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# Evaluating catchment response to artificial rainfall from four weather generators for present and future climate

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## Abstract
The technical lifetime of urban water infrastructure has a duration where climate change has to be considered when alterations to the system are planned. Also, models for urban water management are reaching a very high complexity level with e.g. decentralized stormwater control measures being included. These systems have to be evaluated under as close-to-real conditions as possible. Long Term Statistics (LTS) modelling with observational data is the most close-to-real solution for present climate conditions, but for future climate conditions artificial rainfall time series from weather generators (WG) have to be used. In this study we run LTS simulations with four different WG products for both present and future conditions on two different catchments. For present conditions all WG products result in realistic catchment responses when it comes to the number of full flowing pipes and the number and volume of combined sewer overflows. For future conditions, the differences in the WGs interpretation of the expectations to climate change is evident. Nonetheless, all future results indicate that the catchments will have to handle more events that utilize the full capacity of the drainage systems. Generally WG products are relevant to use in planning of future changes to sewer systems.

Keywords: Climate Change, Combined Sewer Overflow, CSO, Long Term Statistics, LTS, Weather generator.

## Introduction
Stormwater management systems are traditionally designed using historical data or design storms (Mikkelsen et al., 1998). Sizing of pipes as part of designing a sewer system can be done with high accuracy using design storms, but for some design and analysis problems design storms are less suitable. In particular when considering transport and fate of pollutants (Sharma et al., 2016), impact of introducing local stormwater retention (Locatelli et al., 2015), and testing real-time control strategies (Vezzaro et al, 2014), the use of design storms are difficult or even impossible. Even simple design situations such as sizing of a series of detention basins and statistics in relation to combined sewer overflows (CSOs) require

simulations using historical time series because of non-linear responses. Such analyses are traditionally carried out using Long Term Statistics (LTS) modelling with historical time series of rainfall (Thorndahl 2009; Davidsen et al., 2017). LTS is a technique used to ensure detailed calculations of all interesting periods in a long time series, while excluding less interesting periods of the time series in order to reduce computational time. Given expectations to climate change, LTS simulations should not, however, be based solely on historical rainfall data but should be supplemented with rainfall time series that represent expected future climate to give an indication of what future impacts a changing climate might entail. When simulating the impact of climatic changes the use of climate factors have been advocated and implemented many places (Arnbjerg-Nielsen et al, 2013). However, this approach is closely linked with the use of design storms and is therefore not suitable when calculating impacts to the very non-linear statistics discussed above.

Arnbjerg-Nielsen et al (2013) show that there is a profound lack of precipitation data with a resolution suitable for urban drainage for both present and future climates and that weather generators are the best mean to overcome this shortcoming. Many formulations of weather generators for creation of synthetic rainfall time series have been proposed (Olsson and Burlando, 2002; Vrac et al., 2007; Burton et al., 2008; Onof and Arnbjerg-Nielsen, 2009; Chen et al., 2010; Willems and Vrac, 2011; Cowpertwait et al., 2013; Müller and Haberlandt, 2016; Peleg et al., 2017; Thorndahl et al., 2017). Common for all of them is that synthetic rainfall time series are generated based on statistics of point rainfall observations or re-analysis data. Regarding expectations to a changed climate, weather generators are essential for understanding the dynamics at very small scales (Maraun et al., 2010). For further reading, extensive reviews of weather generators can be found in e.g. Fowler et al. (2007).

In the present study we analyse the results from applying LTS simulations with artificial rainfall time series generated by four different techniques to two catchments with different hydrological characteristics. The four investigated techniques (Onof and Arnbjerg-Nielsen, 2009; Sørup et al., 2016; 2017; Thorndahl et al., 2017) can all be used to downscale climate change signals to scales relevant for urban hydrology, but are tailored for different purposes, which results in time series with differing characteristics that range from different temporal and spatial resolutions to differences in how many characteristics of the historical rainfall series are taken into account when generating synthetic series. Further, different climate scenarios are used as input to the different weather generators, adding further diversity to the time series created for future changed climate conditions.

The overall objective of this study is to compare and investigate the usefulness of various rainfall generators for LTS simulations and furthermore investigate how much the choice of rainfall generator affects the LTS results under the influence of climate change. The study focuses on the response of the urban drainage system identified through LTS simulations and hence indicators representing either aggregated statistics or the non-linear responses of the sewer system are considered. When considering future impacts also other drivers of change should be included as discussed in e.g. Semadeni-Davies et al (2008) and Urich and Rauch (2014). However, for the sake of clarity, we will in this paper restrict ourselves to consider only changes in precipitation and disregard other drivers such as e.g. changes in land use over time or changes in boundary conditions.

# Methods

## Data

For this study, observational data (*OBS*) from two different rain gauges are used along with artificial rain data from four different weather generators.

The observational data originate from two tipping bucket rain gauges in the Copenhagen area (Søborg Vandværk and Rødovre Vandværk, Denmark) situated approximately five kilometres apart where long rainfall records are available (both active from 1979 to present) (Madsen et al, 2017). The reason for using two observed rain series from the same area instead of just one is that this allows for a qualitative comparison of differences between artificial and observed rainfall with the uncertainty of the observed rainfall. We also compare to the regional model (*REG*) for intensity-duration-frequency (IDF) characteristics for extreme rainfall (Madsen et al., 2017), when possible.

