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RESEARCH ARTICLE

Quantification of climate change effects on extreme precipitation used for high resolution hydrologic design

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Design of urban drainage structures should include the climatic changes anticipated over the technical lifetime of the system. In Northern Europe climate changes implies increasing occurrences of extreme rainfall. Three approaches to quantify the impact of climate changes on extreme rainfall are studied, all based on output from historical rain series of the present climate and output from Regional Climate Models. Two models are applied, one being based on an extreme value model, the Partial Duration Series Approach, and the other based on a stochastic rainfall generator model. Finally an approach is based on identification of areas, where the present climate resembles the anticipated future climate for the region in question. The results indicate that design intensities in Denmark are likely to be increased by 10–50% within the next 100 years. The increase in design intensities depend on the duration and the return period in question.

Keywords: extreme events; climate change; design; rainfall

1. Introduction

Global warming of the surface temperature by approximately 0.75°C has been observed over the last 100 years and the speed of warming is expected to increase rapidly if emissions of greenhouse gases are not decreased soon (Meehl *et al*. 2007, Trenberth *et al*. 2007). This will lead to significant changes in the water cycle. Denmark, being situated in Northern Europe, is likely to experience an increase in precipitation, leading to increased risk of flooding (Bates *et al*. 2008). Analysis of observed data indicates that these change may already be occurring (Arnbjerg-Nielsen 2006, Madsen *et al*. 2009). The increase in risk is due to flash floods caused by extreme rainfall, floods caused by rivers, and flooding of coastal regions.

Many structures in cities, including sewer systems, river canals, and dikes, have a technical lifetime of more than 100 years. It is of paramount interest to quantify the anticipated changes in the design input to these structures over the entire lifetime of the structures. Therefore the changes in the design precipitation loading should be assessed and included in the design as well as other changes in the input. The results should be presented in a manner that can readily be used for hydrologic design.

Preliminary studies indicate that an increase in design intensities of more than 20% can be expected over the next 100 years for 1 hour extreme intensities (Jørgensen *et al*. 2006, Larsen *et al*. 2009). Assuming a 30% increase in all precipitation design intensities Arnbjerg-Nielsen and Fleischer (2009) show that there is a very high economic benefit of taking the change into account when designing urban infrastructure.

2. Assessing climate change impacts on urban hydrology

2.1. Climate change impact simulations

Assessing climate change impacts on urban drainage design involves five important steps, see Figure 1. Figure 1 is based on the paradigm used in the fourth assessment report by the IPCC (Meehl *et al*. 2007). Having made a set of assumptions on one level enables assessment of a range of possible outcomes on the next level. Level 1 is typically described by the standardized IPCC scenarios developed by Nakicenovic and Swart (2000). Based on these scenarios a number of General Circulation Models (GCM) have been developed that use emissions to force changes in outputs of key climate variables (Meehl *et al*. 2007). The spatio-temporal scale of GCMs outputs is often rather crude, typically 300 km × 400 km, with seasonal or monthly means of the climate variables.

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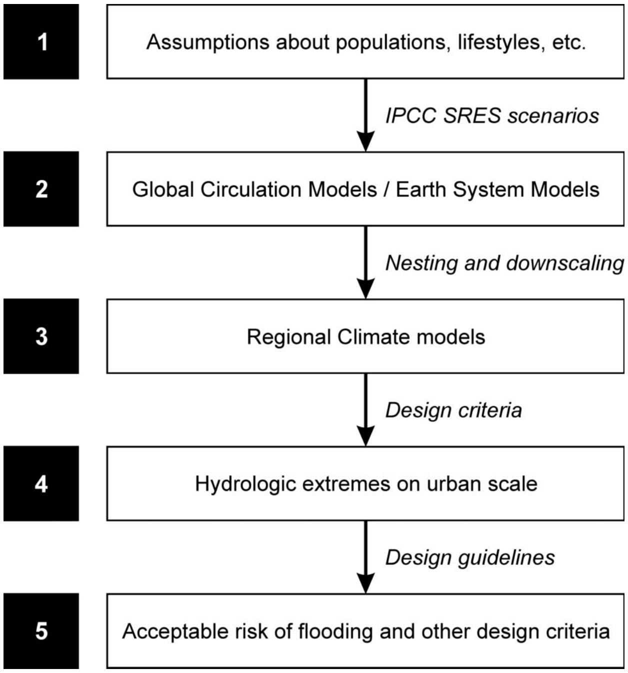

Figure 1. Paradigm for assessing and incorporating climate change impacts in urban hydrology design.

