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# Implications of Long-Term Oscillations in Rainfall Extremes on Urban Drainage Design Practices

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## ABSTRACT
In the last decade damaging floods have affected many European and major Danish cities including Copenhagen. As a result, the concept of integrated resilient water management came in the political agenda for developing climate adaptation plans required for all Danish municipalities. An emerging area within the climate change debate addresses the quantification of natural climatic variations. Recent studies have shown profound multi-decadal oscillations in extreme rainfall over Europe including Denmark. The present study focuses specifically on the variation of historical design values for urban drainage design in Denmark. It showed that historical design values exhibit a similar pattern of variation. The analysis also covered Danish and European legislation on water management, concluding that the main directives on protection of the aquatic environment were adopted during periods of few extreme events. This illustrates the importance of the natural variation as a driver for the development of urban design practice and ranks it alongside technological and scientific advances. Therefore it is highly relevant to incorporate the knowledge of the natural variation in the resilient water management concept and future research strategies.

## KEYWORDS
Extreme rainfall, natural variability, multi-decadal oscillations, urban drainage design

## INTRODUCTION
Within the last decade several damaging pluvial floods have affected major Danish cities. Likewise, many other European cities have suffered from pluvial or fluvial flooding and several studies have found increasing trends in extreme rainfall indices both within Europe (e.g. Rodda *et al.* 2010 and Kysely 2009) and on a global scale (Westra *et al*., 2013). This has together with the ongoing discussion on the link betweenanthropogenic greenhouse gas(GHG) emissions and increases of rainfall extremes raised the public awareness. The concept of integrated resilient water management is now on the political agenda and climate adaptation plans are required for all Danish municipalities. The main goal of these plans is to map high risk areas in relation to pluvial floods to enable a prioritized selection of focus areas for future city planning. The implemented adaptation measures should be robust and allow for a certain degree of flexibility, acknowledging that the exact magnitude of the projected future change remains uncertain.

An emerging area within the climate change debate addresses the natural climatic variations on which the anthropogenic changes are imposed. The natural variations cover all temporal scales, from centuries to daily variation. Part of the variation is random occurring from the many complex and chaotic elements in the climate system. The other part is known or partially known like the variations driven by the change in incoming solar energy e.g. resulting from the rotation of the earthand the activity level of the sun, each leading to distinct cyclical patterns. The technical lifetime for urban infrastructure varies between 80 and 100 years and so do many other city assets. In this aspect the multi- and inter-decadal variation are of greatest interest. Several climate phenomena, mainly resulting from the interplay between oceanic and atmospheric circulations, are known to vary on this temporal scale and some exhibit a surprisingly periodic behavior. For example the El Niño-Southern Oscillation and the Atlantic Multi-decadal Oscillation that are known to oscillate with periods of 3-7 years and 65-80 years, respectively. The persistence of each phase may very well depend on a variety of feedback mechanisms within the climate systems, but the external or internal triggers are still unknown. However, the effect on the weather in different regions of the world, during a specific oscillation phase, has been studied by many authors. To mention a few,Dai (2013) demonstrated a strong correlation between regional precipitation in the US and the Inter-decadal Pacific Oscillation, while Hurrell *et al.*(2003)reviewed the major effects of the North Atlantic Oscillation on temperature and precipitation patterns over the North Atlantic continents. Very few studies addresses multi-decadal variations of the extreme rainfall indices that are highly relevant for design criteria applied for urban drainage infrastructures, and all present guidelines are developed under the assumption that the meteorological process generating the extremes is constant over time, i.e. a stationary process in a statistical sense.

The present paper reviews the result from three recent studies all identifying profound multi-decadal oscillations in extreme rainfall over Europa, and discusses how such oscillation may have influenced the past and present changes of Danish design practices for urban drainage. Finally, this knowledge is used as a new perspective in the debate of climate change adaptation and resilient water management strategies.