Table 1 summarizes the different rainfall series used as input for the LTS simulations. Three out of the four artificial data sets (*SO1*, *SO2* and *THO*) are created based on properties of the two observed time series. For *SO1* and *THO* realizations are created for both rain gauge locations and for both present and future conditions; for *SO2* only realizations for future conditions are generated, as $SO2_{present}$ equals the observations. The fourth data set (*OAN*) is created for average Danish conditions with one realization for present and future conditions respectively. In all cases between 30 and 100 years of data is created and 10 years of continuous data is extracted randomly from each dataset for use in the LTS simulations.

**Table 1 Overview of the data sets used in the comparison in this study.**

| Reference | Name | Number of time series | Temporal reso-lution | Methodology used to create data set |
|---|---|---|---|---|
| Obser-vations | *OBS* | 2 | 1 min | Measured with tipping bucket rain gauges at minute resolution. |
| Onof and Arnbjerg-Nielsen (2009) | $OAN_{present}$<br>$OAN_{future}$ | 1<br>1 | 24 h -> 1 min | Random Parameter Bartlett–Lewis pulse process model at daily scale further temporarily downscaled using a random cascade model.<br>The future scenario is based on the SRES A2 scenario for 2100 dictating a rather large increase in precipitation in Denmark.<br>Both present and future scenarios are generated for average Danish conditions. |
| Sørup et al. (2016) | $SO1_{present}$<br>$SO1_{future}$ | 2<br>2 | 1 h | Spatial Neyman-Scott Pulse Process Model at hourly scale, no further downscaling.<br>The future scenario is based on the SRES A1B scenario for 2100.<br>The four generated time series stem from two simulations (one present and one future) from where time series are extracted for both locations of the rain gauges comprising the observations. Thus, the spatial correlation between the time series are similar to that of the observations. |

| | | | | |
|---|---|---|---|---|
| Sørup et al. (2017) | $SO2_{future}$ | 2 | 1 min | Empirical perturbation scheme applied directly to observations where the individual events are perturbed based on their estimated return level and the season. The future scenario is for 2100 and is based on recent expected estimates for Denmark regarding extremes and seasonal behaviour which includes both SRES and RCP scenarios. |
| Thorndahl et al. (2017) | $THO_{present}$<br>$THO_{future}$ | 2<br>2 | 1 min | A resampling algorithm is applied to observational data to generate stochastic time series resembling present climate. A stochastic perturbation is then performed generating time series representative for future climate conditions represented by the SRES A1B scenario for 2100. |

The different weather generator data sets are expected to perform differently as they have very different preconditions and realizations, but for present conditions they should all be able to generate realistic time series comparable to the observations. For the future scenarios the expectation is that the realizations will be different both due to the different underlying assumptions about climate change and due to the different methodologies.

## Catchments

Two catchments from Aarhus, Denmark, are used for this study. The Western catchment (see Figure 1) is small and flat with an impervious area of 8.3 ha and has one CSO ($CSO_{west}$). The pipe network consists of small pipes with one main connection from the catchment to the CSO structure. The Eastern catchment has a more complex pipe network, is much larger with an impervious area of 142 ha, is much steeper, and has two CSO structures; one directly to the lake ($CSO_{lake}$) and one right before the connection to the wastewater treatment plant ($CSO_{east}$).