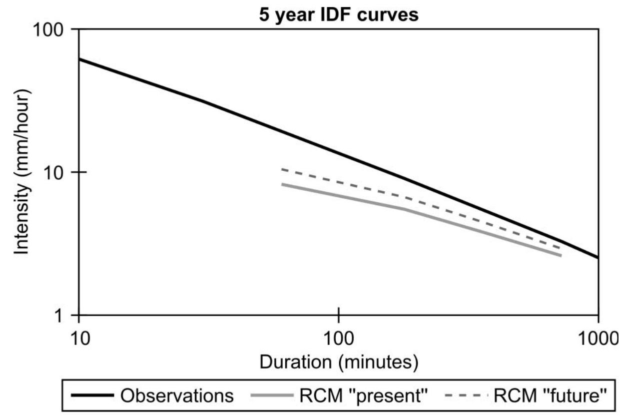

Figure 2. Rainfall intensities for a return period of 5 years recorded at a rain gauge and estimated from regional climate models. For high temporal resolutions the climate change signal is much smaller than the systematic underestimation due to lack of description of convective rainfall activity (Jørgensen *et al.* 2008, Madsen *et al.* 2009).

In order to obtain higher resolution a submodel is nested within the GCMs, denoted Regional Climate Models (RCM). This corresponds to level 3 in Figure 1. Running an RCM under constraints set by the GCM, climate variables can be forecast at scales from 50 km × 50 km down to 10 km × 10 km (Rummukainen *et al.* 2004, Christensen *et al.* 2007).

2.2. *Downscaling to urban hydrology applications*

Several studies suggest using the output from regional climate change models directly when assessing climate change impacts on the river basin management scale, thus assuming that level 3 and 4 are identical in Figure 1 (Kundezewicz *et al.* 2006, Kilsby *et al.* 2007). However, design of structures in small hydrologic catchments such as urban areas needs design intensities at a spatio-temporal scale of a few square km and a time resolution of minutes. The main reason is many important hydrologic processes occur at scales much finer than that of the regional climate models (Baker and Peter 2008). The net result is a systematic underestimation of the design intensities at high temporal resolutions as illustrated in Figure 2.

The climate change impact computed in the GCM/RCM models must therefore be adjusted to account for the bias in the model simulations. The delta change method has been widely used to adjust regional climate change output to observations, e.g. Lettenmaier *et al.* (1999). The method scales the variable of interest, x, according to the following formulae:

$$\Delta = \frac{x_{future,RCM}}{x_{present,RCM}} = \frac{x_{future,higher\ resolution}}{x_{present,higher\ resolution}} \qquad (1)$$

Figure 2 shows that the approach should be carried out with caution, because the processes are in part scale dependent. Therefore other methods are used as well, primarily based on regression to climatic variables. However, the delta change method is a simple and effective way of showing the net impacts of design intensities, regardless of the downscaling method. Δ will be denoted delta change throughout the paper.

The steps needed to go from level 4 to level 5 in Figure 1 is not the focus of the present paper. A recent review of the considerations in this respect can be found in Arnbjerg-Nielsen (2011).

2.3. *Evaluation of uncertainties*

The scenarios developed by Nakicenovic and Swart (2000) show only deviations between the scenarios up until 2010 and the measured concentrations in the atmosphere match the predictions well (Juckes *et al.* 2010). However, as pointed out in their report substantial differences will develop during the 21st century, leading to substantial differences in the atmospheric concentrations of greenhouse gasses and thus the forcing of the climate.

van der Linden and Mitchell (2009) report the main findings of a major research project comprising the use of several GCMs and RCMs in order to assess the overall uncertainties of modelling of climate change impacts. As part of that project Hawkins and Sutton (2011) attribute uncertainties of changes in precipitation to internal variation, model variation, and scenario variation. Their conclusion is that the model uncertainty is the major contributor to the overall uncertainty, with only minor attribution to differences between scenarios. This could imply that differences in emissions due to different scenarios are less important than the climate sensitivity of the GCM/RCM model complex in question. The fact that their study focuses on global decadal mean changes in precipitation imply that the signal to noise ratio for high temporal and spatial resolutions is indeed very low. In other words, it is questionable if it is possible to establish formal and quantifiable uncertainty estimate changes of high resolution precipitation variables even at the RCM scale.

