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Schaarup-Jensen, Kjeld; Rasmussen, Michael R.; Thorndahl, Søren

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To what extent does variability of historical rainfall series influence extreme event statistics of sewer system surcharge and overflows?

K. Schaarup-Jensen[1]*, M. R. Rasmussen[1] and S. Thorndahl[1].

[1] *Division of Water and Soil, Department of Civil Engineering, Aalborg University, Sohngaardsholmsvej 57, DK-9000 Aalborg, Denmark.*

**Corresponding author, e-mail ksj@civil.aau.dk*

ABSTRACT
In urban drainage modeling long term extreme statistics has become an important basis for decision-making e.g. in connection with renovation projects. Therefore it is of great importance to minimize the uncertainties concerning long term prediction of maximum water levels and combined sewer overflow (CSO) in drainage systems. These uncertainties originate from large uncertainties regarding rainfall inputs, parameters, and assessment of return periods. This paper investigates how the choice of rainfall time series influences the extreme events statistics of max water levels in manholes and CSO volumes. Traditionally it is rarely to dispose of long term rainfall time series from a local catchment rain gauge. In the present case study this is actually the case. 2 rainfall gauges have recorded events for approximately 9 years at 2 locations within the catchment. Beside these 2 gauges another 7 gauges are located at a distance of max 20 kilometers from the catchment. All gauges are included in the Danish national rain gauge system which was launched in 1976. The paper describes to what extent the extreme events statistics based on these 9 series diverge from each other and how this diversity can be handled. All simulations are performed by means of the MOUSE LTS model.

KEYWORDS
Historical rainfall series; MOUSE LTS; sewer system surcharge; CSO volumes; extreme events statistics.

INTRODUCTION
In 1997 a research and monitoring station was established as a part of the intercepting sewer from Frejlev, a small town of 2000 inhabitants 7 kilometers southwest of Aalborg, Denmark (Schaarup-Jensen et al., 1998).

According to Thorndahl *et al.* (2006), the total Frejlev catchment covers an area of approximately 87 ha, situated on a hillside facing north from an uphill level approximately 55 m above sea level to a downhill level 15 m above sea level. 67% of the catchment, 58 ha, has combined sewers and the remaining 33%, 29 ha, has separate sewers, figure 1. The impervious part of the catchment is 40% corresponding to 35 ha.

During dry weather conditions waste water flow from Frejlev is diverted into an intercepting pipe through a combined sewer overflow (CSO) structure located downhill approximately 500 meters north of Frejlev. During wet weather conditions CSOs are discharged into Hasseris, a stream which flows into the Limfjord about 6 kilometers north-east of Frejlev.

The research and monitoring station in Frejlev is located upstream and close to the CSO structure in which continuous high quality time series of both dry and wet weather flow are measured in order to gain general long term knowledge of the characteristics of both weather conditions. Upstream from the station, the sewer pipe system is divided into two: a 300 mm diameter “dry weather pipe” and a 1000 mm diameter “wet weather pipe”. Within the station both of these pipes are equipped with high quality electromagnetic flow meters of the Parti-Mag type manufactured by ABB Automation Products GmbH, Göttingen, Germany. According to the specifications of the manufacturer, both of these flow meters function with a maximum flow rate error of 1-1.5%. The flow is measured every 20 seconds.

