CIEM 2021 Power up our Future
14-15 october 2021
10th International Conference on Energy and Environment

Urbanisation and Climate Change Impact on Urban Water

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2021 10th International Conference on ENERGY and ENVIRONMENT (CIEM) | 978-1-6654-4584-9/21/$31.00 ©2021 IEEE | DOI: 10.1109/CIEM52821.2021.9614740

***Abstract*—The Earth's climate has been in a state of constant change throughout the ages, to which cities have had to adapt. Heavy rain events and other extreme meteorological phenomena are becoming more and more common. Climate change in relation with extreme rain events affects cities around the globe. The consequences of climate change and urbanisation makes the transport capacity of the sewer system exceeded, the sewer system gets under pressure and floods are occurring. The research presented in this paper focuses on investigating the behaviour of the sewer system during a 10-year rain event considering the urbanisation and climate change. Different Scenarios are created and tested using the 10-year rain event. This rain event is calculated considering the expected changes in intensity and urbanisation by using the regional climate model to define the climate scenarios.**

***Index Terms*—1D modelling, climate change, sewer system, urban water, urbanisation.**

I. Introduction

In the past, predictions based on historical observations in Denmark suggested that the extreme rain events of the past two decades will increase. However, the increase in extreme rain events over the last two decades was higher than anticipated, most likely due to greenhouse gas emissions, as previously demonstrated (Arnbjerg-Nielsen, 2012). The dimensioning of sewer systems has traditionally been based on historical precipitation records, without considering the climate change. Therefore, in the last two decades, different urban areas in Denmark had been flooded, as the sewer systems could not cope with the increased precipitation events.

'The effect of climate change on urban drainage: an evaluation based on regional climate model simulations' (Grum et al., 2006) has recently shown that the weather forecast of the 21st century predicts an increase in the torrential rains. If an extreme rainfall with a probability of occurrence of 10 years will have an increase by 32%, it means that urban areas will be flooded three times more often than they are currently flooded. Currently, in Denmark the rainwater system is designed to handle a 5-year event and the combined systems are designed to handle a 10-years rain event, as previously described (Ioan et al., 2017).

The area where this research was applied is Ølsted town, located in the municipality of Halsnæs, Hovedstaden, with a population of 1,943 inhabitants (2016) located 51 km northwest of Copenhagen. In Ølsted, a big part of the rainwater collection is using the municipality combined and rainwater systems, and a small part of the rainwater system that is private where the harvesting systems are used for non-potable domestic uses in houses and gardens. In the presented research we use the hydraulic model of Ølsed already calibrated, as has recently been shown (Ioan et al., 2017). The hydraulic model includes only the sewer system owned by the Municipality of Halsnæs. The calibration of the sewer system was made based using 16 rain events with a total volume larger than 3mm recorded from October 2016 until February 2017.

The calibrated hydraulic model is used in this research to simulate the 10-year event using different climate horizons. The results of the research will be able to answer some very important questions: is the Ølsed sewer system designed to cope with a 10-year event that had increased in magnitude in the last two decades? How will the Ølsed sewer system behave on a 50-years climate horizon if climate change and urbanisation are considerate? What about on a 100-years climate horizon?

II. Materials and Methods

Because of the increase in extreme rain events in the last two decades, there is a focus on including climate change and urbanisation in calculating the statistical rain events when there is a need of designing new sewer systems or, when an existing sewer system is being rehabilitated. The most advanced method to calculate statistical rain events is to switch from a single rain measurements station data set to a data set of data that contains information from multiple rain measurements stations (Sørup H.J.D., 2014). This approach is called a regional approach and is used to create regional models. The basic rule of the regional model is that when the regional variability is studied, a sensitivity analysis of the parameters used to create the model is sought to find a parameter on which the other parameters studied depend and which could determine the regional variability. In this regional model the number of extreme events and the magnitude of the extreme events are analysed to verify the existence of their regional variability. The regional model has 2 advantages: the uncertainty (safety rate) is reduced because it has a very large data packet, and the second advantage is that the resulting information (the resulting parameters) can be obtained not only in the location where a station is physically located, but throughout the entire country.

