torrential nature of rainwater, a special interest has emerged in studying changes due to climate change in daily and extreme precipitation events. In the coming decades, a significant increase in the frequency and intensity of precipitation is expected. The present PhD Thesis aims to present the effects due to climate change of the daily and extreme precipitation events, taking into account the urbanization. At the same time, it is desired to present the benefits of installing sustainable urban drainage systems by creating and using mathematical models that use complex modelling approaches designed to describe as much as possible the effects of climate change in terms of precipitation.

To exemplify the impact of climate change and urbanization on the rain, the Ølsted catchment was studied. Chapter 5 presents the need for a better understanding of how to model the runoff and thus the volumes of water transported by the sewer system. Validation and calibration of the sewer system is a mandatory first step to follow. The calibration of the mathematical model was carried out exclusively taking into account the hydrological parameters that directly influence the amount of rainwater discharged into the sewer system. The target of this calibration was that the volume and maximum errors recorded to be up to 10%, and the correlation coefficient (R) to be between 0.8 - 1. All events were calibrated separately, and the analysis performed on the runoff parameters resulted in values that matched in more than 50% with the recorded events. In order to determine the water flows transported by the sewer system, the hydrological reduction factor, the concentration time and the initial losses as recommended in the literature were taken into account, thus making it possible that after calibration, the model would be able to convey a transported flow rate and a depth of water in the channel similar to the measured data. Climate change has a significant impact on the urban environment, so it was important to develop a mathematical model that would be able to reproduce present situations in terms of precipitation.

After the mathematical model of the sewer system is calibrated, it can be used in the rapid analysis of the consequences of increasing the intensity of precipitation due to climate change and urbanization (the emergence of new impermeable or very poorly permeable areas in sewer basins). The sewer system in Ølsted is dimensioned, according to design standards, to cope with an event with the probability of exceeding it once every 10-years, an event calculated exclusively on the basis of the historical rainfall records available until the design time. Because it is desired to quantify the effects of climate change on the sewer system in Ølsted, the calibrated network model will be used to analyse the vulnerability of the system in case of occurrence of precipitation events that take into account climate change and urbanization.

Thus, 5 scenarios were created. The first scenario and wants to test the behaviour of the Ølsted sewer system, in case of occurrence of a precipitation event with a 10-year event, created according to the rain events measured in the last two decades. The 4 scenarios that take into account Skrift 30's recommendations regarding climate change on a climate horizon of 50 and 100-years.

In the past, forecasts based on historical observations suggested that precipitation events over the past two decades would increase. The results of this research have proven that this increase is actually higher than anticipated at the time of designing the Ølsted sewer system. It is noticed that in the forecast the sewer system cannot cope with a precipitation event with a 10-year event (it is undersized). Increasing the intensity of precipitation and urbanization leads to very large runoff and thus to an increase in the risk of flooding. Increasing rainfall intensity and urbanisation will lead to flooding in different parts of Ølsted. The results indicated the clear need to include climate change and urbanisation when a new sewer system is sized or when an existing sewer system is rehabilitated. As a result of the simulations made, it was possible to identify and analyse the sections of the sewer system whose transport capacity is exceeded, and which implicitly lead to the pressure entry of the sewer system. This is very important because once the vulnerable areas in the system have been identified, various solutions can be sought and tested to reduce floods, thus protecting the Ølsted area from the effects of climate change and urbanisation.

A better understanding of how to model the runoff and thus the volumes of water transported by the sewer system is needed. Therefore, modelling hypotheses must be very well defined. Denmark is one of the countries that is making great progress in developing sustainable urban drainage systems (SUDS) that give rise to so-called "green-blue" cities. This requires local analysis that can be done by building mathematical models that are used to test the effectiveness of various rainwater management solutions designed to protect the urban environment. Chapter 6 focuses on the complexity of modelling rainwater movements in urban basins during extreme events, with an emphasis on modelling green areas and sustainable urban drainage systems. Different modelling approaches were presented and applied to the Nørrebro catchment (276 ha) where a large number of sustainable urban drainage systems will be implemented as part of Copenhagen's climate adaptation plan. 4 different flood modelling approaches are developed, tested and compared. In the M1 and M3 modelling approaches, runoff is included in the mathematical model as a drain that charges the sewer system in both waterproof and green areas through an initial loss in the model as it happens in the M1 modelling approach or by using the Horton equation, where infiltration decreases exponentially with the high infiltration capacity at the beginning of the event as it happens in the M3 modelling approach. When the transport capacity of the sewer system becomes insufficient, the water reaches the 2D surface causing its flooding. In the modelling approaches M2 and M4, runoff is included in the mathematical model as a drain that loads the drainage system only in the case of impermeable or very low-permeable areas by using an initial loss as it happens in the M2 moderation approach or by using the Horton equation, where infiltration decreases exponentially with high infiltration capacity at the beginning of the event as it happens in the M4 modelling approach. In the M2 and M4 modelling approaches, the surface drain from the green areas is applied directly to the 2D surface without prior interaction with the sewer system thus seeking a preferential drainage path to the sewer system. When the transport capacity of the sewer system becomes insufficient, the water again reaches the 2D surface causing its flooding.

