

## Impacts of climate change on rainfall extremes and urban drainage systems: a review

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### ABSTRACT

A review is made of current methods for assessing future changes in urban rainfall extremes and their effects on urban drainage systems, due to anthropogenic-induced climate change. The review concludes that in spite of significant advances there are still many limitations in our understanding of how to describe precipitation patterns in a changing climate in order to design and operate urban drainage infrastructure. Climate change may well be the driver that ensures that changes in urban drainage paradigms are identified and suitable solutions implemented. Design and optimization of urban drainage infrastructure considering climate change impacts and co-optimizing these with other objectives will become ever more important to keep our cities habitable into the future.

**Key words** | climate change adaptation, extreme rainfall, review, urban drainage

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### INTRODUCTION

Over the past 150 years urban drainage systems have secured human health and enabled denser city development and are considered to be one of the most important achievements of mankind, enabling development to modern societies (Ferri-man 2007). At the same time we have increased our knowledge of precipitation extremes and improved our understanding of hydrological responses and hydraulic transport phenomena in cities. This knowledge has been used to design urban drainage infrastructure to meet often increasing service levels. Hence much urban drainage research has focused on understanding and describing precipitation extremes.

The IWA/IAHR Joint Committee on Urban Drainage established the International Working Group on Urban Rainfall to focus on these research needs. Members of this group recently initiated an extensive review of current methods for assessing long-term historical and future trends in urban rainfall extremes and their effects on urban drainage systems due to anthropogenic climate change (Willems *et al.* 2012). This paper presents the main findings of this review and these demonstrate that in spite of significant advances there are still many limitations in our understanding of how to describe precipitation in a

changing climate in order to design and operate urban drainage infrastructure.

## RAINFALL MEASUREMENTS AND MODELS

### Spatio-temporal resolutions for urban hydrology

The characteristic spatio-temporal scales of urban drainage are generally small, often characterized by temporal scales of a few minutes and spatial scales of 1–10 km<sup>2</sup> (Schilling 1991; Einfalt *et al.* 2004; Willems *et al.* 2012). This high resolution places special requirements on climate change impact studies since many of the approaches developed for catchment hydrology cannot be implemented directly, but must be adapted to account for the finer resolution requirements. This is a research area in itself which has developed over

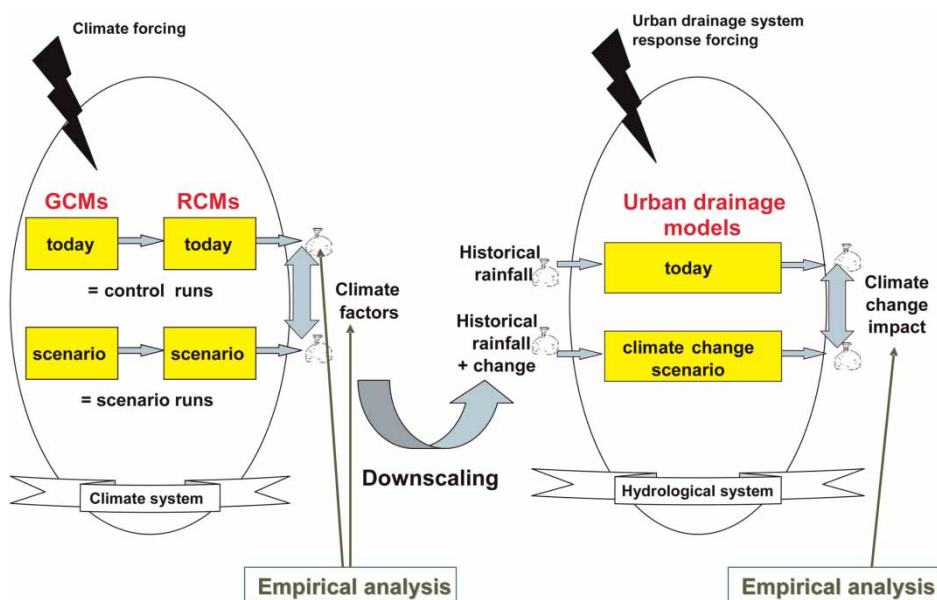
several decades, originally to account for lack of suitable precipitation data for urban drainage design, as described by Niemczynowicz & Sevruk (1991). Table 1 shows the typical types of precipitation data that are used in urban hydrology for the impact analyses of climate change shown in Figure 1.