In Denmark, the so-called 'Skrift' (guides) are used to create statistical rain events. These guides cannot be called standards because they are not required by law. The guides are provided by the Danish Wastewater Committee (SVK - Spildevandskomitteen) and used by all municipalities and private water companies. For this reason, these guides are very important. Since 1999, when the first guide was created, up to now there have been several updated versions of it. Skrift 30, which appeared in 2014 (Bülow Gregersen et al., 2014) presents the average annual rainfall (the number of extreme events) and the average daily rainfall (magnitude of events) according to the regional climate model (1989-2010).

In Denmark the rainfall statistics are calculated using a tabular format drawn up by the Danish Wastewater Committee. It is based on rainfall measurements since 1979 and uses as input Skrift recommendations. In Denmark there are 145 rain measuring stations installed in 1979, many of these stations are in the centre of the major cities. This rain measuring stations have a resolution of 1 minute.

The calculated rainfall is a CDS (Chicago Design Storm) rainfall, a statistic rain event built using statistical calculations based on measured rainfall events. As the measured rainfalls may be different from zone to zone, in the statistical calculation the research area is identified based on x (East) - y (North) coordinates where the ETRS 1989 UTM ZONE 32N coordinate system is used (Mikkelsen et al., 2005). The (x, y) coordinates are read in the centre of the studied catchment, location that represents the centre of the Grid cell of the regional climate model. Once an area is identified, average annual precipitation and average daily precipitation are automatically identified from the database. Based on this calculation, the average annual precipitation in Ølsted is 668 mm and the average daily precipitation is 27.7mm/day. Depending on the overcoming period of the event a safety factor is calculated. The safety factor is a design factor that considers the climate change, the urbanisation and a trust level of the hydraulic model in calculating the statistical rains:

$$f_c \cdot f_{sm} \cdot f_{cs} = f_s \tag{1}$$

where: f_s represents the safety factor, f_c climatic factor, f_{sm} model safety factor and f_{cs} the imperviousness safety factor.

The 30th version of the guide (Skrift 30) is the version that takes the climate change into account and is providing recommendations of what climate factors (f_c) to use when a statistical rain event is calculated to dimension a new sewer system or for the rehabilitation of an existing sewer system. Two different sets of climatic factors are recommended: "standard" climate factors are those factors that overlap the best match of the effects of climate change, and "high-grade" climate factors are those factors that match the best match of the effects of climate change adding the standard deviation of the climate factor (Table I).

TABLE I. RECOMMENDED CLIMATE FACTORS (SKRIFT 30, 2014)

Overcoming probability	**100 Climate Horizon**		**50 Climate Horizon**	
	„Standard" Climate Factor	***"High-grade" Climate Factor***	***„Standard" Climate Factor***	***"High-grade" Climate Factor***
10 years	1.3	1.7	1.15	1.35

The model safety factor (f_{sm}) is a factor that introduces the safety pattern (trust level) of the sewer system model in calculating the statistical rains. This factor can be considered 1 only when the sewer system model's confidence is very high (when the model is calibrated). Considering that the hydraulic model used in this research is a calibrated model, where the calibration errors are less than 10%, the safety pattern of the network model is very high. Therefore, the safety factor will be considered 1.

The imperviousness safety factor (f_{cs}) is a factor that considers the appearance of new impermeable areas or very low permeable areas (houses, roads, parking lots, etc.). The imperviousness safety factor will be considered 1 only for the present situation, where the CDS rain is calculated only based on historical events and the areas permeability is not changing.

In all four scenarios that consider climate changes and urbanisation, the imperviousness safety factor will be considered 1.1 because in this research the assumption is that in the future not more than 10% of the permeable areas will become impermeable areas or very low permeable areas.