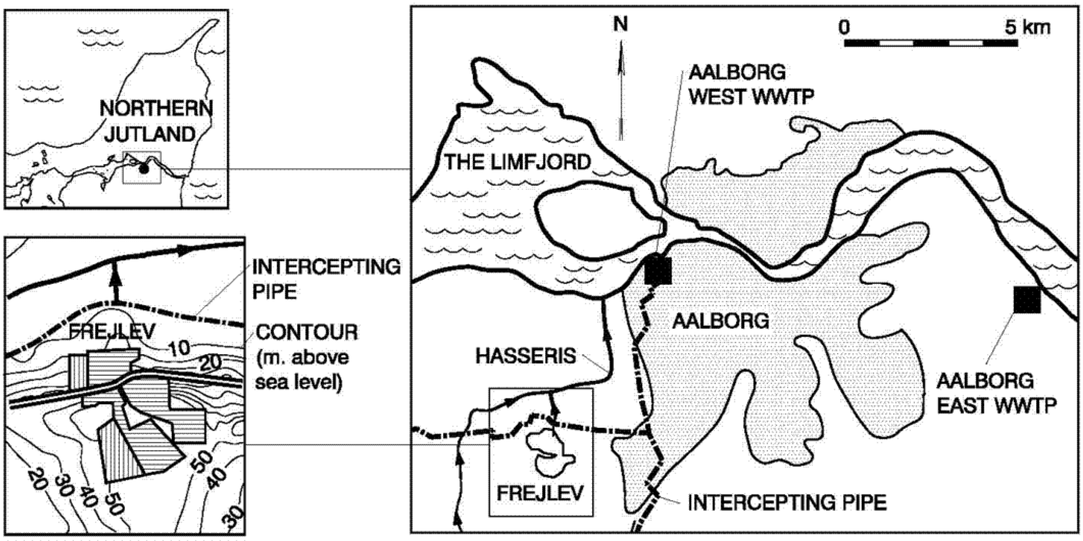

Figure 1. Aalborg, the town of Frejlev, the Hasseris stream and the Aalborg West waste water treatment plant (WWTP). Horizontal shading: catchments with combined sewers; vertical shading: catchment with separate sewers.

The flow measurements are supplemented by two automatic rain gauge stations which are included in the Danish national rain gauge system managed by the Danish Waste Water Control Committee and operated by the Danish Meteorological Institute (2007). One of the rain gauges (gauge no. 20458) is placed on top of the research station, 15 m above sea level. The second one (gauge no. 20456) is placed uphill, 55 m above sea level, in the south-western part of the town at a distance of approximately 1.9 kilometer from gauge no. 20458 – cf. figure 2.

Consequently, a number of long dry and wet weather flow time series from this catchment today are available. These time series have been subject to various investigations, – e.g. Schlütter and Schaarup-Jensen (1997), Vollertsen and Hvitved-Jacobsen (2003), Schaarup-Jensen and Rasmussen (2004), Thorndahl and Willems (2008), Thorndahl *et al*. (2008) and Thorndahl (2008).

In some of the investigations related to wet weather conditions the object has been the assessment of key parameters in the surface description of the Frejlev catchments (Thorndahl *et al*., 2006, Schaarup-Jensen *et al*., 2005).

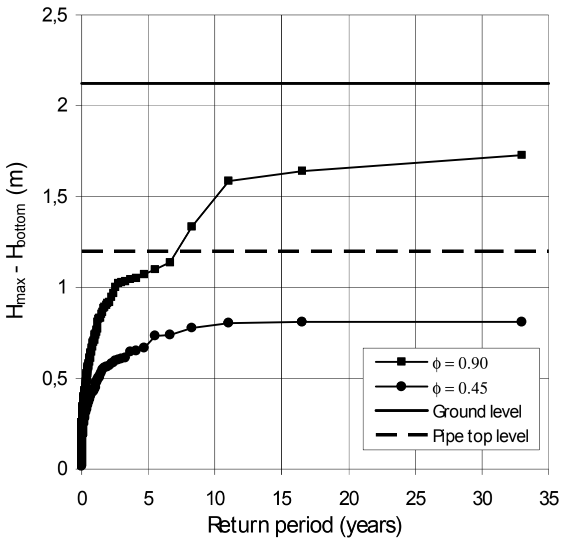

Figure 3. Flooding frequencies in an arbitrarily chosen manhole in the Frejlev sewer system.