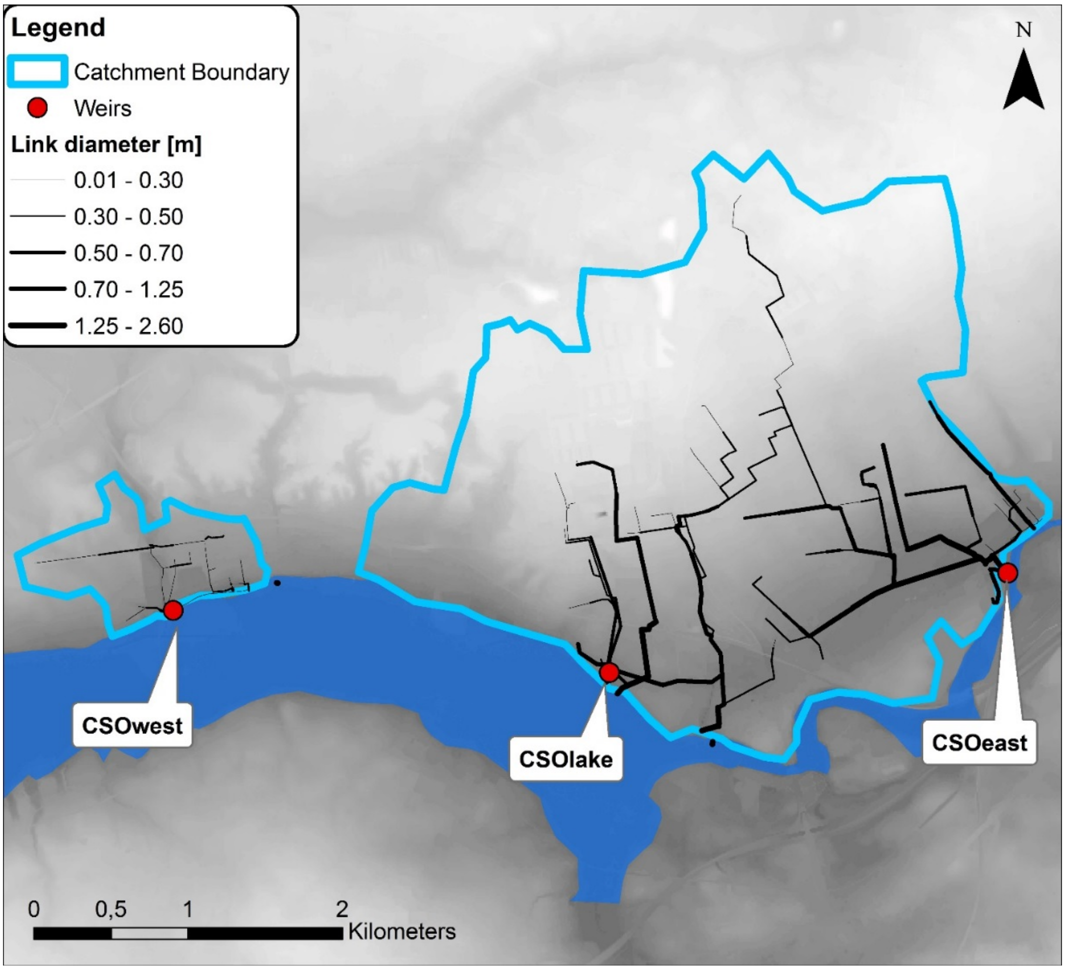


**Figure 1 Area map of the two catchments used for this study with indications of the simulated drainage system and markings of the three CSO structures. Shaded background colours indicate terrain elevations.**

## Simulation

For each dataset, all rain events included in the selected 10 year time series are identified based on a minimum rain intensity of 0.02 mm/min. Rain events are considered individual if separated by a period of 24 hours of dry weather. LTS simulations are performed for the series of rain events using the 1D hydraulic model MOUSE (DHI, 2003). The simulation of individual events starts with the beginning of rainfall and continues after rainfall has stopped until all the following conditions are met: All basins in the catchments are empty, the water level has fallen below the weir crest for the CSO structures and the flow in all the outlets is below a critical threshold of 0.1 $m^3/s$, whereby the drainage network has nearly returned to idle conditions. All the considered rainfall time series are applied to both catchments and a spatially homogenous rainfall is assumed.

## Comparison Metrics

To compare the performance of the catchment under the influence of the different precipitation products we analyse a number of variables.

To be able to directly compare the different time series in present climate we derive:

- the mean seasonal precipitation,

- the annual mean number of events per season, and
- the intensity-duration-frequency (IDF) curves for 0.5-, 1- and 5-year return periods.

This enables us to evaluate whether the time series used in the LTS simulation from the different WGs have the same characteristics as the observations for moderate extremes in the range expected to generate CSO events. Furthermore, the same metrics enables us to directly evaluate the implication of climate change on the different WGs through evaluating the changes in metrics from present to future conditions.

The main focus of this study will however be on the response of the urban drainage system identified through LTS simulations. Most important is the non-linear responses, represented by the following indicators:

- the return period of full flowing pipes,
- the total number of CSO events for the 10-year simulation, and
- the total CSO volumes for the full simulations

Together these metrics are used to discuss the applicability of the different artificial rainfall series for analysis purposes, the differences between catchments and the implications of climate change.

# Results and Discussion

## Direct Comparison of Time Series

The time series from the different weather generators are compared to the observations with respect to the mean seasonal precipitation and the number of events per season (see Figure 2). With respect to seasonal precipitation all weather generators have some problems in reproducing the present seasonal pattern and seem to underestimate the summer precipitation (Figure 2A); $SO1_{present}$ underestimates precipitation for all seasons and in particular for the summer season, $OAN_{present}$ overestimates precipitation in the autumn season, leaving $THO_{present}$ as the overall best weather generator with respect seasonal variation. Regarding future precipitation (Figure 2B) $OAN_{future}$ and $SO1_{future}$ predict increases in spring and winter and slight decreases in summer and autumn. Compared to *OBS*, $SO2_{future}$ predicts virtually no change in spring and winter, large decreases in summer and large increases in autumn. Finally, $THO_{future}$ predicts large increases in spring, autumn and winter and no particular change in summer. Some of these differences are in line with the differences between the underlying climate scenarios, but e.g. $OAN_{future}$ should be much stronger, but similarly, forced than $THO_{future}$ and $SO1_{future}$; that is not very obvious from the results.

