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, for example, 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 (WGs) have to be used. In this study, we ran LTS simulations with four different WG products for both present and future conditions on two different catchments. For the 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 (CSOs). For future conditions, the differences in the WGs representation 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.

Key words | climate change, combined sewer overflow, CSO, long term statistics, LTS, weather generator

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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 of 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 to simply scale present rainfall 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

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for urban drainage for both present and future climates and that weather generators (WGs) are the best means of overcoming this shortcoming. Many formulations of WGs for creation of synthetic rainfall time series have been proposed (Olsson & Burlando 2002; Vrac *et al.* 2007; Burton *et al.* 2008; Onof & Arnbjerg-Nielsen 2009; Chen *et al.* 2010; Willems & Vrac 2011; Cowpertwait *et al.* 2013; Müller & Haberlandt 2016; Peleg *et al.* 2017; Thorndahl *et al.* 2017). Common in 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, WGs are essential for understanding the dynamics at very small scales (Maraun *et al.* 2010). For further reading, extensive reviews of WGs can be found in, for example, 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 & 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 WGs, 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 indicators representing either aggregated statistics or the non-linear responses of the sewer system are considered. When considering future impacts other drivers of change should be included as discussed in e.g. Semadeni-Davies *et al.* (2008) and Urich & 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 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 WGs.

The *OBS* 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). These two rainfall time series are located in an area where the expectation is that they should have very similar statistical properties. Hence, 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 statistics of the *OBS* 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 are created and 10 years of continuous data are extracted randomly from each data set for use in the LTS simulations.

The different WG 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

As the focus of this study is on catchment response to different rainfall input, two catchments from Aarhus, Denmark are used

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
Observations	*OBS*	2	1 min	Measured with tipping bucket rain gauges at minute resolution.
Onof & Arnbjerg-Nielsen (2009)	$OAN_{present}$ OAN_{future}	1 1	24 h > 1 min	Random Parameter Bartlett–Lewis pulse process model at daily scale further temporarily downscaled using a random cascade model. The future scenario is based on the SRES A2 scenario for 2100 dictating a rather large increase in precipitation in Denmark. Both present and future scenarios are generated for average Danish conditions.
Sørup *et al.* (2016)	$SO1_{present}$ $SO1_{future}$	2 2	1 h	Spatial Neyman-Scott Pulse Process Model at hourly scale, no further downscaling. The future scenario is based on the SRES A1B scenario for 2100. 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)	$THO_{present}$ THO_{future}	2 2	1 min	A resampling algorithm is applied to OBS 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.

for this study instead of the catchment where the rain gauges are actually located. The catchment where the rain gauges are located is a flat, rather large, hydraulic complex urban catchment, whereas the chosen catchments represent smaller and simpler catchments as well as more diversity with respect to the steepness. Unfortunately, we do not have rainfall data available for the catchments of similar quality as the rainfall data used. The western catchment (see Figure 1) is small and flat with an impervious area of 8.3 ha out of a total area of 28.7 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 out of a total area of 1,263 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}).

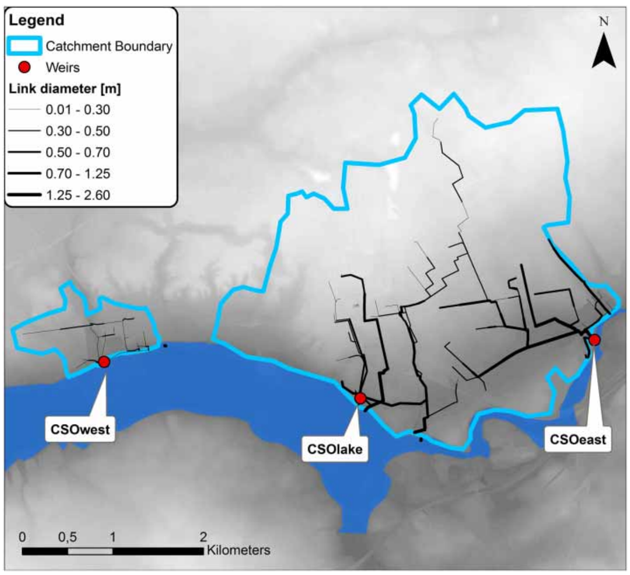

Figure 1 | Area map of the two catchments used for this study with indications of the simulated drainage system and markings of the three CSO structures. Shaded background colours indicate terrain elevations.