The sewer system 1D model used in this research has a 46ha catchment area. This catchment area is divided into 921 sub-catchments. 80% of the sewer system is combined system and 20% of the sewer system is rainwater system.

The model has 291 manholes, 292 circular pipes, 2 pumping stations, 1 overflow and one wastewater treatment plant (Figure 1). The calibrated 1D sewer system uses the hydrological model 'MOUSE Model A' where the houses have 95% imperviousness, roads have 90% imperviousness, parking lots have 85% imperviousness, partially permeable areas have 30% imperviousness, and the green areas have 0% imperviousness. The hydrological model uses an initial loss of 9×10^{-4} m, a 0.7 reduction factor a time of concentration of 9 min (Ioan et al., 2017).

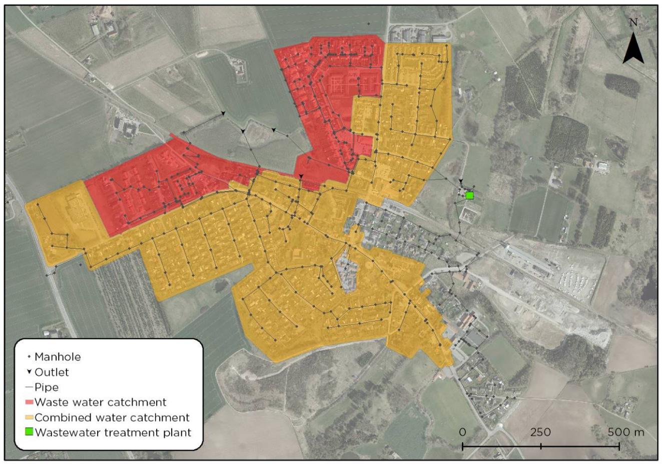

Figure 1. 1D model representation

The duration of the calculated rain events is 6 hours, and the time step is 10 minutes, considering this time enough for the water to enter and got out from the system. The statistical rain events are used to simulate five scenarios (Table II) to study the behaviour of the sewer system during the event with a 10-year probability of occurrence.

TABLE II. HYDROLOGICAL PARAMETERS USED IN THE STATISTICAL RAIN CALCULATIONS

Statistical Rain Events	Safety Factor	Annual Average Rainfall (mm)	Mean Extreme Daily Precipitation (mm/day)	Rainfall Intensity (mm/s)
Event no. 1	1	668	27.7	21.03
Event no. 2	1.43	668	27.7	30.08
Event no. 3	1.87	668	27.7	39.33
Event no. 4	1.265	668	27.7	26.61
Event no. 5	1.485	668	27.7	31.24

The first scenario is using the CDS 10 1.00 rain event and the climate change, and the urbanisation are not included. This is a scenario that was created to answer the research first question: 'is the Ølsed sewer system designed to cope with a 10-year event that had increased in magnitude in the last two decades?'. In order to answer 'how will the Ølsed sewer system behave on a 50-years climate horizon if climate change and urbanisation are taken into account? But on a 100-years climate horizon?' another four scenarios were created. A detailed description of the created scenarios is presented as it fallows:

A. *Scenario 1 – the statistical rain event CDS 10 1.00*

Scenario 1 is investigating the behaviour of the existing sewer system, in case of a 10-year probability rain event, created according to the increase in extreme rain events over the past two decades (Skrift 30). In this scenario, the runoff model uses the statistical rain event CDS 10 1.00 where the precipitations reach 41.65 l/m^2 in 6 hours. This scenario has the role of observing the behaviour of the existing sewer system and to identify vulnerable areas in the system. The results (Figure 2) show that in Scenario 1, a number of 23 out of the 291 manholes will be flooded due to the sewer system undersize. The most affected area is in the eastern and southeast part of the studied area.