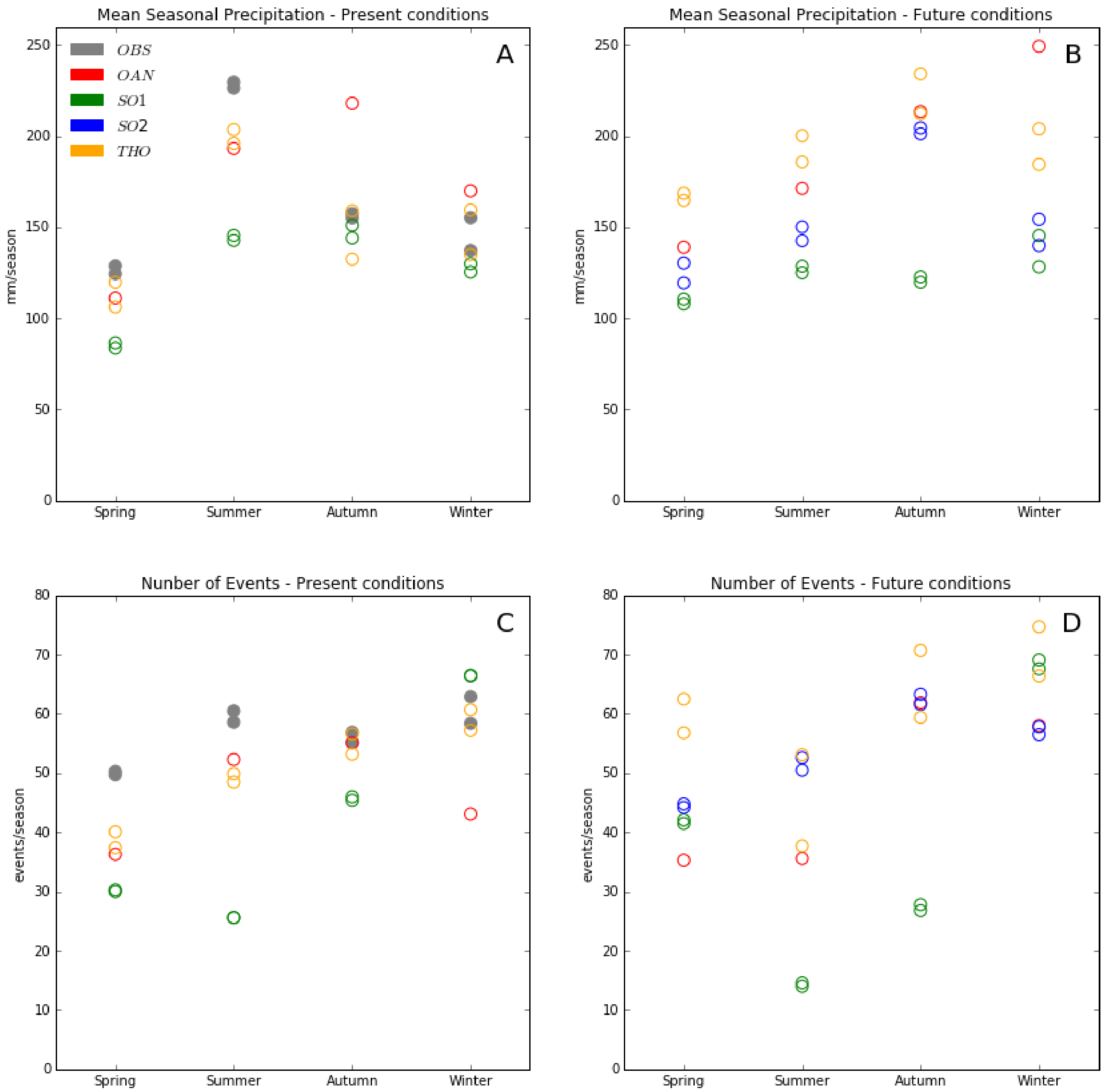


**Figure 2 Seasonal precipitation for present (A) and future (B) simulations. Likewise, number of events per season for present (C) and future (D) conditions.**

All weather generators underestimate the number of events for present conditions (Figure 2C) with $SO1_{present}$ deviating substantially from the observations and $THO_{present}$ performing marginally better than $OAN_{present}$, but still underestimating the number of events during spring. For future conditions (Figure 2D) $OAN_{future}$ has a stable number of events for spring and autumn, less events in summer and more events in winter. $SO1_{future}$ generate the same amounts of spring and winter events and produce less summer and autumn events. $SO2_{future}$ produces slightly less events in spring, summer and winter and more events in autumn whereas $THO_{future}$ produces more events in spring, autumn and winter and less in summer. There is not a clear link between number of events and mean seasonal precipitation within or among different weather generators.