Downscaling to hydrologic extremes on the urban scale entails further in part unknown uncertainties. Much research has been carried out that study precipitation properties at various scales with the objective of identifying scale-invariant properties, e.g. Onof *et al.* (2005), Michele *et al.* (2001), and Molnar and Burlando (2005). However, much research is needed before the processes are fully understood and the use of statistical methods can be replaced by deterministic processes (or at least understand why the functional relationships established in the statistical models are good approximations). It therefore remains a critical assumption that the properties of downscaling from an RCM model outputs will not change over time when the objective is to study how greenhouse gas is forcing a change to the average RCM outputs. However, this assumption is needed.

As such it is not feasible to try to establish confidence bounds for how extreme precipitation will change due to climate change. However, in order to identify proper adaption options to climate change it is of paramount interest to obtain at least a good estimate of the mean of the anticipated changes. It is also of paramount interest to get it fast because huge investments in new urban infrastructure are carried out every year. The optimal design depends highly on an assessment of the loading of the infrastructure due to extreme precipitation.

As pointed out above differences in emission scenarios can be compensated by choosing a GCM/RCM complex that responds well to forcing by greenhouse gasses. As such the optimal solution is to obtain a number of high resolution outputs from RCMs as done in the ENSEMBLES project (van den Linden and Mitchell 2009) and combine it with other types of information. However, the public database from the ENSEMBLES project does not provide data with sufficient temporal resolution to allow downscaling to urban hydrology applications. As such case studies must be a compromise between a need for speed and a need for accurate assessments.

2.4. *Data available for the study*

The regional climate change simulations used in the present study are based on a HIRHAM4 model with a spatial resolution of 12 km by 12 km and a temporal resolution of 1 hour. The global climate change model is the HadAM3H AGCM simulation based on a scenario corresponding to an IPCC A2 emissions scenario. The model is described further in Christensen *et al.* (1998). The historical rainfall series in high temporal resolution is based on the network of rain gauges maintained by The Water Pollution Committee of The Society of Danish Engineers (Madsen *et al.* 2009). This network has been in operation since 1979 and currently consists of more than 100 rain gauges.

3. Methods

The objective is to establish a climate change signal according to the following characteristics:

(1) Location/region
(2) Duration of time
(3) Return period (frequency of distribution)

For each of the models applied a resulting delta change will be calculated for each of the characteristics. Initial analysis showed that systematic variation within Denmark was very likely to be superseded by other phenomena in the data (Jørgensen *et al.* 2006). It is therefore assumed that that Denmark is a homogeneous region with respect to climate change impact on extreme precipitation.

A total of three methods will be applied, two of them using the GCM/RCM output described by Christensen *et al.* (1998). In order to validate these results a completely different method is applied, based on a different GCM/RCM complex.

3.1. *Partial duration series*

The partial duration series approach has been used to model extreme hydrologic events of both historical rainfall series and rainfall series output from regional climate models, e.g. Madsen *et al.* (2002, 2009), Frei *et al.* (2006), and May (2007). The model can be formulated in several ways. In this study the formula from Madsen *et al.* (2002) is employed, using a Generalized Pareto Distribution to model the exceedances:

$$z_T = z_0 + F^{-1}\left(1 - \frac{1}{\lambda T}; \mu, \kappa\right) = z_0 + \mu\frac{1+\kappa}{\kappa}\left[1 - \left(\frac{1}{\lambda T}\right)^{\kappa}\right] \tag{2}$$

Where z_T is the design intensity at return period T, z_0 is the threshold value defining the extreme value population of the rainfall statistic in question, λ is the average annual number of threshold exceedances, μ is the mean of the exceedances, and κ is the coefficient of variation of the exceedances. The variable z_0 is chosen based on a compromise between having a suitable number of observations and ensuring that only the extreme population is included in the model. Estimation of the remaining parameters is carried out by means of L-moment estimation as described in Hoskins and Wallis (1995) and Madsen *et al.* (2002).