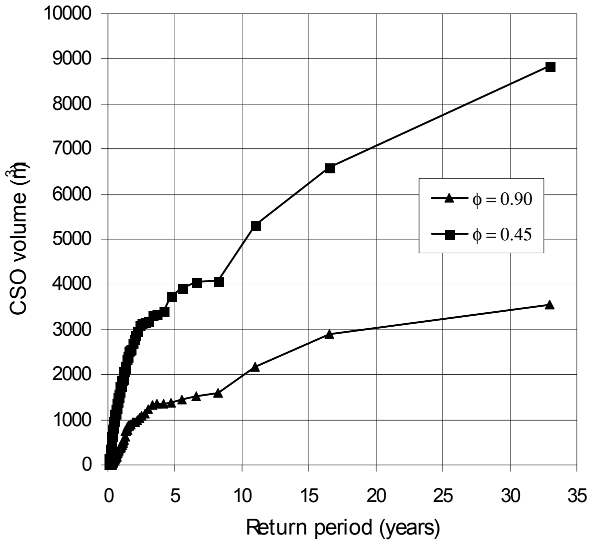

Figure 4. CSO volumes as a function of (average) return period.

This article will focus on the selection of rainfall series for such MOUSE LTS simulations in order to investigate if the selection of rainfall series influence the uncertainties related to extreme event statistics of CSO volumes and flooding frequencies in the same manner as e.g. the above mentioned reduction factor.

SELECTED RAINFALL TIME SERIES

9 rainfall time series originating from tipping bucket rain gauges in the surroundings of Aalborg have been selected for this investigation – cf. figure 2 and table 1.

From table 1 it appears that the maximum diagonal and latitude distance between 2 of these gauges are 23.7 and 13.0 kilometers respectively.

Table 1. Upper triangular matrix: diagonal distance between gauges; Lower triangular matrix: latitudinal distance between gauges. All distances are in kilometres. The outer right columns state the period of investigation for each gauge and the length of the corresponding time series.

gauge no	**20456**	**20458**	20461	20307	20309	20304	20298	20212	20211	Period	Length of series (years)
20456	0	1.9	3.8	6.3	9.6	9.8	11.1	17.2	20.7	1997-2006	9.5
20458	0.0	0	5.7	4.8	8.2	8.9	11.3	16.1	19.0	1997-2006	9.2
20461	1.1	1.1	0	9.5	12.2	11.7	10.8	19.2	23.7	1979-2006	18.9
20307	3.0	3.0	1.9	0	3.6	5.1	9.8	11.5	14.3	1998-2006	8.8
20309	6.0	6.0	4.9	3.0	0	2.7	9.0	8.0	11.5	1998-2006	8.8
20304	8.0	8.0	7.0	5.1	2.0	0	6.3	7.5	13.0	1990-2006	16.8
20298	11.1	11.2	10.1	8.2	5.2	3.1	0	11.3	18.7	1999-2006	7.3
20212	13.0	13.0	11.9	10.0	7.0	5.0	1.9	0	8.4	2000-2006	6.9
20211	8.8	8.9	7.8	5.9	2.9	0.8	2.3	4.1	0	1979-2006	28.0

The annual mean value of precipitation at Aalborg is approximately 700 mm.

In recent investigations Thorndahl *et al.* (2008) have shown that maximum water levels in the manholes of the Frejlev sewer system are reasonable correlated to the peak intensities in the rainfall events - while the CSO volumes in Frejlev are correlated to the rain depths. For this reason the selected 9 rainfall time series has been analyzed in order to uncover the mutual gauge variability between these 2 parameters. In this case the 10 minute peak intensity during a rain event has been chosen as a characteristic peak intensity value.

As illustrated in figure 5 and 6 this analysis displays a remarkable mutual difference between the extreme events statistics of these parameters. When the return period exceeds 1-2 years the statistics of each gauge diverge in a distinct manner. E.g. a 10 minute peak intensity of 20 µm/s seems to have a return period between 2.5 and approx. 10 years and similarly a rainfall event depth of 50 mm has a return period between 2 and 14 years depending on the choice of rainfall time series. It is also noticeable that some gauges have a tendency to have a high "rank" considering rain intensity and a low "rank" considering rain depths. This is e.g. the case for the Frejlev gauge stations, which both have a low intensity "rank" and at the same time a high rain depth "rank".

The fact that the extreme events statistics of rain gauge intensities and rain depths have a tendency to coincide for return period values below 1-2 years can be interpreted as a general feature of these types of statistics where the length of the coinciding period is depending on the length of the time series in question. That is, if e.g. the length of these 9 time series had been 100 years and not between 7 and 28 the length of the coinciding period perhaps could have been – let's say 10 or 20 years, according to10- 20% of the length of the series.