Simulation

For each data set, 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 h 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 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 WGs 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 WGs have some problems in reproducing the present seasonal pattern and seem to underestimate the summer precipitation (Figure 2(a)); and $SO1_{present}$ 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 WG with respect to seasonal variation. Regarding future precipitation (Figure 2(b)), 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; however, THO_{future} and $SO1_{future}$ should be forced similarly to OAN_{future}, the latter stronger, though, which is not obvious from the results.

All WGs underestimate the number of events for present conditions (Figure 2(c)) 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 2(d)), OAN_{future} has a stable number of events for spring and autumn, fewer events in summer and more events in winter. $SO1_{future}$ generates the same amounts of spring and winter events and produces fewer summer and autumn events. $SO2_{future}$ produces slightly fewer events in spring, summer and winter and more events in autumn, whereas THO_{future} produces more events in spring, autumn and winter and fewer in summer. There is not a clear link between the number of events and the mean seasonal precipitation within or among different WGs.

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 the

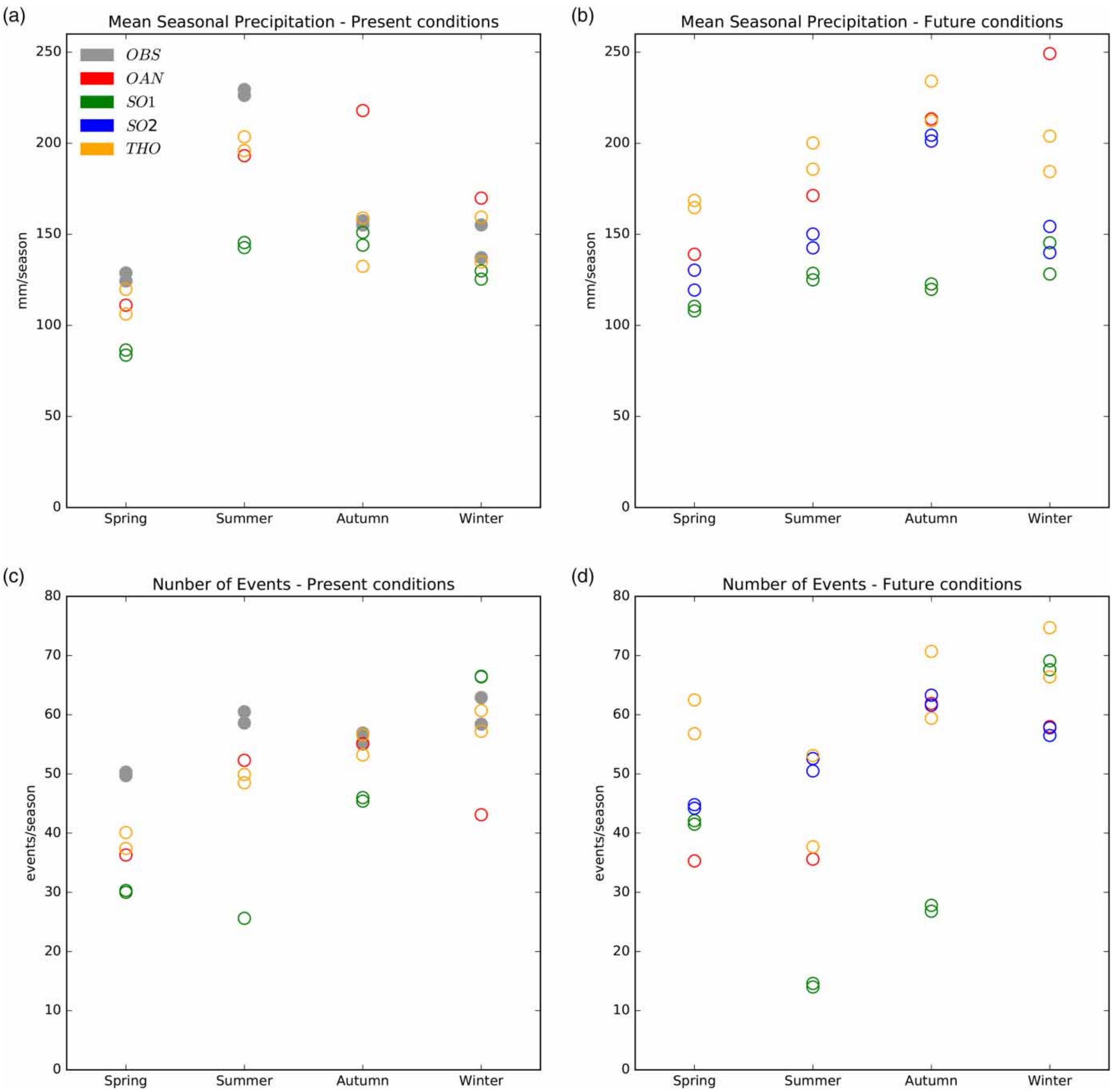

Figure 2 | Seasonal precipitation for present (a) and future (b) simulations. Likewise, number of events per season for present (c) and future (d) conditions.

present climate, it seems that all WGs 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 3(b), 3(d) and 3(f)). $SO1_{future}$ and THO_{future} project quite consistent increases in intensities for all return levels and durations. OAN_{future} predicts decreases at the 0.5- and 5-year return levels and moderate increases at 1-year return levels. Conversely, $SO2_{future}$ 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 WGs themselves. As only 10 years of data are sampled from each time series, the uncertainty at 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 periods. For the more frequent return periods, the differences are believed to originate in the methodology for inclusion of climate change of the individual WGs. $SO2_{future}$ is the only WG that predicts a decrease of the magnitude of frequent summer events and