The delta change factors are calculated based on the time slices in the RCM model output and applied to the parameters estimated based on historical rainfall series representing the Danish region. This way a model covering the region of Denmark was constructed. This method has previously been applied to the GCM/RCM output that is used for the current study (Larsen *et al.* 2009). Larsen *et al.* focuses on variation of one-hour precipitation extremes throughout Europe, whereas this study focuses on assessing changes in precipitation for durations between 1 and 24 hours focussing on Denmark only.

The estimated changes in the parameters between present and future are listed in Table 1. The resulting changes in the three hour design intensities are shown in Figure 3 and the estimated overall delta changes are shown in Figure 4. As shown in Figure 3 the resulting delta changes are significant compared to the uncertainty of the current estimates. The results also indicate that perhaps there is a tendency towards lower delta changes for higher durations, especially for high return periods. However, bearing in mind the inherent uncertainties this may also be an artefact in the GCM/RCM-model.

Table 1. Estimated delta change for each of the parameters of the partial duration series model for each of the durations.

Duration (hours)	λ	μ	τ_2
1	1.252	1.365	1.030
3	1.218	1.269	1.040
6	1.205	1.175	1.047
12	1.326	1.103	1.020
24	1.451	1.132	1.020

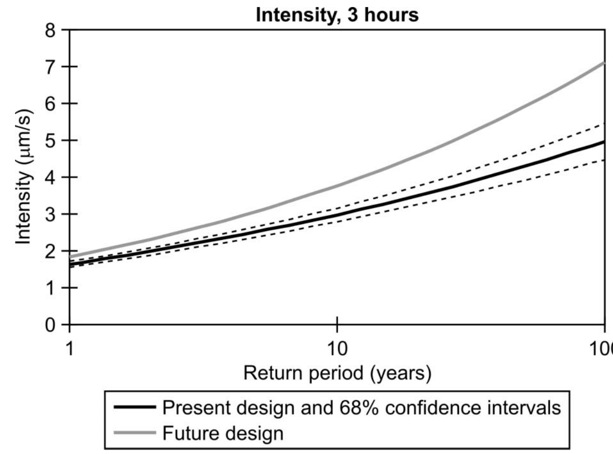

Figure 3. Estimated design intensities for a duration of three hours based on the partial durations approach. The current design values are shown including 68% confidence intervals as well as the estimated design rainfall in the future.

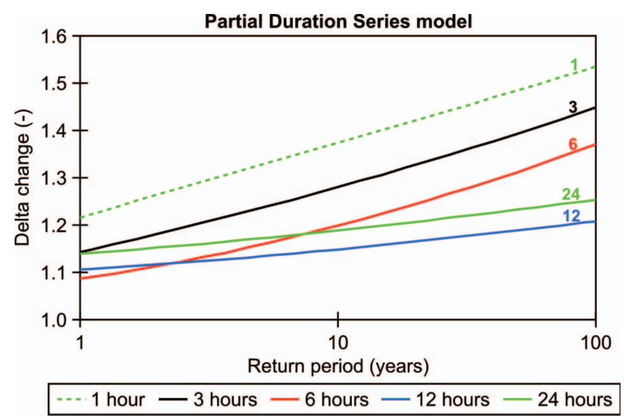

Figure 4. Climate change factors as a function of return period and duration for the partial duration series approach.