## MULTI-DECADAL OSCILLATIONS IN RAINFALL EXTREMES

Profound local multi-decadal oscillations in extreme rainfall were first identified by Ntegeka and Willems (2008),who used a 5-15 years moving window to enhance the multi-decadal signal. In this approach selected extreme rainfall indices are estimated for both the sub-series, defined by the moving window, and the full series. The ratio between the two is expressed as a perturbation factor (*pf*), where a value above one indicates that the extreme index for the given sub-period is higher than the averages of the entire series. Willems (2013a) extended the analysis and identified a consistent oscillating pattern in a 107-years long time series from Uccle, Belgium. Furthermore, Willems (2013a) showed that these variations appear throughout Europe in a study focusing on the 15 highest daily rainfall events per year in the winter season. Inspired by these studies Gregersen *et al.* (submitted) analyzed five Danish and one Swedish rainfall series with 137 years of daily measurements, focusing on extremes with a recurrence level relevant for flood hazard analysis. Here *pf* were calculated specifically for the annual frequency and annual mean magnitude of the extreme eventsdefined by the Peak-Over-Threshold method(Coles 2001).Gregersen *et al.* (submitted) concluded that the frequency of the extreme events shows both a general increase from 1874 to present and an oscillation with a cycle of 25-40 years, see Figure 1. The magnitude of the extreme events also oscillates, but with a cycle of 15-30 years and a smaller amplitude. Furthermore, the authors found the oscillation signal along the west coast of Denmark to be dominated by the changeable coastal weather of this region, while the eastern part of Denmark shows a more consistent signal, which partly can be linked to an index derived from sea level pressure (SLP) over the North Atlantic.

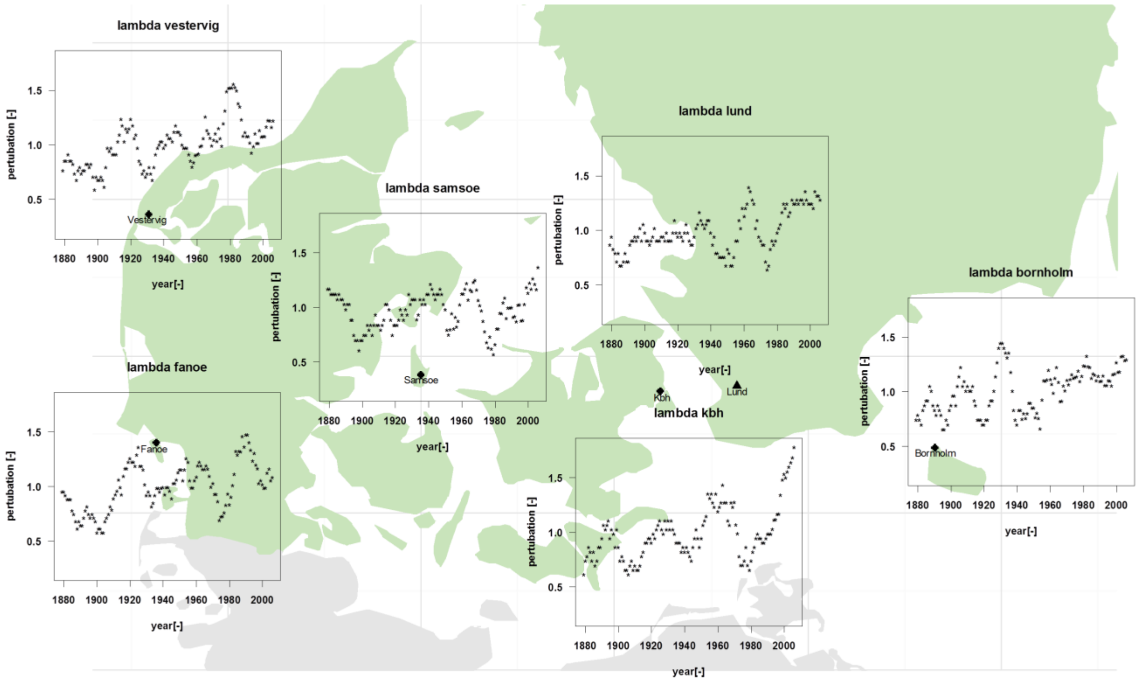


**Figure 1**.Multi-decadal variation in the frequency of extreme events over Denmark. Based on six stations with 137 years of measurements, events exceeding 19.2 mm/day, and a moving window length of 10 years (adapted from Gregersen *et al.*, submitted).