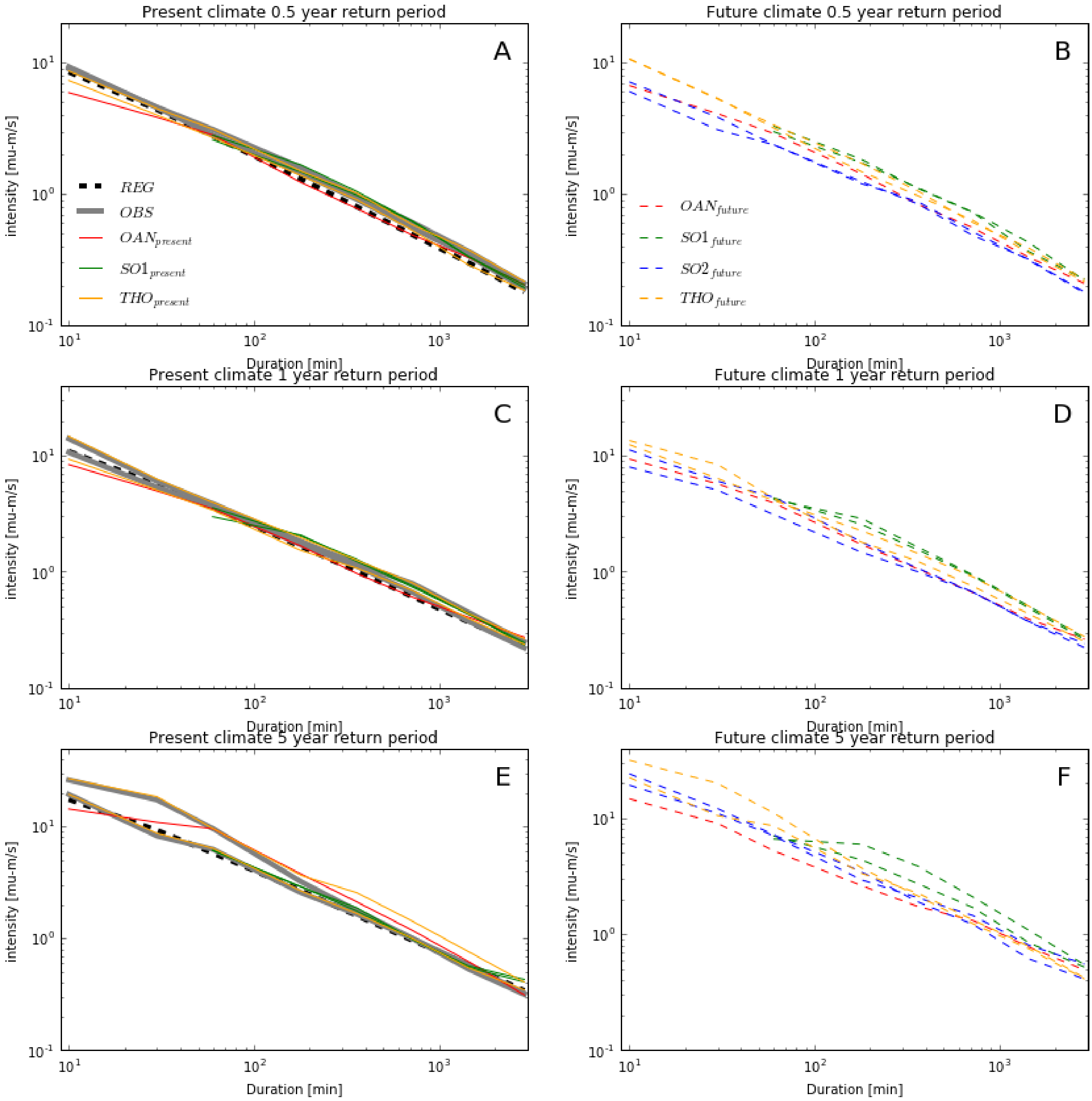


**Figure 3 IDF curves between 10 minutes and 2 days for the different data sets for return periods of 0.5- (A+B), 1- (C+D) and 5-years (E+F).**

IDF-curves for 0.5-, 1- and 5-year return periods are compared (see Figure 3). For 0.5- and 1-year events all simulations are very close to each other. For 5-year events the spread is somewhat larger, but most simulations are within the envelope defined by the observations. For present climate it seems that all weather generators produce time series that resemble observed precipitation at the event level for the considered return periods.

Regarding the influence of climate change some differences are observed (Figure 3B, D and F). $SO1_{future}$ and $THO_{future}$ project quite consistent increases in intensities for all return levels and durations. $OAN_{future}$ projects decreases at the 0.5- and 5-year return levels and moderate increases at 1-year return levels.

Somewhat opposite, $SO2_{future}$ projects no change to moderate increases at 5-year return level and decreases at the 0.5- and 1-year return levels. These differences can partly be explained by the sampling strategy and partly by the setup of the weather generators themselves. As only 10 years of data is sampled from each time series the uncertainty on the 5 year return levels is high, which is believed to be the main influence affecting the behaviour of $OAN_{future}$ and $SO2_{future}$ where the expectation would be an increase for these return levels. For the more frequent return levels the differences are believed to originate in the methodology for inclusion of climate change of the individual weather generators. $SO2_{future}$ is the only weather generator that projects a decrease of the magnitude of frequent summer events and that is likely causing the decrease observed for the 0.5- and 1-year events. It is noteworthy that $OAN_{future}$ predicts less increase than $SO1_{future}$ and $THO_{future}$ despite being based on a more severe climate change scenario (SRES A2 versus SRES A1B for the others, see Table 1).

As different climate scenarios were used as input for the different weather generators, we refrain from a detailed discussion on what is the most likely effect of climate change on precipitation on these scales. We note that there are differences between the historical and the artificial rainfall time series and that these differences, especially for more frequent extremes, can influence the occurrence of CSOs or full-flowing pipes.

## Effect on Full Flowing Pipes

The number of full flowing pipes is analysed separately for the two catchments (see Figure 4). For the small Western catchment full flowing pipes occur very frequently under present conditions (around 80 to 90 times per year for the *OBS*, see Figure 4A) and 40% of the pipes are full flowing approximately 10 times per year, indicating the effect of a downstream bottleneck that dominates the flow regime in part of the system. Apart from this part of the system the full flowing pipes start occurring around a return period of 1 year for the Western catchment. Both *OBS* data sets perform very similar and all weather generator simulations for present climate also follow this behaviour with $THO_{present}$ most closely resembling *OBS*. $SO1_{present}$ systematically underestimates the fraction of full flowing pipes which is likely due to the temporal resolution of this data set where all the sub-hourly peaks are lacking. Conversely, $OAN_{present}$ show an overestimation of the very frequent full flowing pipes; this could well be due to large but very short peaks in frequent events that influences pipes on a very local basis. The time of concentration of both catchments are relatively short with $t_c(West) << 1\ hour$ and $t_c(East) \sim 1\ hour$. This supports that a high temporal resolution in the rainfall time series is needed if performing LTS simulation.