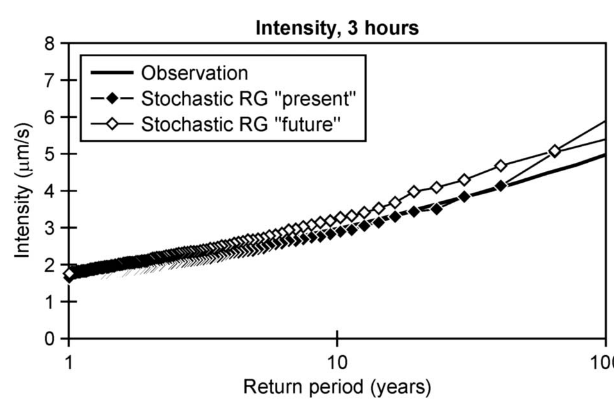

Figure 5. Median values of present and future design intensities for a three hour rainfall compared to actual measurements of current design values.

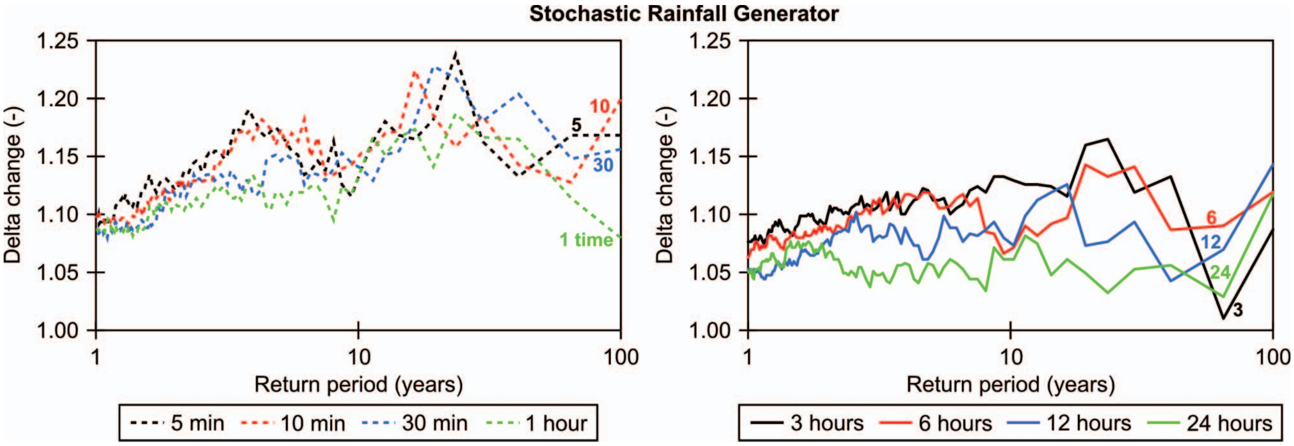

Figure 6. Climate change factors as a function of return period and duration for the Stochastic Rainfall Generator approach.

3.2. *Stochastic rainfall generator*

This study has been reported in detail in Onof and Arnbjerg-Nielsen (2009). The methodology and approach is briefly summarized below.

Stochastic modelling of rainfall with the objective of encompassing the properties of an entire rainfall series has been the objective of many researchers (Waymire and Gupta 1981, Rodriguez-Iturbe *et al.* 1987, Onof *et al.* 2000). Currently such models are used in several countries for generation of regionalized artificial rain series with hourly or daily data, and software has been developed to handle data rather easily (Burton *et al.* 2007). Disaggregation to higher resolutions is typically obtained by means of multifractal scaling (e.g., Marani 2005, Molnar and Burlando 2005).

The model used by Onof and Arnbjerg (2009) uses an improved version of the Random Parameter Bartlett-Lewis Rectangular Pulse Model in combination with a multi-scaling disaggregator. Each of the 10 parameters of the stochastic rainfall generator is estimated for each month separately, yielding a total of 120 parameters to be estimated. The delta change factors are calculated based on the time slices in the RCM model output and applied to the parameters estimated based on historical rainfall series representing the Danish region. The model is estimated based on data with a temporal resolution of one hour. Higher temporal resolutions are obtained by means of a disaggregation method described in Onof *et al.* (2005). This way a model covering the region of Denmark was constructed.