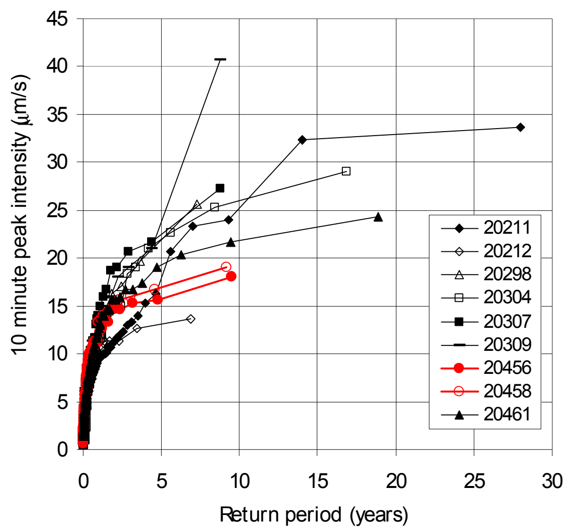

Figure 5. 10 minute peak intensity as a function of (average) return period.

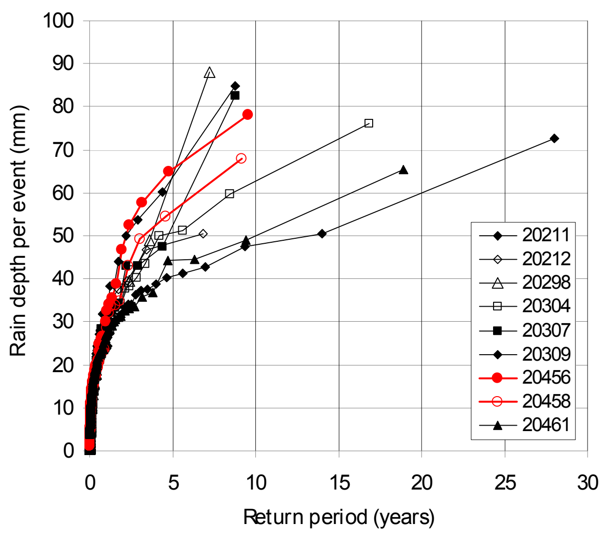

Figure 6. Rain event depth as a function of (average) return period.

In Spildevandskomiteen (2006) and Madsen and Arnbjerg-Nielsen (2006) 66 of the gauges in the Danish national rain gauge system have been used to estimate key rainfall parameters with return period uncertainty based on measurements from 1979 – 2005. The datasets from these gauges is statically approximated to a partial duration series model (Madsen and Rosbjerg 1997a; Madsen and Rosbjerg 1997b; Mikkelsen *et al*. 1998). Applying a generalised Pareto distribution, a fit of the return periods is estimated (Spildevandskomiteen 2006):

$$\hat{z}_T = z_0 + \hat{\mu}\frac{1+\hat{\kappa}}{\hat{\kappa}}\left(1-\frac{1}{\hat{\lambda}\cdot T}\right)^{\hat{\kappa}} \tag{1}$$

z_T is the value corresponding to the return period T, e.g. 10 minute peak intensity or rainfall event depth, z_0 is a cutoff level, μ is the mean of the exceedings of z_0, κ is a shape parameter, and the number of yearly exceedings, λ is estimated by (Spildevandskomiteen 2006):

$$\hat{\lambda} = \hat{\beta}_0 + \hat{\beta}_1 \cdot YMP \tag{2}$$

β_0 and β_1 are linear regression parameters and YMP is the regional accumulated yearly precipitation. The variance of the number of yearly exceedings is based on:

$$\mathrm{var}(\hat{\lambda}) = \mathrm{var}(\hat{\beta}_0) + 2\cdot YMP\cdot \mathrm{cov}(\hat{\beta}_0,\hat{\beta}_1) + YMP^2\cdot \mathrm{var}(\hat{\beta}_1) + \hat{\sigma}_d^2 \tag{3}$$

The statistics presented in Spildevandskomiteen (2006) have resulted in a division of the Danish rainfall in two regional zones, one for the Western part of Denmark and one for the Eastern part. Using the accumulated yearly precipitation a local estimate of the return period uncertainty can be calculated. Shown here are observed local values of the 10 minute peak intensity (Figure 7) and the rainfall event depth (Figure 8) from the 9 selected rainfall gauges along with the presented Pareto model.