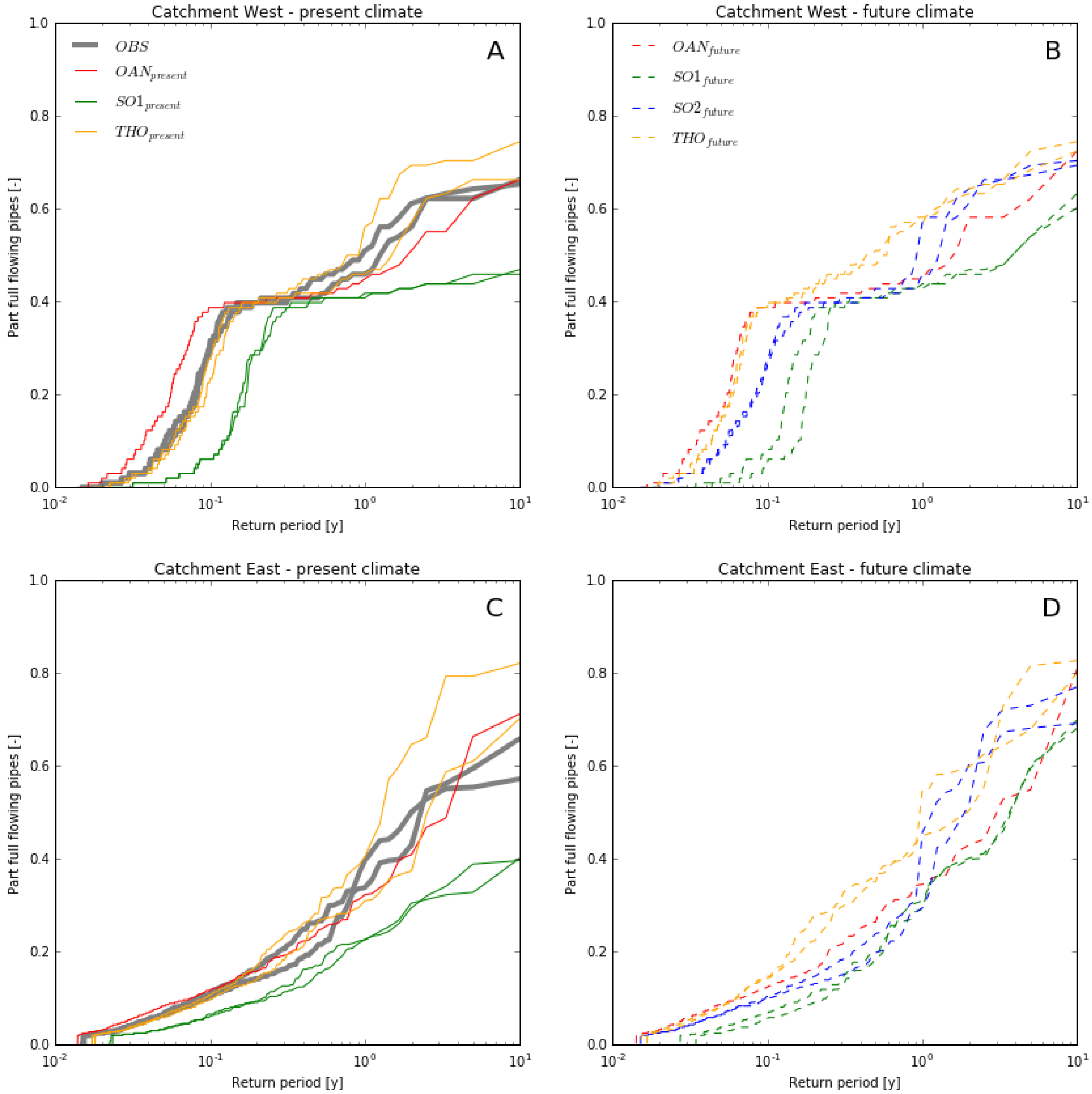


**Figure 4 Part full flowing pipes for the different data sets for the Western (A+B) and the Eastern (C+D) catchments. *OBS* represents the same historically observed rainfall in all plots. For present climate *SO2* is by definition identical to *OBS*.**

For most data sets, the influence of future climate (Figure 4B) seems to be a slight increase in how often full flowing pipes are observed irrespective of the precipitation behaviour observed in Figure 3. The level of change in performance of the sewer system seems to be the same irrespectively of which method is used, except for *OAN* that seems to predict no change.

The larger Eastern catchment responds different to the rain input (Figure 4C). The first pipes run full just as frequent but the increase in the part of full flowing pipes is much more gradual. This indicate that the pipe system experiences local full flowing pipes due to the direct runoff and that the system as such does not experience a lot of backwater. For the more rare events (from approximately a 1-year event) the two catchments behave very similar with a large part of the pipes being full flowing and the part increasing steadily with the rarity of the rainfall. Again, the coarse resolution of the *SO1* data sets is evident and the influence of future climate (Figure 4D) is similar as for the Western catchment.