The delta changes for each return period are then calculated by producing twenty synthetic rainfall series, each consisting of 100 years of simulated data. These rainfall series are constructed based on the parameters estimated on a generic Danish rainfall series, each parameter modified by the estimated delta change from the time slices from the RCM models. Comparisons were then made based on the empirical distribution functions. In general there was a pronounced increase in the probability of observing high increases in the design intensities for high return periods. However, the estimated changes in the median value between present and future time slices were small, as indicated in Figure 5. Due to uncertainty of the estimation procedure there are no differences between the median of the two time slices corresponding to a 50 year return period. As seen in Figure 6 the delta change seems to be smaller than the ones calculated by means of the partial duration series.

3.3. *Climate analogue*

In engineering applications it is often necessary to use rainfall data from another area than the design catchment in question because local data are not available. This situation is often dealt with simply by choosing the nearest rainfall data of suitable resolution or by choosing data from a region with similar characteristics.

This method can also be applied in order to assess climate change impacts on extreme rainfall. Hallegatte *et al.* (2007) identifies suitable climate analogues for 17 cities in Europe based on this approach, using monthly relative changes of precipitation and monthly absolute changes in temperature as input. Hallegatte *et al.* (2007) makes their analysis based on two different GCM models. One of them is the same GCM that is used to force the RCM models used in the other approaches, while the other is the model CNRM ARPEGE (Déqué 1994). In order to obtain the highest possible independence between the methods only the results from the CNRM ARPEGE model will be used here.

Based on the results in Hallegatte *et al.* (2007) the region currently representing future Danish weather conditions are Holland, Belgium, the Northwest parts of Germany and France. Denmark lies near the coast and the altitudes are in general low, which was used as a further criterion for identifying suitable locations for climate analogues. High resolution measurements were identified for locations in France as well as Germany (Coste and Loudet 1987, Malitz 2005). The actual sites are shown in Figure 7.

At the French sites the available information is restricted to parameters defining intensity-duration-frequency relationships for return periods of 2 years and 10 years. In Germany the Kostra project has provided nationwide estimates of exceedance series from which data has been extracted for selected locations and durations. The German study uses a different formulation of the partial duration series, using a two-parameter model rather than the three-parameter model used in the present study. This corresponds to assuming that κ is equal to zero in Equation (1). This leads to systematic underestimation of the Danish data for high return periods. Therefore the German model is only used to assess low and moderate return periods to avoid ambiguity due to differences in model formulation. Therefore design precipitation intensities are only calculated for return periods of 2 years and 10 years, i.e. the same return periods as available from the French study. The model provides estimates of durations from 5 minutes to 48 hours.

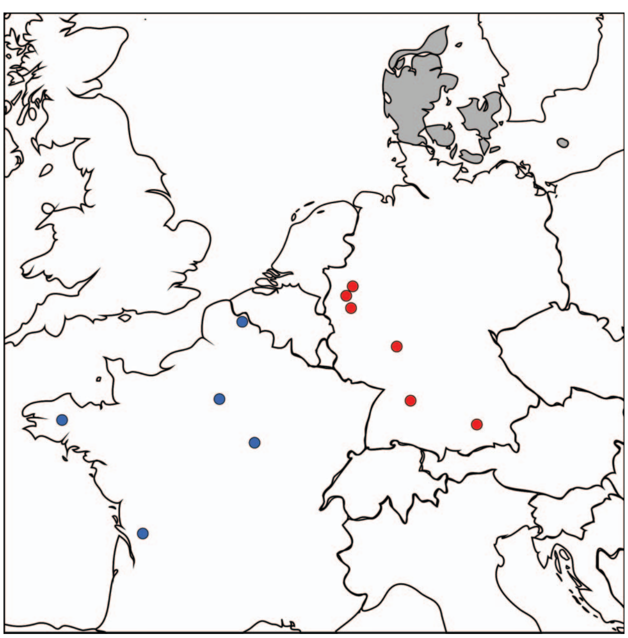

Figure 7. Identified sites where suitable high resolution datasets are available that can be used as climate analogues.

The results obtained by using this approach are illustrated in Figure 8. There is some variation in the climate analogues, but all in all a moderate increase in the design intensities can be observed. Averaging the climate analogue intensities lead to delta change factors between 1.18 and 1.40 depending on duration and return period, see Table 2.

4. Discussion of results

The calculated delta change factors are shown in Table 2 and in Figure 9. The following can be observed when comparing the results:

- There are systematic differences between the methods. Generally the partial duration series approach gives the highest estimates of climate change impacts while the stochastic weather generator gives the smallest estimates.