The study by Gregersen *et al.* (submitted) is limited by the temporal resolution of the long rainfall series, which are inadequate to draw conclusions regarding urban design rainfall as this requires sub-hourly rainfall information. However, from Figure 2, based on the 10-min rainfall series from Uccle, Belgium (Ntegeka and Willems 2008; Willems 2013a,b)it is concluded that the oscillation are consistent for rainfall durations between 10 min and 1 day. In fact, the amplitude of the oscillations seemingly increases when the aggregation level decreases, see Figure 2.

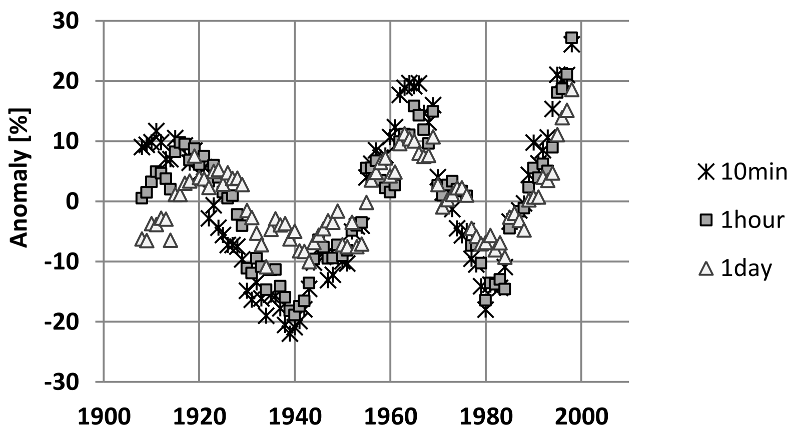


**Figure 2**.Multidecadal variation for different rainfall durations based on the Uccle rain series. The applied threshold corresponds to an average of three exceedances pr. year, in the JJA season. The length of the moving window is 15 years.

## LONG TERM VARIATIONS OF URBAN DESIGN VALUES

The Danish design practices for urban drainage have changed significantly since the very first guidelines were published by the Danish Water Pollution Committee in the early 1950'ties. The recommended design values have fluctuated over time, but this has been interpreted as a result of increased knowledge and understanding of the meteorological processes, not as an indication of potentially non-stationary rainfall mechanisms. In addition to the design values also the recommended calculation practice has changed from the simple rational method to high-resolution distributed 1D hydraulic models forced by historical rainfall series (Arnbjerg-Nielsen, 2011). The major official recommendations published by the Water Pollution Committee of The Society of Danish Engineers on design rainfall are as follows (WPC, 2014):

(1) **1950-1953**Schemes with design values for the four major Danish cities
(2) **1974**Update of (1) with additional years of measurements
(3) **1979**Establishmentof dense regional rain gauge network
(4) **1999** Regional model for extreme rainfall based on data from (3)
(5) **2006** Updated regional model for extreme rainfall
(6) **2014 – in preparation** Updated regional model for extreme rainfall

where(1) – (2) are based on assumptions of using design storms, and (4) – (6) combinations of design storms and precipitation series depending on the problem to be analysed. Focusing on the Greater Copenhagen area in the eastern part of Denmark, Table 1 shows the historical variations of the 2-year event for rainfall with a duration of 10 min. It is seen that the change in the recommendations thought to be represented by better knowledge and data is highly biased by the assumption of a stationary climate.