Green areas without a drainage system should be treated carefully, especially in the case of very large green areas (parks). If a very large green area is connected at a single point (dormitory) to the sewer system, it will cause an unrealistic flood around the connection point. As a result of the results obtained, it was observed that extreme rainfall events due to climate change lead to very large runoff. To consider both permeable and non-permeable areas connected to the manholes of the sewer system thus contributing directly to the volumes of water transported by the sewer system (M1 and M3), if the surface leaks become quantitatively important, can lead to unrealistic loadings of the sewer system. It has also been observed that in the case of modelling methods M2 and M4 where runoff from permeable surfaces were applied directly to the surface of the 2D land, some of the surface leaks remained blocked in the depression areas and thus, the modelling methods M2 and M4 manage to better simulate reality. Thus, the M2 and M4 modelling approaches manage to describe similarly the sustainable urban drainage systems that will be implemented in the Nørrebro district proving their proper functioning. Instead, the M1 and M3 modelling approaches unrealistically load the sewer system, thus causing fictitious flooding at many points of the system.

The studies presented in this PhD Thesis address the hydraulic and hydrological modelling of urban basins. Throughout this doctoral thesis, it has been illustrated that urban areas have a complex watershed. In addition, due to increasing urbanization, water infrastructure is constantly being modified, we are also facing a changing system with a high degree of uncertainty. Despite technological improvements that have taken place in recent decades, the practical aspects of flood risk assessments still lead to various uncertainties regarding the assessment of flood risk. In modelling these particularly complex systems, modelling hypotheses must be very well defined. Through this PhD Thesis, a contribution is made to a better understanding of the modelling hypotheses, the advantages, and disadvantages of using the modelling approaches presented.

7.1. Personal contributions

The bibliographical study was carried out by consulting the specialized literature (scientific articles, research papers, guides, cartographic materials, etc.) both at the level of Denmark and consulting the existing similar studies. This helps to create a common language on modelling the impact of climate change on precipitation and runoff.

7.1.1. Calibration of sewer systems

A first contribution is to develop a concept of calibration of sewer systems in order to obtain calibration errors below the limit used so far. This was achieved, the calibration errors resulting from this research were below 10%, and the correlation coefficient was between 0.8 and 1. For the calibration of the studied sewer system, they were used in the calibration of the model 3 parameters:

- initial loss (IL) – represents the depth of precipitation required to start the runoff;
- hydrological reduction factor (RF) – introduces in the surface hydrological model a reduction of the runoff generated from the sewer basins following the water losses caused by evapotranspiration, increased permeability of partially permeable areas, etc.;
- concentration time (TOC) - represents the length of time during which rainwater fallen on the farthest surface of the catchment into the sewer and reaches the calculation section.

7.1.2. The effects of climate change on sewer systems

Another contribution is to help better understand the creation of mathematical models to study the behaviour of existing sewer systems, networks often sized solely on the basis of historical rainfall records. These models can be successfully used to simulate the occurrence of extreme precipitation events that consider climate change and urbanization.

7.1.3. Runoff modelling

Another contribution is to improve the understanding of the runoff modelling process by creating hydrological models that can be successfully used to simulate runoff arising from precipitation events that take into account climate change and urbanization.