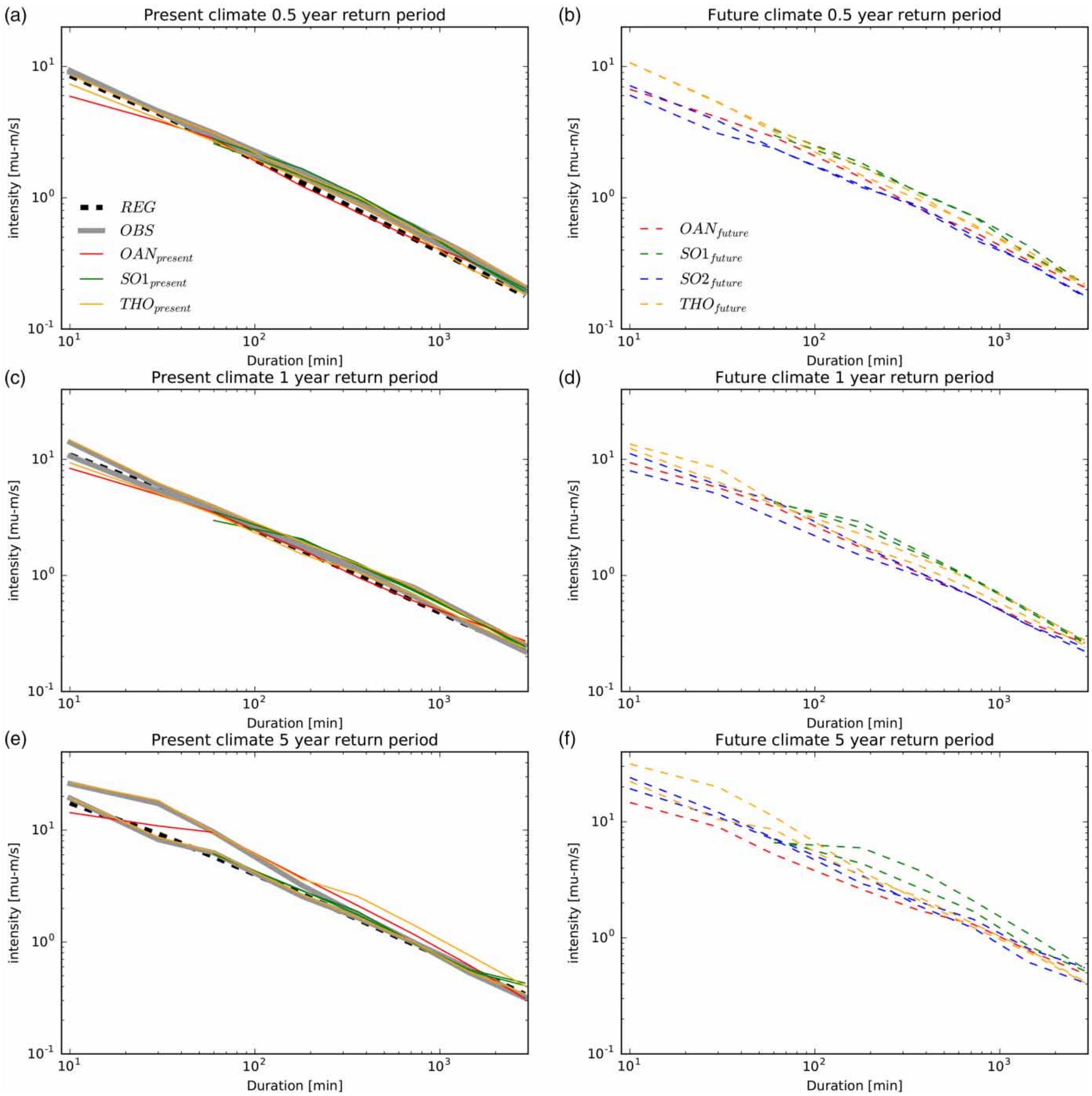

Figure 3 | IDF curves between 10 min and 2 days for all the different data sets as well as the regional model for the location of the rain gauges for return periods of 0.5- (a and b), 1- (c and d) and 5-years (e and f) for present (a, c and e) and future (b, d and f) conditions.

that is likely to cause 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 inputs for the different WGs, we refrain from a detailed discussion on what is the most likely effect of climate change on precipitation on the investigated small urban 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 the present conditions (around 80 to 90 times per year for