## Effect on Number and Volumes of CSOs

The total number of CSOs as well as CSO volumes occurring in the individual 10-year simulations are reported in Figure 5. All results obtained by means of using the weather generators for present conditions result in a number of CSOs at the same level as the observations. The temporal resolution of data does not seem to influence the number of CSOs as the $SO1_{present}$ data sets perform very similar to the other data sets with regard to number of CSOs, thereby supporting the findings that the volumes in drainage systems generally are large enough to attenuate the sub-hourly variation upstream of CSO structures (Schilling, 1991). For the time series representing future climate the results are very different for number of CSOs (Figure 5A-C). $OAN_{future}$ in general suggests no change in the number of CSOs with maybe a slight increase in the direct overflow from $CSO_{lake}$. $SO1_{future}$ suggests large increases in numbers for all CSOs with a doubling in $CSO_{west}$ and $CSO_{east}$ and a smaller increase in number of CSOs for the overflow from $CSO_{lake}$. $SO2_{future}$ suggests no change in the number of CSOs except for the $CSO_{east}$ which is doubled (but from very small numbers). Finally, $THO_{future}$ suggests large increases in number of CSOs with a tripling for $CSO_{west}$ and a doubling for the two other CSOs. This is somewhat in agreement with the small differences observed in the IDF curves in Figure 3 where the $SO1_{future}$ and $THO_{future}$ data sets have the highest intensity levels. It appear that relatively few rare events cause the CSOs and the differences between present and future conditions in IDF-relationship observed in Figure 3 is again reflected in the CSO numbers reported in Figure 5. There is no clear sign to whether to expect more or less CSOs in the future and how large the change will be, but some of the increases observed here represent change factors that are much higher than what is observed for the IDF-relationships highlighting the importance of actually performing LTS simulations and not just expect the same behaviour.

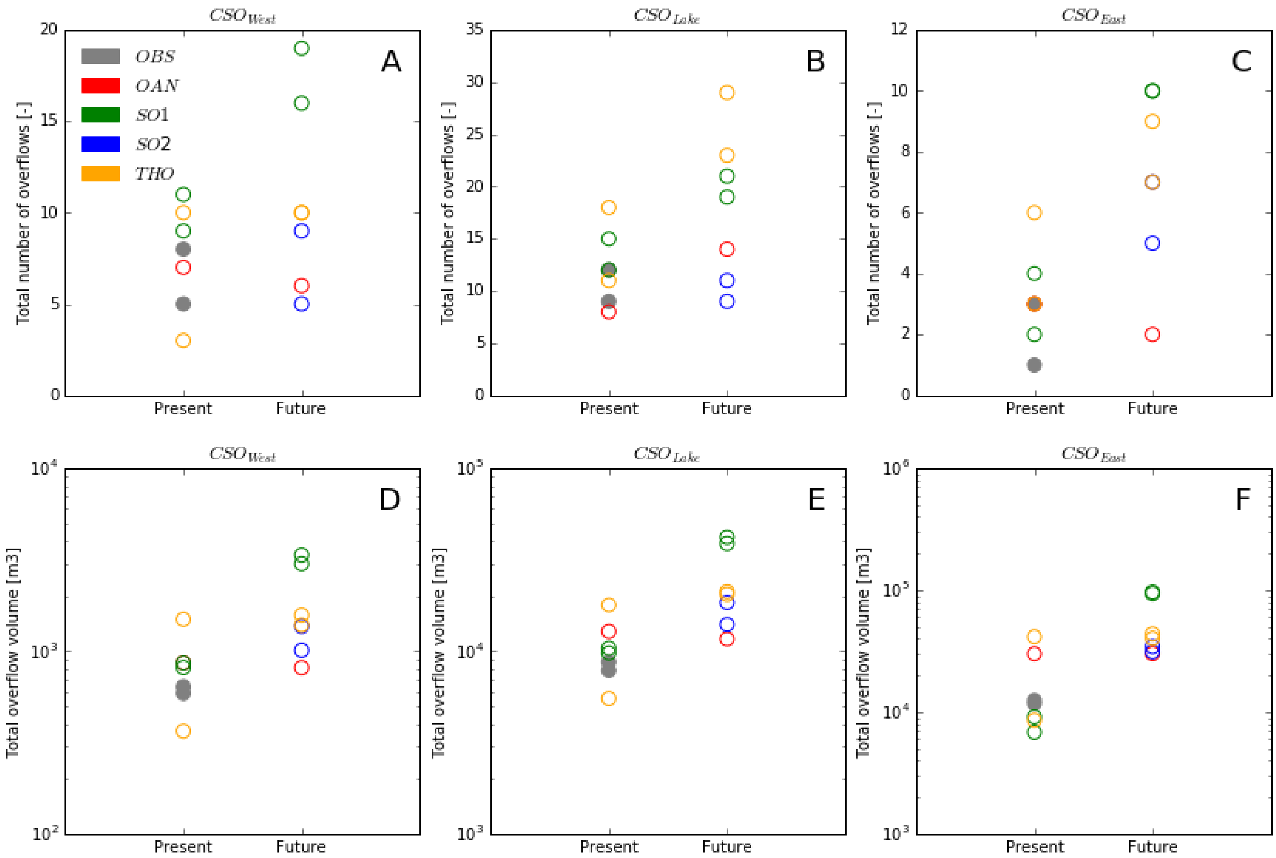


**Figure 5. Total number of CSOs (A-C) and total CSO volumes (D-F) observed at the three CSOs (different columns) in the systems during 10 years of simulation for present and future conditions.**

CSOs do not occur frequently in the considered catchments, and hence the estimated CSO volumes depend highly on the few most severe events generated by the WGs (Figure 5D-F). Hence it seems that all simulations for present conditions produce comparable CSO volumes, and interestingly the $SO1_{present}$ results are quite close to *OBS* even though the temporal resolution is rather poor.