**Table 1.**Variation of design values, 2-year event for a rainfall duration of 10 min. The estimated *pf* is calculated from the multi-decadal variation in Copenhagen, see Figure 3. Note that *pf* information is only available until 2006, an average*pf* value for (6) can therefore not be estimated.

| Publication | Design intensity [l/s/ha] | Observation period | Average *pf* during the observation period |
|---|---|---|---|
| (1) schematic design value | 106 | 1933-1947 | 0.88 |
| (2) schematic design value | 122 | 1933-1962 | 1.03 |
| (4) regional model | 122 | 1979-1996 | 0.95 |
| (5) regional model | 130 | 1979-2005 | 1.13 |
| (6) regional model | 139 | 1979-2012 | - |

The monitored increase of the frequency of extreme events from 1979, where the rain gauge network was established, to present is evaluated by Gregersen *et al.* (2013). The found rate of change in the annual frequency of extreme events corresponds to a change of 30% in the 2-year event over the 34 years of measurement. This change equals the anticipated effect from anthropogenic emissions of GHG over a projection period of 100 years. As noted by Gregersen *et al.* (submitted), the most recent oscillation high in the series from Copenhagen appears larger and more persistent. Although the series is too short to allow formal statistical testing of a hypothesis of change it might be interpreted as a sign of anthropogenic climate change.If so, this will bias the comparison ofthe relative importance between the effect of natural variation and anthropogenic climate change.

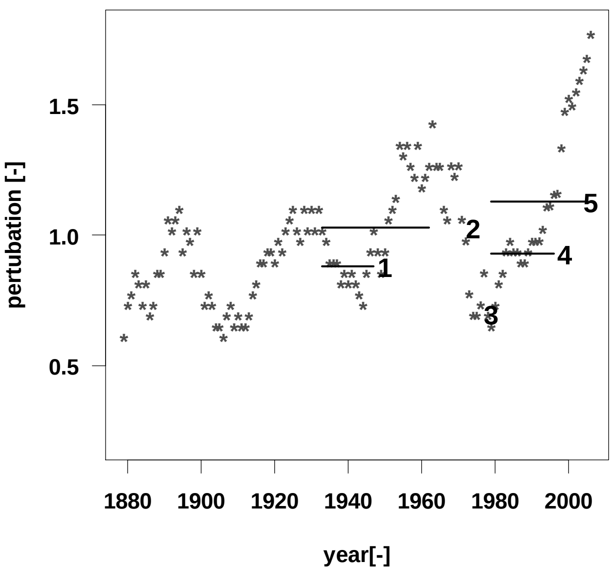


**Figure 3**.The publication year of the five major Danish publications on design rainfall compared to the oscillation in the frequency of extreme events for Copenhagen. For the publications based on observations, the average perturbation factor in the observation period is indicated by a horizontalline.

## IMPLICATION OF NATURAL RAINFALL OSCILLATION

As demonstrated above, the natural variation has unknowingly dominated the official recommendations of best design practice. The question is if the oscillation has been a driving mechanism itself in line with technological and scientific advances. Figure 3 shows that the first publication on design values came in a period with a naturally low number of extremes.The following decade of more frequent extremes forced an update (guideline no.2).Even though the available data material did not cover the entire period of the peak, this led to an increase of recommended design value (see Table 1). Concurrently,research was initiated at the Technical University of Denmark to study properties of extreme rainfall (Johansen, 1974), eventually leading to the investment in a national rain gauge network. Due to the laborious planning and installation phase the actual measurement period started in 1979, i.e. in a period of few extremes. This period was also dominated by great advances within drainage system modelling, as a response to growing computational capabilities. The use of high-resolution distributed 1D hydraulic models forced by historical rain series is discussed by WPC in a publication from 1984 and recommended depending on the required detail of calculation (WPC, 2014). Guideline no.4 was published after scientific advances on statistical methods for regional extreme value modelling (Madsen *et al.*, 2002). Again the observations behind the recommendations were,unwittingly, from a period with relatively few extremesforcing an update (guideline no.5) relatively few years later and yet another one presently in preparation.