7.1.4. Choosing the right urban flood modelling approach

A contribution to improving the understanding of the urban flood modelling process was the elaboration of the 4 modelling approaches studied in Chapter 6, each of which had a different approach to a common problem, selecting the modelling approach:

- The first modelling approach chosen for this study (M1) includes an initial loss in the calculation of the hydrological model, both in the case of runoff from permeable surfaces and in the case of runoff from non-perishable surfaces. The conceptual model used here is 'MOUSE Model A';

- The second modelling approach (M2) introduces in the calculation of the hydrological model only the runoff coming from non-perishable areas, these will directly contribute to the loading of the drainage system. The conceptual runoff model used here will be 'MOUSE Model A' which means that runoff from Impermeable areas will be calculated the same as in the case of the M1 modelling approach, and the runoff coming from the permeable areas will be applied directly to the 2D surface;

- The third modelling approach (M3) uses the conceptual model of leakage "MOUSE Model B", a model that uses Horton's equation. In this case, runoff from non-perishable surfaces and permeable surfaces will be directly connected to the sewer system as in the case of the M1 modelling approach;

- The fourth modelling approach (M4) is to include only surface leaks from Impermeable areas calculated with the conceptual drainage model "MOUSE Model B" as a direct load on the sewer system. Runoff from permeable areas will be applied directly to the 2D surface as in the M2 modelling approach.

7.2. Future research directions

There is now a global need for recommendations on runoff modelling. This research has shown that the availability of as much input data as possible is particularly important in the creation of hydrological and hydraulic models. This research aims to provide a better understanding of existing modelling approaches, being support in choosing the most appropriate modelling approach.

The following will be listed various recommendations that could lead to improved understanding of the capacity to take over city rainwater in the conditions of climate change:

- Include as many existing hydrological analyses as possible and/or create new hydrological analyses that take into account climate change and urbanisation. Verification of the estimates of the design flows used. Depending on the availability of data, the approach to estimating debts may be different.

- In this work, in 1D modelling, calibration and validation of hydraulic models, two variables were used: the flow rate and the water level. Also, a recommendation is to use in the process of calibration and validation of hydraulic models can be the recorded speeds. This could reduce calibration errors.

- In this research, in 2D modelling, a calibration based on measured values was not possible because flood observations were not available. The Nørrebro catchment has been applied to it where a large number of SUDS will be implemented as part of Copenhagen's climate adaptation plan. The calibration of the models used in the 4 proposed modelling methods was done by the method of comparing the models, allowing the investigation of the different choices that must be made in the hydrological modelling process. The recommendation to use measured values could have an important impact on the calculation of runoff in case of extreme events.

- In this research for 2D modelling, a model with rectangular elements was used, having a single cell size along the boundaries of the model (models with finite differences). A recommendation for future research is to use another of 2D modelling methods, namely, to create flexible mesh 2D models (finite element models). This method uses triangular elements that can vary in size and shape along the boundaries of the model that could improve the running times of the model, as well as the accuracy of the description of the elements introduced in the 2D model.

8. REFERENCES

Articles:

Arnbjerg-Nielsen K., (2012), *Quantification of climate change effects on extreme precipitation used for high resolution hydrologic design*, Urban Water Journal, 9, 57-65.

Arnbjerg-Nielsen K., Leonardsen L., Madsen H., (2015), *Evaluating adaptation options for urban flooding based on new high-end emission scenario regional climate model simulations*, Climate Research, vol. 64(1), 73–84.

Brown R.R., Keath N.,Wong T.H.F., (2009), *Urban water management in cities: historical, current and future regimes*, Water Science andTechnology, 59(5), 847-855.

Bruni G., Reinoso R., van de Giesen N.C., Clemens F.H.L.R., ten Veldhuis J.A.E., (2014), *On the sensitivity of urban hydrodynamic modelling to rainfall spatial and temporal resolution*,Hydrology and Earth System Sciences Discussions, 11, 5991-6033.

Fratini C.F., Geldof G.D., Kluck J. and Mikkelsen P.S., (2012), *Three Points Approach (3PA) for urban flood risk management: A tool to support climate change adaptation adaptation through transdisciplinarity and multifunctionality*, Urban Water Journal, 9, 317.

Gregersen, I.B., Sunyer Pinya, M. A., Madsen, H., Rosbjerg, D., & Arnbjerg-Nielsen, K. (2014), *Climate changes of extreme precipitation in Denmark from 1874 to 2100. In Clima change adaptation adapting adapting to change: from research to decision-making: Abstracts* (pp. 66), Copenhagen.

Grum M., Jørgensen A.T., Johansen R.M., Linde J.J., (2006), *The effect of climate change on urban drainage: an evaluation based on regional climate model simulations*, Water Science &Technology, 54, 9-15.

Hijmans R., Cameron S., Parra J, Jones P, Jarvis A., (2005), *Very high-resolution interpolated climate surfaces of global land areas,* International Journal of Climatology. 25. 1965-1978. 10.1002/game.1276

Ioan A.G., Anton A., (2017), *Sewer system calibration for smart cities*,2017 International Conference on ENERGY and ENVIRONMENT (CIEM), 475-479, Bucharest, Romania.