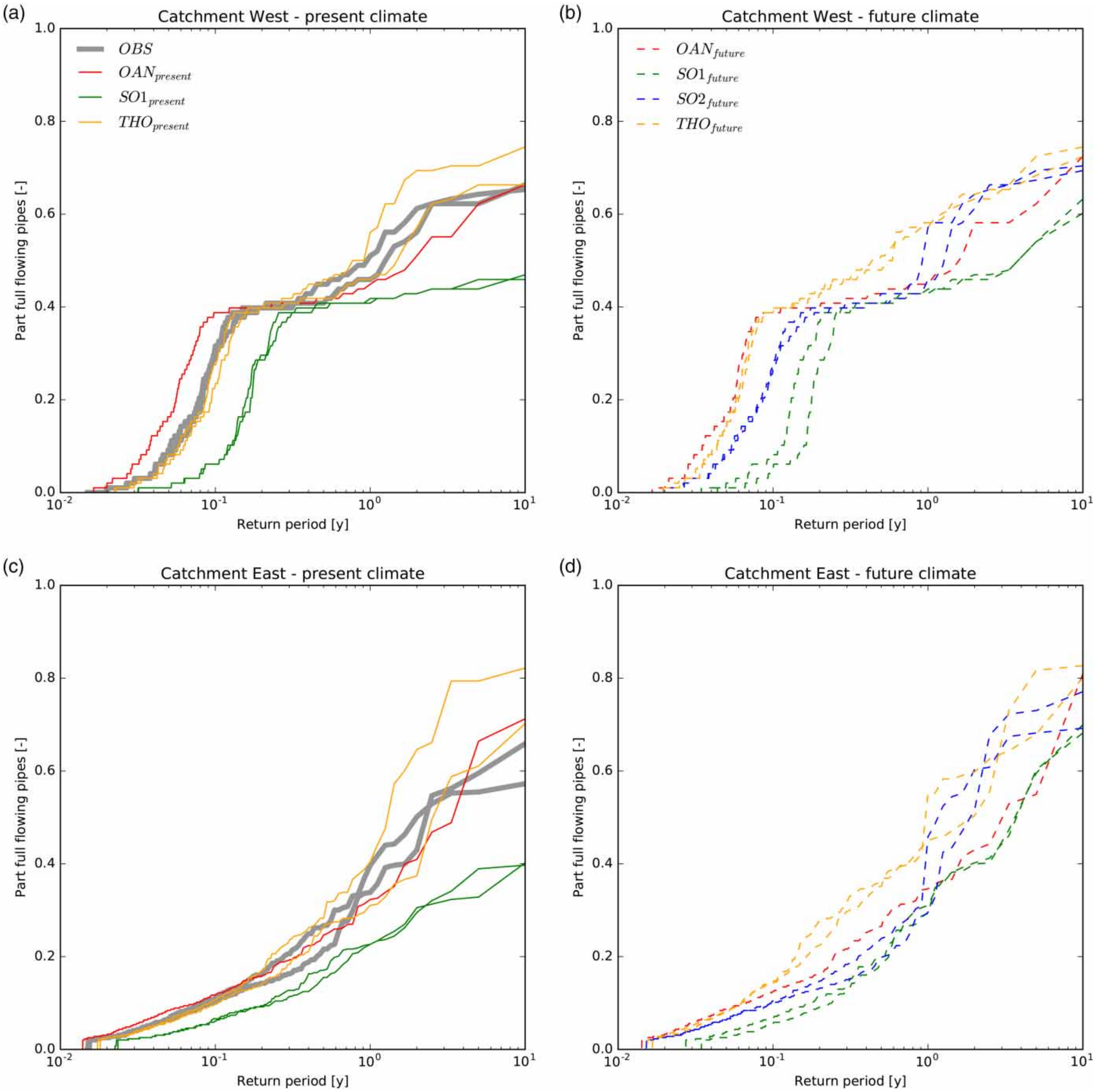

Figure 4 | Part full-flowing pipes for the different data sets for the western (a and b) and the eastern (c and d) catchments for present (a and c) and future (b and d) conditions. *OBS* represents the same historically observed rainfall in all plots. For the present climate, *SO2* is by definition identical to *OBS*.

the *OBS*, see Figure 4(a)) 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 similarly and all WG 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, $OAN_{present}$ shows an overestimation of the very frequent full-flowing pipes; this could well be due to large but very short peaks in frequent events that influence pipe behaviour on a very local basis. The times of concentration of both catchments are relatively short with $t_c(West) \ll 1$ *hour* and $t_c(East) \sim 1$ *hour*. This supports the conclusion that a high temporal resolution in the rainfall time series is needed if performing LTS simulation.

For most data sets, the influence of future climate (Figure 4(b)) 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 irrespective of which method is used, except for *OAN*, which seems to predict no change.

The larger eastern catchment responds differently to the rain input (Figure 4(c)). The first pipes run full just as frequently but the increase in the proportion of full-flowing pipes is much more gradual. This indicates 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 an approximately 1-year event) the two catchments behave very similarly with a large part of the pipes being full flowing and the proportion of pipes running full increasing steadily with the rarity of the rainfall. Again, the coarser temporal resolution of the *SO1* data sets is evident and the influence of future climate (Figure 4(d)) is similar to that 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 using the WGs 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 similarly 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 the number of CSOs (Figure 5(a)–5(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 the number of CSOs for the overflow from CSO_{lake}. $SO2_{future}$ suggests no change in the number of CSOs except for the