All together this shows that the natural variation clearly has affected the development and the question is if the influence goes beyond the changes of design levels and perhaps also beyond the borders of Denmark. An example of the first isthe WPC guideline from 1984, which reflects high confidence in the technological advances within drainage system modelling, possibly caused by that fact that the models where tested during a period with few extreme events. In 1985-1987 two important legislations were adopted on a national level (Danish EPA, 2014):a) Agovernmental action plan on reduction of Nitrate, Phosphorous and organic matter and b) Legislation on discharge of pollutants from combined sewer overflows and agriculture. Without neglecting the influence from other significant drivers, it seems that these two important predecessors on protection of the aquatic environment were adopted during periods of few extreme events, where the confidence in the primary performance of the drainage system was high. This national level is matched by similar findings on a European scale, where the dates of main water directives are the following (EUR-lex, 2014):

76/160/EEC: Bathing water directive ("rare" events, i.e. 95-percentile)
76/464/EEC: Dangerous substances (annual discharges)
80/68/EEC: Ground water protection (annual discharges)
91/271/EEC: Urban Waste Water Directive (annual discharges)
91/676/EEC: Limits on emissions of nitrate to surface waters (annual discharges)
96/61/EC: Integrated pollution prevention and control (annual discharges)
2000/60/EC; Water Framework Directive (annual discharges)
2007/60/EC: Floods Directive (rare events, up to 1 in 100 years)

It is seen that within the 30 year framework only the first and the last of the eight directives are related to extremes. According to Figure 3 the year of these two legislationscoincidewith periods of high extremes in Denmark. Obviously, it is a strong assumption to insinuate that the natural variation of the Danish rainfall has influenced European legislation, but Denmark has played a very active role in EUas an ardent proponent of environmental protection. In addition there is a strong spatial correlation in the occurrence of rainfall extremes in north-western Europe Willems (2013a).

## FUTURE STRATEGIES ACCOUNTING FOR BOTH CLIMATE CHANGE AND NATURAL VARIATION

The natural variation is,in the section above,demonstrated to be a driver of change within drainage design and environmental legislation and of high importance for the prevailing recommendations of best urban design practice. In theory it can easily be incorporated in the existing framework for managing inherent uncertainties in design of drainage systems (Arnbjerg-Nielsen, 2011), where a relationship is suggested for including uncertainties on the design value$q_{rain}$ estimated from a (short) local rain series. The main sources of uncertainty are: Model uncertainty ($f_{model}$), Regional variation ($f_{regional\ variation}$) given that extreme rainfall indices of the local series differ from the extreme rainfall of the region, Projected relative change due to anthropogenic climate change ($f_{climate}$) andProjected change of the connected paved areas($f_{paved\ area}$). A correction factor for the natural variation ($f_{natural\ variation}$) can be included on similar term leading to the following optimal design value ($q_{design}$):

$$q_{design} = f_{model} \cdot f_{regional\,variation} \cdot f_{climate} \cdot f_{paved\,area} \cdot f_{natural\,variation} \cdot q_{rain}$$

$f_{natural\ variation}$must depend on the observation period of $q_{rain}$compared to the oscillation pattern of the natural variation as inWillems (2013b).The challenging part is to estimate a long term temporal mean of the design values for use in this bias-correction of $q_{rain}$. Especially, as the oscillation pattern varies over Denmark, see Figure 1.Thefound link to SLP over the North Atlantic can perhaps be used as a predictor for the oscillations. If thisis incorporated into a framework based on Bayesian decision theory (Gregersen *et.al*, 2012),itmaybe used as a tool for deciding the proper time to upgrade an existing system (Arnbjerg-Nielsen, 2011) given that projections of future behaviour are sufficiently well known.However, the relation between the large scale driver and the variation of the rainfall extremes is based on observations from the past. Moderate anthropogenic climate change is expected to increase the natural variability, perhaps in form of amplified oscillations, while the fundamental mechanisms of the climate system could change if the global warming reaches an unknown, but critical level (IPCC, 2012).