### Measuring urban rainfall extremes

State-of-the-art monitoring of urban precipitation is based on either a (network of) rain gauge(s) or on weather radars. Both types of instruments have their merits and shortcomings. Rain gauges generally give a very poor description of the spatial heterogeneity of the precipitation process but are accurate with respect to the accumulated volume over time for the location where the gauge is situated. However, orographic effects and other physical characteristics can

**Table 1** | Use of precipitation data for urban drainage applications. Based on Schilling (1991), Einfalt *et al.* (2004), and Willems *et al.* (2012)

Type of data	Return period of primary interest	Problem at hand
Two-dimensional precipitation fields	0–1 years	Understanding precipitation processes Real-time control On-line forecasting/off-line analysis
Time series of point processes	0.1–50 years	Design of hydraulic structures Environmental studies
Design storms	0.5–1,000 years	Design of hydraulic structures Risk analysis



**Figure 1** | Components of urban hydrological impact analysis of climate change (GCMs: general circulation models; RCMs: regional climate models). From Willems *et al.* (2012).

lead to significant changes in rainfall characteristics within distances of less than 1 km. Weather radars provide the spatial resolution that rain gauges cannot provide, but at the cost of poor resolution of precipitation extremes, because the rainfall intensity is proportional to the logarithm of the measurement signal. Hence even under the best of circumstances good assessments of precipitation over urban areas are often quite uncertain.

The requirement for estimation of extreme precipitation characteristics imposes a particular challenge with respect to the length of the rainfall records. In general it is recommended to use averaging over 30 years to account for interannual variations in seasonal and annual means. In urban drainage applications the quantiles of interest are the 99.9 percentile and higher, and hence the demand for record length is in practice much greater than 30 years. Such record lengths are rarely available and even then are generally only available as single gauge recordings. Often such records are also influenced by changes in measurement device and environmental changes. Thus, in a trend analysis the signal-to-noise ratio depends on the record length, the trend magnitude, the 'noise' level (e.g. the magnitude of the variations in the values), and the frequency of events under consideration.

Adjustments to rainfall measurements might be required to account for site relocation, changes in measurement programs, known instrument changes, measurement program deficiencies or changes in the micro-climate (e.g. changes in sheltering effects or urban heat island effects). These changes take the form of bias correction because they aim to remove changes in observations that are occurring due to external factors rather than real changes in the precipitation extremes.

### Quantifying extreme precipitation for design and validation

The most fundamental properties of extreme rainfall can be expressed as *intensity–duration–frequency* (IDF) relationships (also denoted *depth–duration–frequency* relationships) that summarize precipitation intensities for different durations and return periods (Chow *et al.* 1988; WMO 2009). These relationships can be calculated for both point rainfall and spatial averages. Typical empirical IDF relationships found in the literature are of the form (Bilham 1962; WMO 2009):

$$i(D) = \frac{\alpha}{(D^\zeta + \theta)^\eta}$$

$$i(D, T) = \frac{\alpha T}{(D^\zeta + \theta)^\eta}$$

$$i(D, T) = \frac{\alpha + \beta \log T}{(D^\zeta + \theta)^\eta}$$

where  $i(D)$  and  $i(D, T)$  are the intensities for a given aggregation level or duration  $D$  and/or return period  $T$ ,  $\alpha > 0$  and  $\beta > 0$  are scale parameters,  $\theta \geq 0$ , and  $0 < \eta < 1$  and  $\zeta$  are shape parameters ( $\zeta$  is most often taken equal to 1 and also  $\eta$  has, for many cases, the value 1).

IDF relationships can be estimated directly based on historical measurements, and these can be used to verify that the basic properties of extreme rainfall are captured by a model such as a weather generator.

### Weather generators based on point process theory

Several types of stochastic weather generators exist. One of the oldest types frequently used within catchment hydrology is based on Markov chain modelling (e.g. Cox & Miller 1965; Richardson 1981; Srikanthan & McMahon 1983, 2002; Stern & Coe 1984; Woolhiser 1992). The states within the Markov chain are typically formulated in daily time steps, although other formulations exist, with one state denoting dry weather and one or more states denoting wet weather conditions. The precipitation amounts within the wet states are then modelled by a probability distribution.