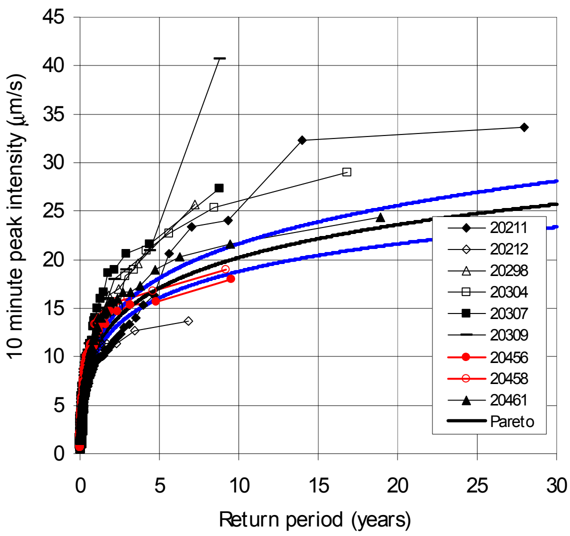

Figure 7. 10 minute peak intensity as a function of (average) return period. Danish Pareto model with 95% confidence band (blue).

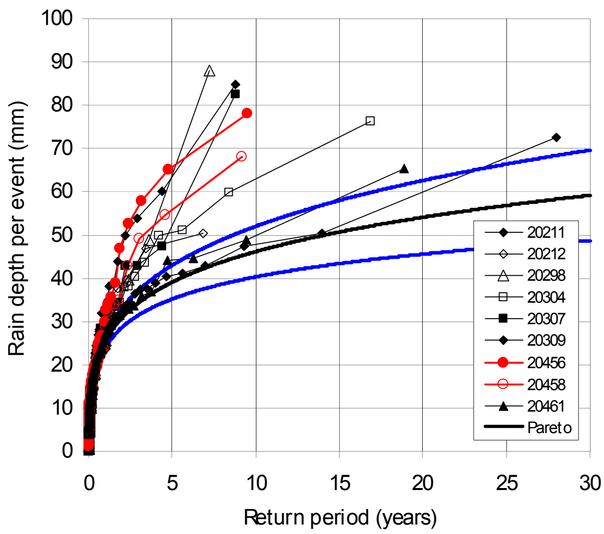

Figure 8. Rain event depth as a function of (average) return period. Danish Pareto model with 95% confidence band (blue).

Concerning the 10 minute peak intensity figure 7 illustrates some agreement between the Danish Pareto model and a good part of the 9 gauge series in question, but this is not the case regarding rainfall depths, cf. figure 8.

Still, there is a weak tendency towards accordance between series and model the longer the series are. This could be taken as an indication of a more than normal presentation of extreme events in the local Aalborg series – an indication which is supported by the fact that e.g. series with a length of 10 years all contains values of both intensity and rainfall depths which are more extreme than those of the Pareto model. So, if the Aalborg area during the last decade has been overtaken of rainfall events with more extreme values of peak intensity and rainfall depths compared to a “normal” 10 year long period, then this tendency must be present in a majority of the series. This could be the case - as illustrated by figure 7 and 8. On the other hand the utmost extreme values in the longest series (20211, 20461 and 20461) have all been recorded before 1998 which is inconsistent with this attempt to interpret the discrepancy between the Aalborg series and the Pareto model.

Another problem linked to extreme events statistics of rainfall depths could be the definition of a rainfall event. In Denmark the Danish Meteorological Institute defines a rainfall event as at least 2 tipping of the gauge bucket provided that at least 1 hour has passed without any tipping events. One single isolated tipping event is thus not considered as a rainfall event. This definition could to some extent influence an extreme events statistics of rainfall depths e.g. if a very extreme event at some gauges are recorded as one - and at other nearby gauges as two or more.