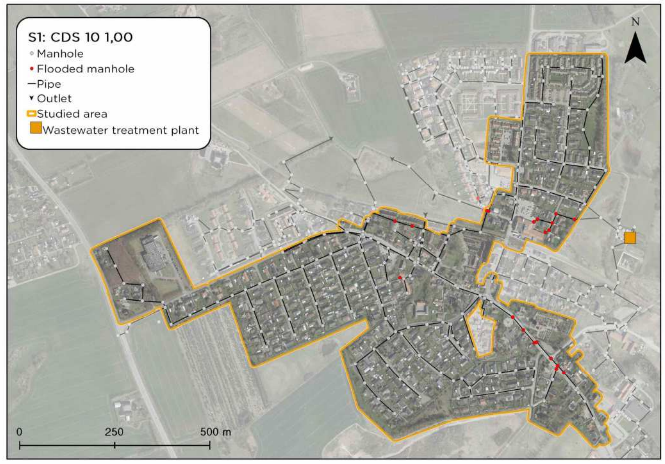

Figure 2. CDS 10 1.00 - Representation of vulnerable parts of the sewer system

B. *Scenario 2 – the statistical rain event CDS 10 1.43*

The second scenario studied in this research includes the uncertainties calculated according to Skrift 30. Scenario 2 uses the event with a 10-year probability of occurrence considering climate change over a 100-year horizon considering a standard climate factor of 1.3. At the same time, it considers the appearance of new impermeable or slightly permeable areas in the catchment area. The rainfall model uses the CDS 10 1.43 statistic rain event where the precipitation reaches 59.56 l/m^2 in 6 hours. This scenario is designed to study the behaviour of the existing sewer system and to identify vulnerable areas in the system over a 100-year climate horizon according to the best match of the effects of climate change. The modelling results (Figure 3) indicate that a number of 55 out of the 291 manholes will be flooded due to the undersize of the sewer system. The vulnerable parts of the system are situated in the centre and southeast of the Ølsted area.

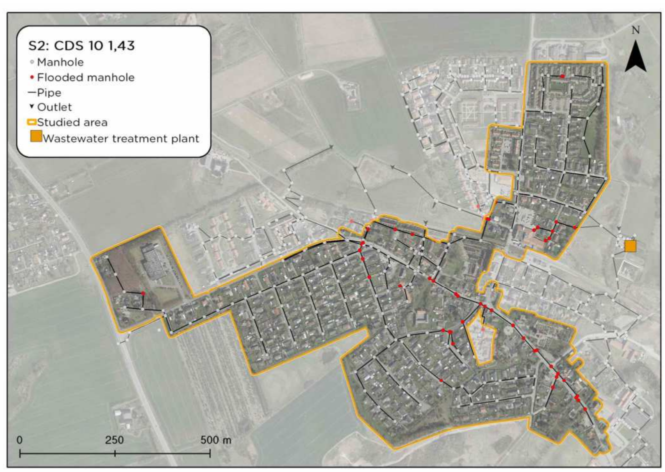

Figure 3. CDS 10 1.43 - Representation of vulnerable parts of the sewer system

C. Scenario 3– the statistical rain event CDS 10 1.87

The third scenario studied is the most intense scenario, which considers the event with a 10-year probability of occurrence where climate change is introduced over a 100-year horizon considering a 1.7 high-grade climate factor. This event also considers the appearance of new impermeable or slightly permeable areas in the catchment area. The runoff model uses the statistical rainfall event CDS 10 1.87 where the precipitation reaches 77.88 l/m^2 in 6 hours. This scenario has the role of studying the behaviour of the existing sewer system and identifying vulnerable areas in the system over a 100-year horizon according to the best match of the effects of climate change adding the standard deviation of the climate factor. The modelling results (Figure 4) indicate that a number of 133 out of the 291 manholes could be flooded due to the undersize of the sewer system. According to this scenario, a big part of the Ølsted sewer system becomes vulnerable.