The distribution parameters and transition probabilities can vary seasonally or in time depending on the influence of atmospheric indices (e.g. Hyndman & Grunwald 2000; Wheeler *et al.* 2005; Furrer & Katz 2008). Examples of atmospheric influences include the El Niño Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), atmospheric pressure, weather type or type of atmospheric circulation pattern, temperature, wind speed, humidity or a slowly varying trend function. This type of Markov chain model is denoted non-homogeneous as the parameters are conditional on one or more of the above-mentioned influences or indices. Such dependencies can be described with generalized linear models (McCullagh & Nelder 1989; Kiely *et al.* 1998; Chandler & Wheeler 2002; Chandler 2011).

### Stochastic rainfall generators

Another set of methods for stochastic point rainfall generation make use of the stochastic representation of rain cells in time and/or space. The best known stochastic

rainfall generator of this type for point rainfall is the rectangular pulse model. Originally developed for the spatial distribution of galaxies, two versions are most commonly applied to the modelling of rainfall, namely the Neyman–Scott (NSRP) (Cowpertwait *et al.* 1996; Kilsby *et al.* 2007) and the Bartlett–Lewis (BLRP) (Rodriguez-Iturbe *et al.* 1987a, b; Verhoest *et al.* 1997; Onof *et al.* 2000; Vandenberghe *et al.* 2011) models. Both of these models schematize rain storms as a cluster of rain cells by means of rectangular pulses. To describe the rain storm occurrences in time, or the rain cells within a rain storm, Poisson processes are often assumed. This means that the rain storm or cell arrivals are random in time with exponential or related inter-arrival times, which are independent from each other.

The models use in the order of five to eight parameters that typically have a seasonal variation. The parameters describe the probability distributions of pseudo-physical rain storm properties such as the mean rain cell intensity or cell volume, the mean cell duration, the dry spell lengths or inter-arrival times of storms, and the waiting times from the origin to the rain cell origins. Although these properties can be interpreted physically, their distributions are commonly estimated on empirical moments of an observed series of precipitation data with a temporal resolution of between 1 hour and 1 day.

Spatial versions of the NSRP and BLRP rainfall generators exist as well. In the simplest formulation, the spatial structure is assumed to be circular discs moving over the catchment with uniform velocity with cells being generated according to a two-dimensional Poisson process (Cowpertwait 1995; Cowpertwait *et al.* 2002; Fowler *et al.* 2005; Burton *et al.* 2008).

In general these generators tend to underestimate precipitation extremes for short durations (Verhoest *et al.* 1997; Back *et al.* 2011). Several authors have suggested improvements to the basic formulation of the stochastic weather generators, but none have so far succeeded in generating time series of precipitation at the resolution needed for urban drainage analysis. This may be due to the fact that the semi-physical parameters are physically inconsistent over different time scales, as pointed out by Foufoula-Georgiou & Guttorp (1987).

### Scaling properties of spatio-temporal structure in precipitation

Fractal theory (Mandelbrot 1982) has been used to describe both spatial and temporal structures in precipitation

(Schertzer & Lovejoy 1987, 1991; Gupta & Waymire 1990, 1993). This approach is based on scaling laws, which describe the scale-invariant properties or relationships that connect the statistical properties of rainfall at different scales. Based on the scaling properties, the variability of rainfall at different temporal and spatial scales can be described using a small number of parameters.

Following the description of Gupta & Waymire (1990), scaling can be described as a power relation for each of the rainfall distribution parameters  $\beta$  depending on the scale (e.g. time scale  $D$ ):

$$\beta_D = a D^b$$

or:

$$\beta_{\lambda D} = \lambda^b \beta_D$$

where  $\lambda$  is the scale factor and  $b$  the scaling exponent. The scaling exponent equals the slope of the linear relationship between  $\beta$  and  $D$  in a double logarithmic plot. It is constant in the simple scaling case, which means that the variability in the rainfall process does not change with time scale. It also means that for a time scale  $\lambda D$  the same distribution holds as for time scale  $D$  if the rainfall intensities  $x$  are scaled with a factor  $\lambda^b$  (Gupta & Waymire 1990; Burlando & Rosso 1996):

$$F_{\lambda D}(\lambda^b x) = F_D(x)$$

The scale invariance then also holds for the distribution moments:

$$E[X_{\lambda D}^l] = \lambda^{lD} E[X_D^l]$$

where  $E[X_D^l]$  denotes the non-central moment of order  $l$  for the rainfall distribution at time scale  $D$ .