RESULTS AND DISCUSSION

Without any doubt the 9 local Aalborg rainfall series diverge from each other considering 10 minute peak intensity and rainfall depths. This leads to an expectation of a similar series conditional variance of the extreme events statistics considering both maximum water level in manholes and combined sewer overflow volumes.

In order to pursue these expectations 9 MOUSE LTS simulations on the Frejlev catchments were performed based on the selected 9 historical rainfall series. In all simulations were used a “calibrated” MOUSE model with $\phi = 0.45$ – cf. figure 3 and 4.

Figure 9 and 10 illustrates some of the results from these simulations, in this case the extreme events statistics of maximum water level (above bottom) in an arbitrarily chosen manhole (same as used in figure 3) and the CSO volumes from the CSO structure in the Frejlev sewer system.

When comparing figure 5 with figure 9 it is evident that the variability between extreme events statistics on 10 minute peak intensity and maximum water level in a specific manhole has the same order of magnitude, and this is also the case with respect to the extreme events statistics of rain depths and CSO volumes when comparing figure 6 and figure 10. In the first case – rain intensities versus maximum water levels the variability between series seems to have narrowed down - while the opposite is the case with respect to rain depths and CSO volumes.

Looking upon figure 10 the span between the statistics with highest and lowest values of CSO volumes is surprisingly wide. For instance, the 10 year return period value of the CSO volume varies between 3.000 and 7.500 m^3 depending on which rainfall series the MOUSE LTS simulations are based on. The biggest of these values are 150% greater than the lowest value, and the rainfall series originate from local rainfall gauges which in this case are situated within a distance of 10 kilometers.

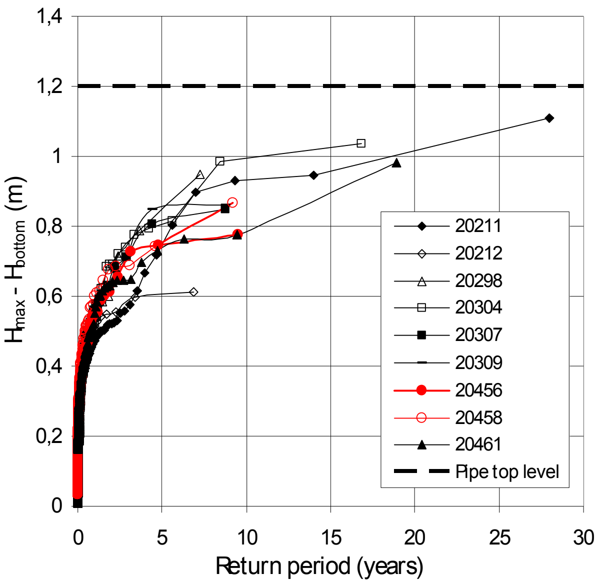

Figure 9. Flooding frequencies in an arbitrarily chosen manhole in the Frejlev sewer system. Ground level is 2.12 m Above manhole bottom level.

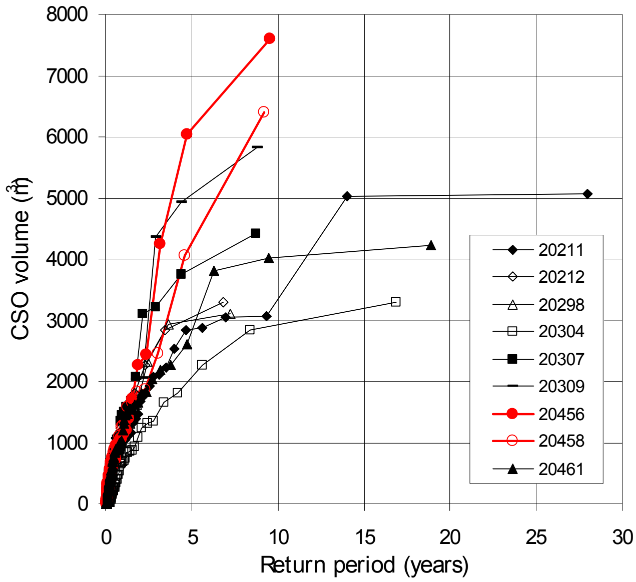

Figure 10. CSO volumes as a function of (average) return period.