For future conditions most weather generators produce increased amounts of CSO volumes except *OAN* that show very stable volumes even though the number of CSO events are changing. $SO1_{future}$ produces the largest amount by far; well in line with the IDF curves presented in Figure 3. Thus, irrespective of the methodology used all weather generators point towards that rare CSO causing events in the future will contain higher volumes of water, but whether there will be more CSO causing events is not clear from running simulations as the different weather generators produce very different results.

## Discussion

LTS simulations are a necessary tool for assessing how drainage systems behave in complex design situations. The results of this study show that artificial rainfall from weather generators can be useful as input for LTS simulations as the different methodologies all produce time series that are sufficiently similar to observed rainfall to generate a realistic response in the drainage network. No weather generator product clearly outperforms the others (see Table 2), but, depending on the actual application, high temporal resolutions and geographical representativeness are important parameters to consider for smaller catchments (in favour of *SO2* and *THO*) even though all products performed reasonable well in predicting numbers and volumes of CSOs. The length of the used time series was a limiting factor, since it is questionable whether 10 years of data is enough for a representative simulation of phenomena that might only occur once a year.

**Table 2 Relative qualitative performance of each of the indicators for present climate, rated between perfectly within uncertainty of calculation (+++++) and definitely outside uncertainty of calculation (+)**

| | *OAN* | *SO1* | *SO2* | *THO* |
|---|---|---|---|---|
| Application for small catchments (where point rainfall is appropriate) | ++ | + | ++++ | ++++ |
| Seasonal statistics | +++ | ++ | (+++) | ++++ |
| Estimation of full flowing pipes (small catchments) | +++ | + | ++++ | ++++ |
| CSO frequency | ++++ | ++++ | ++++ | ++++ |
| CSO volume | ++++ | ++++ | ++++ | ++++ |
| Flexibility in inclusion of climate change (as in how easy it is to get hold of relevant data for perturbation) | +++ | + | +++++ | +++ |

For LTS simulations under influence of climate change artificial rainfall from weather generators are essential. The results show that irrespective of the methodology applied for generating the artificial rainfall time series, climate change in all cases lead to more severe events that influences the drainage system performance. Inclusion of climate change in weather generators generally requires generation of a range of relevant expected changes based on e.g. regional climate models; in practice this limits some of the approaches as *SO1*'s performance is dependent on hourly climate information for estimation of a weather generator for future climate. *THO* and *OAN* both include climate change based on a set of statistics from Regional Climate Models and scales that are generally available. *THO* has the possibility of flexibility in assigning different weights to different target variables, e.g. higher weights can be given to target seasonal precipitation than extremes – or vice versa. The generation of rain series for this analysis has focused on an overall performance on all target variables. Lastly, *SO2* is an extremely flexible framework that allows for custom changes to the distribution of rainfall based on any (or in principle none) input and can be used for changing a time series to meet any desired criteria. In practise use of more than one generator should be pursued to reveal results less dependent on the actual model used and all other models than *SO1* seem viable options.

## Conclusions

We have run LTS simulations with precipitation time series from two rain gauges as well as from four different weather generators that represent different methodologies for producing artificial rainfall time series for present and future climate conditions. In general, all weather generators produce time series for present climate that have characteristics comparable to the observations.

Looking at the catchment response it is evident that the temporal resolution is important for simulation of pipe flow and the fraction of full flowing pipes. The $SO1_{present}$ data with one hour resolution systematically underestimated this fraction. Considering the number and volumes of CSOs for present conditions all weather generator data sets performed well indicating that the fine dynamics are not important for CSO numbers or volumes. Even though the hydrological responses of the two catchments were very different, the relative response to the different artificial rainfall time series was very similar. This indicates that the physical build-in robustness towards diversity in rainfall that these drainage systems should have, when modelled acts as a mediator when the input is from even more diverse artificial sources.

For future climate the results point in different directions as both different weather generators and climate scenarios were considered. The IDF curves for future conditions has larger differences than for present climate and show both increases and decreases for different return levels. Despite this, pipes run full more often and CSO volumes increase in all future conditions even though the number of CSOs only increases in some of the simulations.

Using time series from weather generators to run LTS simulation is a useful tool in situations where observational data is lacking or where simulations for future conditions has to be evaluated. The length of the LTS simulations is a design parameter that could influence some parameters and should be a consideration when designing studies. For some indicators having a sub-hourly resolution is a necessity, and a good suggestion for the choice of a weather generator scheme would be to use a good reshuffling algorithm (e.g. the one from *THO*) and combine it with a flexible climate change procedure (e.g. the one from *SO2*) to ensure the generation of time series that represent expected changes well.

## Acknowledgement

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