Mark, Ole & Weesakul, Sutat & Apirumanekul, Chusit & Boonya-aroonnet, Surajate & Djordjević, Slobodan. (2004). Potential and limitations of 1D modelling of urban flooding. Journal of Hydrology. 299. 284-299.

Mikkelsen P.S., Rosbjerg D., Harremoës P., (2005), *Selection of regional historical rainfall time series as input to urban drainage simulations at ungauged locations*, AtmosphericResearch, 77, 4-17.

Mitchell V.G., Deletic A., Fletcher T.D., Hatt B.E., McCarthy D.T., (2007), *Achieving multiple benefits from storm water harvesting,*Water Science andTechnology, vol. 55(4), 135-144.

Roy A.H., Wenger S.J., Fletcher T.D., Walsh C.J., Ladson A.R., Shuster W.D., Thurston H.W., Brown R.R., (2008), *Impediments and solutions to sustainable, watershed-scale urban stormwater management: lessons from Australia and the United States,*Environmental Management42(2),344–359.

Semadeni-Davies A., Hernebring C., Svensson G., Gustafsson L.-G., (2008), *The impacts of climate change and urbanisation on drainage in Helsingborg, Sweden: Suburban stormwater*, Journal ofhydrology (350), 114-125.

Thorndahl S., Rasmussen M.R., (2013), *Short-term forecasting of urban storm water runoff in real-time using extrapolated radar rainfall data*, Journal of Hydroinformatics, 15(3), 897-912

Thorndahl S, Willems P., (2008), Probabilistic modelling of overflow, surcharge and flooding in urban drainage using the first-order reliability method and parameterization of local rain series, Water Res. Jan, 42(1-2): 455-66.

Zhou Q, Panduro T.E., Thorsen B.J., Arnbjerg-Nielsen K., (2013), *Adaption to Extreme Rainfall with Open Urban Drainage System: An Integrated Hydrological Cost-Benefit Analysis*, Environmental Management, 51(3), 586-601.

Dissertations:

Ioan A.G., (2014), *Coupled model for calculating floodplains in residential areas in case of exceptional rainfall. Rainwater management* solutions., Dissertation, Department of

Hydraulics, Urbanity and Environmental Protection, Technical University of Constructions Bucharest, Bucharest, Romania.

Web:

Bülow Gregersen I., Madsen H., Linde J.J., Arnbjerg-Nielsen K., (2014), Opdaterede klimafaktorer og dimensionsgivende regnintensiteter, Spildevandskomiteen, Skrift no. 30, 10-12, 20, On line: https://ida.dk/om-ida/spildevandskomiteen/skrifter-spildevandskomiteen#se-og-hent-skrifter

City of Copenhagen, 2012, *Cloudburst management plan 2012*, Copenhagen: Technical and Environmental Administration. On line: http://en.klimatilpasning.dk/media/665626/cph_-_cloudburst_management_plan.pdf

DHI. (2015). Storm Water Runoff from Green Urban Areas - Modellers' Guideline, (March), 39., On line: https://watersensitivecities.org.au/wp-content/uploads/2016/05/TMR_B4-1_StormWaterRunoffGreenUrban.pdf

Copenhagen Municipality, Copenhagen Climate Adaptation Plan, 2011, On line: https://en.klimatilpasning.dk/media/568851/copenhagen_adaption_plan.pdf

Spildevandskomiteen/Danish Wastewater Committee,(1949), Skrift No. 1, On line: https://ida.dk/media/2971/01undersoegelseafmoelleaaenfralyngbysoetiloeresund.pdf

Spildevandskomiteen/Danish Wastewater Committee,(1950), Skrift No. 2, On line: https://ida.dk/media/2972/02diagrammerfrastadsoghavneingenioerforeningen.pdf

Spildevandskomiteen/Danish Wastewater Committee,(1995), Skrift No. 25, On line: https://ida.dk/media/2952/nedsivning-af-regnvand-dimensionering.pdf

Spildevandskomiteen, (1999), Opdaterede klimafaktorer og dimensionsgivende regnintensiteter, Skrift nr. 26, https://ida.dk/media/2951/26regional-variation-af-ekstremregn-i-danmark.pdf

Spildevandskomiteen/Danish Wastewater Committee,(regular updates), On line: https://ida.dk/media/7068/regionalregnraekke_ver_4_1.xls

Research projects:

"Fifth Assessment report". IPCC. IPCC (2013): *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535.