The state-of-art estimates of $f_{climate}$ for a 2-year design event are 1.2 and 1.45 under a mean and high climate scenario, respectively (Sunyer*et al.*, 2014).Figure 4 compares the relative influence of $f_{natural\ variation}$and$f_{climate}$by outlining several possible projections for the future design values. It is seen that the natural variations are important for short projection periods, while climate change gain importance for long projection periods, especially considering the high scenario.This stresses why decisions on climate change adaptation and resilient water managementmust be based on bravery (Geldof, 1997), where risks are incorporated and robustness added, but room remains for some degree of chance in planning and indeed also periods with little extreme precipitation. Furthermore, the public and political focus on flood risks might well diminish if we again reach a period with relatively few extreme rainfall events and instead turn focus towards water resources and pollution.

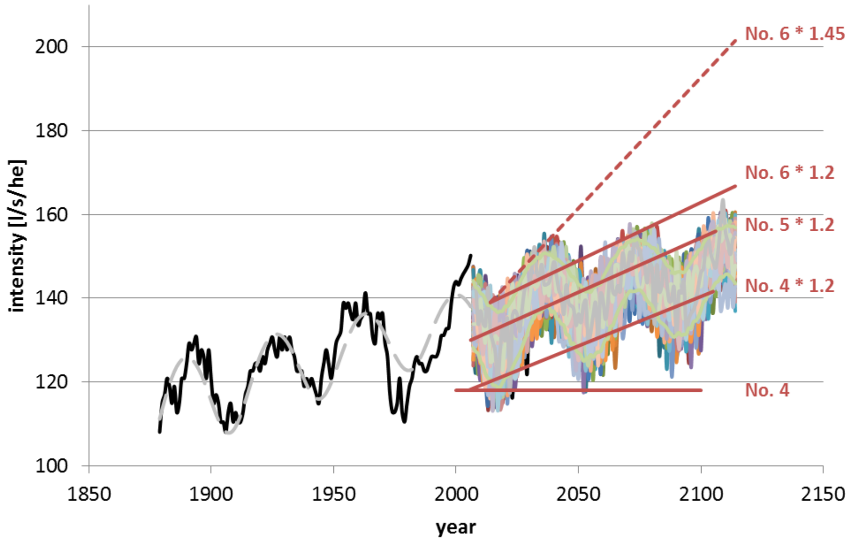


**Figure 4**.The *pf* series from Copenhagen is converted to design intensities by assuming that the rainfall intensities follow the model in Guideline no.6 (black line). A sine-model is fitted to the *pf* series (grey line) (Gregersen *et al.*, submitted) and extrapolated into the future accounting only for parameter uncertainties and random variation (multi-colored lines). Red lines indicate recommended design values published in 1999 (No 4), 2005 (No. 4*1.2), 2006 (No.5*1.2), and 2014 (No. 6*1.2 and No. 6*1.45), respectively.

## CONCLUSIONS

Recent studies show profound multi-decadal oscillations in extreme rainfall over Europa including Denmark. An analysis of the historical design values for urban drainage design in Denmark confirms the found pattern of variation, suggesting that the importance of this natural variation is in line with technological and scientific advances, which also are important drivers for the development of urban design practice. The analysis is extended to Danish and European legislation on water management, concluding that the main directives on protection of the aquatic environment were adopted during periods of few extreme events. For long technical lifetimes such as sewer systems the impacts of anthropogenic GHG emissions seems to be larger than the natural variation, but for other systems it may be very relevant to incorporate knowledge on the natural variation.

## ACKNOWLEDGEMENT

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