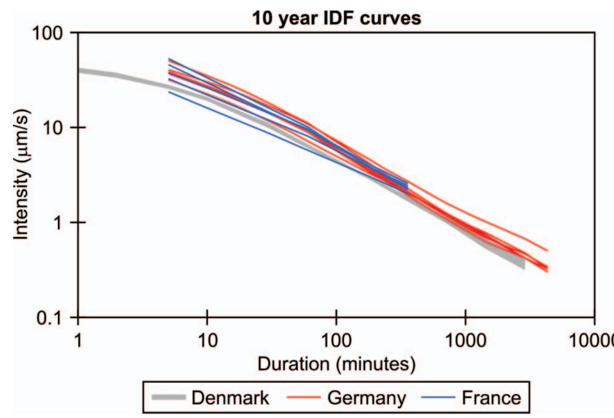

Figure 8. Intensity-duration-frequency relationships for Denmark and the selected climate analogues.

Table 2. Calculated delta change calculated by means of the three methods for different return periods and durations.

	2 year return period			10 year return period			100 year return period	
	A	B	C	A	B	C	A	B
5 min	–	1.12	1.23	–	1.14	1.39	–	1.17
10 min	–	1.13	1.22	–	1.15	1.30	–	1.27
30 min	–	1.12	1.31	–	1.14	1.30	–	1.15
1 hour	1.27	1.11	1.32	1.37	1.14	1.37	1.53	1.11
3 hours	1.18	1.10	1.19	1.28	1.13	1.25	1.45	1.14
6 hours	1.12	1.09	1.15	1.21	1.07	1.19	1.38	1.09
12 hours	1.12	1.08	–	1.15	1.07	–	1.21	1.07
24 hours	1.18	1.07	–	1.21	1.06	–	1.27	1.08