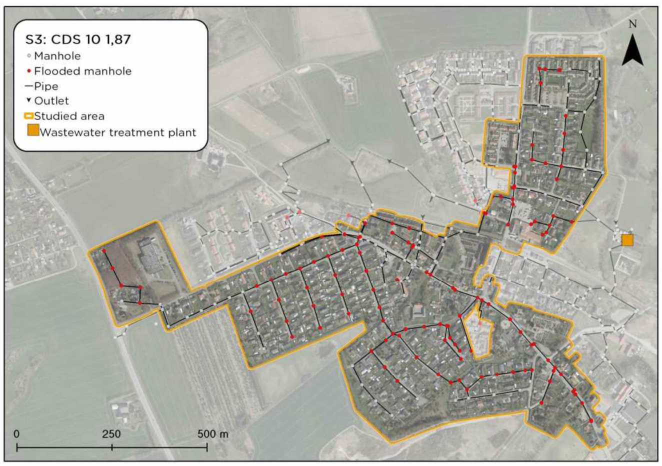

Figure 4. CDS 10 1.87 - Representation of vulnerable parts of the sewer system

D. Scenario 4– the statistical rain event CDS 10 1.265

The fourth scenario studied is the one that uses the event with a 10-year probability of occurrence, considering climate change over a 50-year horizon, considering a standard climate factor of 1.15 and taking into account the appearance of new impermeable or slightly permeable areas in the catchment area. In this scenario, the rainfall model uses the synthetic rainfall event CDS 10 1.265, where the precipitation reaches 52.69 l/m^2 in 6 hours. This scenario has the role of studying the behaviour of the existing sewer system and identifying vulnerable areas in the system over a 50-year horizon in the best match with the effects of climate change. The modelling results (Figure 5) show that a number of 37 out of the 291 drains could be flooded during event 4 due to under-dimensioning of the sewer system. The affected areas are situated in the centre and southeast of the studied area.

Figure 5. CDS 10 1.265 - Representation of vulnerable parts of the sewer system

E. Scenario 5– the statistical rain event CDS 10 1.485

The fifth scenario studied is the one that uses the rain event with a 10-year probability of occurrence and takes account the climate change over a 50-year horizon considering a 1.35 high-grade climate factor, also considering the appearance of new impermeable or slightly permeable areas in the catchment area. In this scenario, the rainfall model uses the statistical rain event CDS 10 1.485, where the precipitation reaches 61.85 l/m^2 in 6 hours. This scenario is designed to study the behaviour of the existing sewer system and to identify vulnerable areas in the system over a 50-year climate horizon according to the best match of the effects of climate change adding the standard deviation of the climate factor. The modelling results (Figure 6) indicate that a number of 63 out of the 291 drains could be flooded due to undersize the sewer system. The affected sewer system parts are in the centre and southeast of the Ølsted area.