Furthermore it is conspicuous – cf. figure 10 – that the utmost local rainfall series (20456 and 20458) are among those who produce the utmost ranked statistics of all 9 rainfall series. A reasonable explanation to this fact is that these series by chance contains events which with respect to depths have a return period much greater than the length of the series.

The opposite could also be the case. That is, rainfall series can by chance contain rainfall events with depths which all have return periods smaller than the length of the series. Through the spectacles of the authors this is what figure 7, 8, 9 and 10 individually is showing. The extreme events statistics coincide at return periods which are small compared to the length of the series, but they tend to diverge quite a lot when it comes to events with return periods corresponding to more than 10-20% of the length of series. This is a natural expectation to have when dealing with a stochastic process as rainfall.

When urban drainage simulations based on historical rainfall time series today has become an important tool - e.g. when renewals of a given sewer system is under consideration – this is mainly due to the fact that decisions on whether a system shall be rebuild or not often is based on extreme events statistics on the results from an operation of e.g. MOUSE LTS. Keeping this in mind, figure 9 and 10 indicate that such long term statistics can only produce reliable results if the rainfall series have a considerable length. Wishing to have reliable results for return periods until 20 years could mean that the rainfall series must have a length of 100 years!

None of the series in the Danish national rain gauge system has a length of this magnitude and this is – as far as the authors know – also the case worldwide.

Most often a specific catchment in Denmark does not have a rain gauge from the national gauge system within the catchment – even though the number of gauges within this system today has exceeded 100. For this reason an urban drainage engineer often will have to use historical rainfall data from a nearby situated gauge as the basis of his LTS-simulation. The investigations conducted in this paper took benefit from the fact having 2 gauges within the catchment areas and 7 other gauges situated within a distance of 20 kilometers.

When local rainfall series are of a relatively short length there are indications from figure 9 and 10 pointing at, that a reasonable conduct would be to use all accessible series within a specific (unknown) distance instead of using just 1 or 2 series - even though some of these are situated within the catchment. Performing 10 instead of 1 simulation will produce a set of extreme event statistics on decision-important parameters, and the decisions might be better grounded if some kind of "average extreme event statistics" is used instead of 1. For instance – cf. figure 10 - a reasonable prediction of the 10 year return period CSO volume could be 5000 m^3 instead of e.g. 7000 m^3 based on the 2 local extreme statistics as these are based on rainfall series with a length comparable to 10 years.

CONCLUSIONS

The title of this paper is: *To what extent does variability of historical rainfall series influence extreme events statistics of sewer system surcharge and overflows?* Based on the presented results the answer to this question is: *To a high extent!*

Using the Frejlev catchment as a case study and using 9 selected local rainfall time series as rainfall input to 9 MOUSE LTS simulations result in a great variety of extreme event statistics both for sewer system surcharge and CSO volumes – even though the local rainfall series originate from high precision rain gauges situated within a distance of 20 kilometers from the catchment.

In urban drainage modeling long term extreme statistics has become an important basis for decision-making. Therefore it is of great importance that uncertainties concerning the size of return periods of extreme events are suitable low. In this connection Schaarup-Jensen *et al.* (2005) have documented the importance of performing a catchment specific calibration of the selected urban drainage model in order to reduce the uncertainties of extreme events statistics. This paper illustrates that the selection of rainfall time series also is of great importance to these statistics.

In order to have very precise values of flooding levels or CSO volumes with a specific return period – e.g. 10 year - it can be necessary to use rainfall series with a length up to 10 times greater. As this "demand" is almost impossible to comply with, other methods must be considered. One possibility could be to perform long term statistics simulations based on a suitable numbers of local rainfall series and then – if a diverged set of extreme statistics is the result of this "method" - introduce an "averaging procedure" based on the variability within this set. Having only 1 rainfall series at your disposal for urban drainage modeling on a long term basis, could result in extreme event statistics which do not estimate the average return period of a specific flooding level or a specific CSO volume with an appreciable accuracy.

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