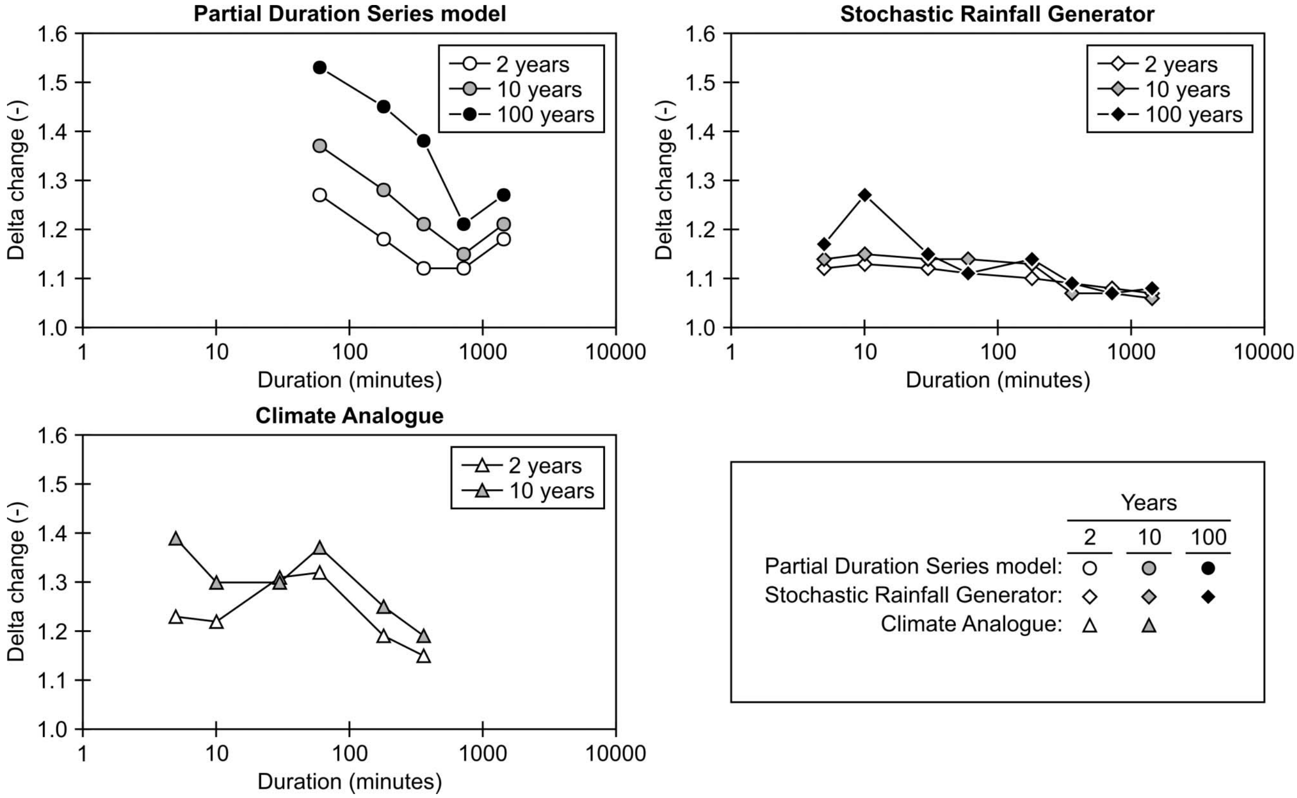

Figure 9. Overview of all delta change factors for all three methods, durations, and return periods.

- There is very good agreement between the results obtained by partial duration series approach and the climate analogues approach.
- The calculated delta change tends to be higher for small durations and higher return periods.

The three approaches are independent of each other, except for raw data being identical for the first two methods. The first two approaches have the virtue of being more objective than the last approach; on the other hand the last approach has proved to be a simple and effective tool in many engineering applications.

The partial duration series model and the climate analogue approaches have the advantage, that they specifically address the extreme part of rainfall. When modelling an entire rain series the Stochastic Rainfall Generator model needs to address more general properties of rainfall and will therefore automatically put less emphasis on the extreme statistics of the rain series than the other two methods. This may indicate that calculation of delta change factors for extreme rainfall should be assessed mainly on the other two approaches. However, the use of the rain series is very important in situations where environmental impacts are to be addressed. This is particularly true in situations where the impacts are known to be subject to annual variations. As such climate change impacts on river basin management could improve if urban discharges to streams and rivers are calculated by using these types of rain series.

Table 3. Suggested delta change when designing urban water systems with an anticipated technical lifetime of 100 years.

	2 year return period	10 year return period	100 year return period
All durations	1.2	1.3	1.4

This analysis was evaluated at The Water Pollution Committee of The Society of Danish Engineers, responsible for defining and maintaining good practices for design of urban drainage systems. Based on this analysis it was recommended to use fixed delta change factors for design of all urban drainage systems with high technical lifetimes for a given return period. The climate factors given in Table 3 have now been incorporated into Danish design guidelines for urban drainage design (Arnbjerg-Nielsen 2008).

Referring back to the section on uncertainties it should be emphasised that the range of variation shown in Table 2 and Figure 9 cannot be interpreted as the overall variation of the climate factors. Rather they can with some caution be used to assess what is the mean value of the delta change for Denmark.

5. Conclusions

The main findings of the study can be summarized as follows:

(1) The increase in design precipitation intensities tends to be larger with increasing return period and decreasing duration. The influence of changes in the return period is larger than the influence of changes in the duration.
(2) The study shows that the delta change for Denmark is between 1.1 and 1.5 for return periods between 2 years and 100 years and durations between 10 minutes and 24 hours based on available data.
(3) If the expected technical lifetime is different from 100 years the delta change factors should be adjusted accordingly.
(4) The inherent uncertainties when using these methods makes it irrelevant to make regionalized results within Denmark. Therefore a national assessment of delta change factors is made. Further, the results are quite uncertain as they have been based on only one scenario run by one regional climate model, supplemented by one other method. More studies focussing on both different scenarios and different climate change model formulations should be studied to give a more reliable estimate of the overall uncertainties.
(5) Due to lack of understanding of some of the physical processes generating rainfall even the most detailed study of all data from climate change models are likely to underestimate the total uncertainty inherent when assessing properties of future extreme precipitation.

6. Acknowledgement

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