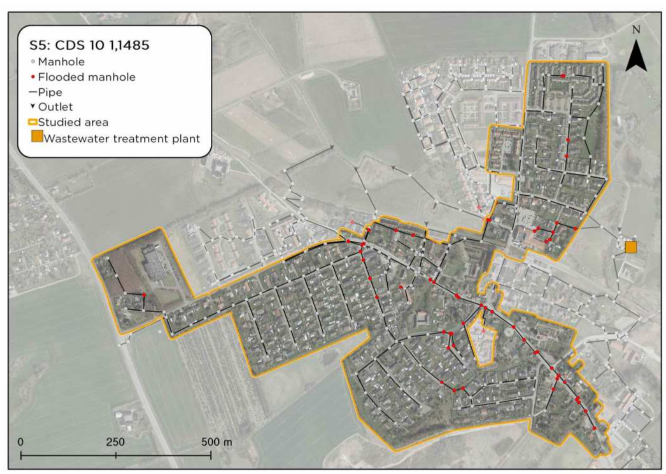

Figure 6. CDS 10 1.1485 - Representation of vulnerable parts of the sewer system

III. Results and Discussion

The sewer system design has been traditionally made based only on historical precipitation records. These old design practices assume there is no climate change. Recent history shows that climate change leads to more intense precipitation, which can lead to urban floods when the sewer system is under-dimensioned. Currently, in Denmark the design standard for a combined sewer system it uses the rain event with a 10-year probability of occurrence. These systems must carry precipitation events up to 50 l/m^2 and almost all (99%) of the annual rain events as previously demonstrated (Fratini et al., 2012). This value of 50 l/m^2 is an average of Denmark, which can vary slightly from area to area as has been shown (Skrift 30). The five scenarios have been created using the most recent way of designing statistical rain events, to investigate if the Ølsted sewer system can handle the new design criteria. A detailed description of the runoff model for each scenario in part is made in Table III, where the wastewater contribution is also marked:

TABLE III. Catchment runoff hydrograph summary

Scenario	Rainfall Intensity (mm/s)	Accumulated rainfall (mm)	Rainfall volume (m^3)	Wastewater volume (m^3)
Scenario 1	21.03	41.65	4068.7	13.1
Scenario 2	30.07	59.56	5837.402	13.1
Scenario 3	39.33	77.88	7645.709	13.1
Scenario 4	26.61	52.69	5159.288	13.1
Scenario 5	31.24	61.85	6063.441	13.1

If the intensity of precipitation does not lead to large flows, the pipeline will control (by transport) all rainwater, and the overflow will occur only when the precipitation crossing the pipe reaches a threshold given by the maximum pipeline transport capacity.

The studied scenarios that include climate change and urbanisation have a bigger risk of floods in different parts of the system. In all studied scenarios, the results showed a significant increase of the runoff and with that an increase of vulnerable parts of the system. Thus, in all 5 studied scenarios there are sections of the sewer system that should be re-dimensioned.

IV. Conclusions

The expected increase of urbanisation and precipitations intensity had led to floods in different parts of Ølsed. The results indicated a clear need of including climate change and urbanisation when a new sewer system is dimensioned or when an existing sewer system is rehabilitated. In Ølsed, climate change and urbanisation will have a significant impact on the urban environment. The calibrated mathematical model of the sewer system was used to reproduce current and future situations regarding rainwater. In that way was possible to quantify the effects of the increase of precipitations intensity and urbanisation in Ølsted area by using the regional climate model and creating 5 different climate scenarios, according to the Skrift 30. The statistical rain events used in this research are: CDS 10 1.0, CDS 10 1.43, CDS 10 1.87, CDS 10 1.265, CDS 10 1.485.

The consequences of climate change and urbanisation can be seen in Scenario 1, where the sewer system was tested to see if it can handle a 10-year event calculated only based on the last two decades changes in rain patterns. So, to the question 'is the Ølsted sewer system designed to cope with a 10-year event that had increased in magnitude in the last two decades?' the answer unfortunately is that in some of the parts, the sewer system needs to be updated.

The presented research shows the consequences of climate change and urbanisation on the sewer system of Ølsed through 4 different scenarios where climate change and urbanisation were considering: Scenario 2, Scenario 3, Scenario 4, Scenario5. Thought these scenarios, the vulnerable locations in the system were identified. There are different climate adaptation approaches that could be tested by using the Ølsted sewer system mathematical model. One solution to help the Ølsed sewer system deal with extreme rain events could be to use the conventional adaptation. In this way, the sewer system will be enlarged. Another solution to help the Ølsed sewer system deal with extreme rain events could be to use the urban landscape to transport or store the storm water. Because the sewer system is a very large investment, it must be kept in operation for many years. The decision about what climate adaptation approach will be used to protect the area of Ølsted should be made considering both the advantage and the disadvantages of the approaches.

Acknowledgment

We are grateful to Henrik Sønderup (Head of Department, Climate Adaptation and Landscape Architecture, Rambøll Denmark) for providing the Ølsted hydraulic model and all the software used in this research.

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