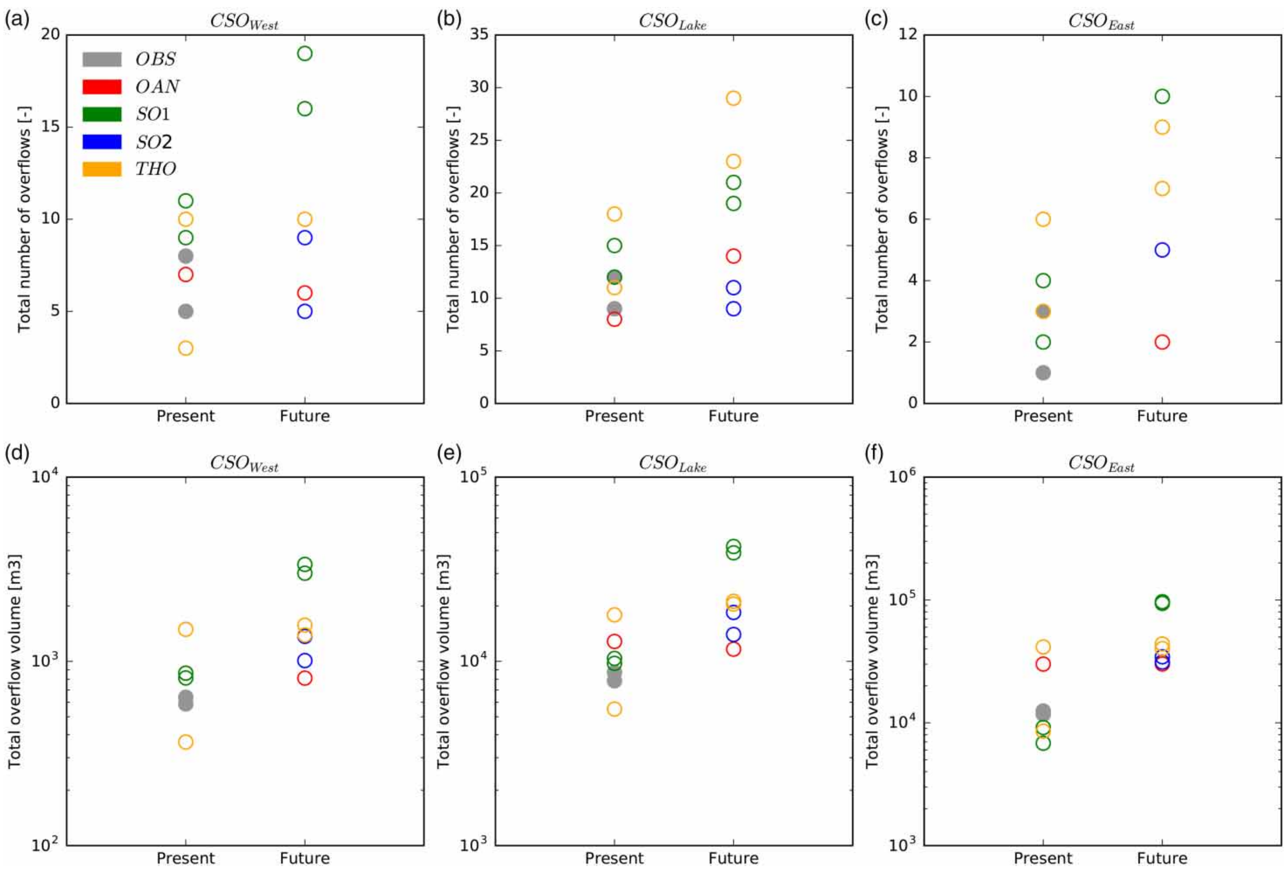

Figure 5 | Total number of CSOs (a–c) and total CSO volumes (d–f) observed at the three CSOs (CSO_{West} (a and d), CSO_{Lake} (b and e) and CSO_{East} (c and f)) in the systems during 10 years of simulation for present and future conditions.

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 appears that relatively few rare events cause the CSOs and the differences between present and future conditions in IDF-relationships observed in Figure 3 is again reflected in the CSO numbers reported in Figure 5. There is no clear sign as to whether to expect more or less CSOs in the future and how large changes 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 expecting the same behaviour.

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 5(d)–5(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 WGs 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 WGs point towards rare CSO causing events in the future that will contain higher volumes of water, but whether there will be more CSO causing events is not clear from running simulations as the different WGs 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 WGs can be useful as inputs 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 WG 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 reasonably 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 are 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 WGs are essential. The results show that, irrespective of the methodology applied for generating the artificial rainfall time series, climate change in all cases leads to more severe events that influence the drainage system performance. Inclusion of climate change in WGs generally requires generation of a range of relevant expected changes based on, for example, 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 WG 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 of all target variables. Last, *SO2* is an extremely flexible framework that allows for custom changes to the distribution of rainfall based on any (or, in principle, no) input and can be used for changing a time series to meet any desired criteria. In practice, use of more than one generator should be pursued to reveal results less dependent on the actual model used. All models other than *SO1* seem viable options for the tested catchments. For larger catchments, the spatial and temporal properties of *SO1* may prove this model to be of greater value and the shortcomings of lesser importance.

CONCLUSIONS

We have run LTS simulations with precipitation time series from two rain gauges as well as from four different WGs that represent different methodologies for producing artificial rainfall time series for present and future climate conditions. In general, all WGs 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 1-hour resolution systematically underestimated this fraction. Considering the number and volumes of CSOs for present conditions all WG 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 built-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 WGs and climate scenarios were considered. The IDF curves for future conditions show larger differences than for the present and show both increases and decreases for different return periods. 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 WGs to run LTS simulation is a useful tool in situations where observations are lacking or where simulations for future conditions have 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 WG 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.

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