When the slope of the relation between the moments  $E[X_D^l]$  and the time scale  $D$  are plotted against the moment order  $l$ , a linear increase is found in the simple scaling case. When the relation is non-linear and concave, extreme rainfall statistics are called multi-scaling (Gupta & Waymire 1990).

A wide range of scaling-based modelling approaches have been developed, focusing on the temporal structure (e.g. Menabde *et al.* 1997a; Cârsteanu *et al.* 1999; Veneziano & Iacobellis 2002), the spatial structure (e.g. Menabde *et al.* 1997a, b, 1999a, b; Deidda 1999) or the full space–time structure (e.g.

Lovejoy & Schertzer 1990; Over & Gupta 1996; Seed *et al.* 1999; Venugopal *et al.* 1999; Deidda 2000; Jothiyangkoon *et al.* 2000).

Some work has focused explicitly on extreme rainfall. Nguyen *et al.* (2002) and Willems (2000) both established scaling functions ranging from a few minutes to daily values. A range of studies have established IDF relationships based on scaling properties of rainfall, e.g. Burlando & Rosso (1996), Menabde *et al.* (1999a), Yu *et al.* (2004), and Langousis & Veneziano (2007).

## USING CLIMATE MODELS TO PREDICT FUTURE HIGH-RESOLUTION PRECIPITATION

### Global climate models

Climate models aim to predict the statistics of atmospheric conditions for given external forcings such as emissions of greenhouse gasses. The models are based on numerical implementations of the conservation of mass, momentum and heat, as well as the perfect gas law. Water is typically considered as a separate constituent having its own conservation equation including a description of all possible phases of water. These general circulation models (GCMs) often have as boundary conditions the incoming radiation energy from the sun and the corresponding radiation leaving the earth.

The emission of greenhouse gases is introduced into the models by means of representative concentration pathways (RCPs), that represent the imbalance between incoming and outgoing energy in the earth-atmosphere system, measured in radiative forcing reached by 2100 (Moss *et al.* 2008). In contrast to the previous SRES scenarios (Special Report on Emissions Scenarios; Nakicenovic *et al.* 2000) used in the fourth assessment report of the Intergovernmental Panel on Climate Change (IPCC) (Solomon *et al.* 2007), the RCPs are not linked to specific emission scenarios but rather represent the combined impact of a combination of the socioeconomic, technological, political, and physical assumptions of the scenarios (Ward *et al.* 2011).

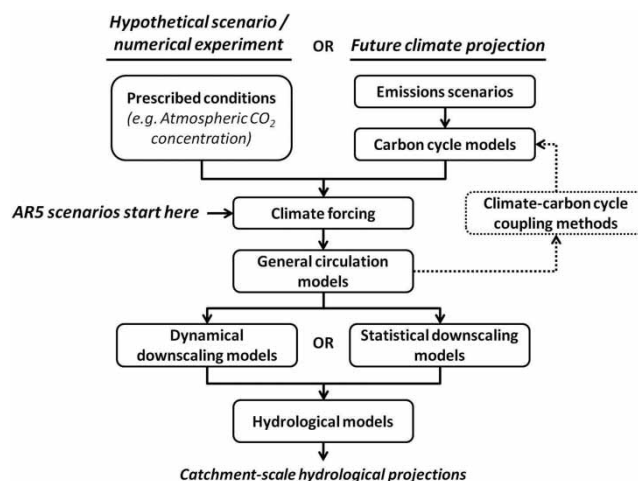
The IPCC Distribution Data Centre makes the data used in the fourth assessment freely available for download via the internet (IPCC 2013). Currently GCM data are being collected for the fifth assessment report (AR5) as part of the CMIP5 (fifth phase of the Coupled Model Intercomparison Project) multi-model experiment (Taylor *et al.* 2012). This data will also be freely available as soon as the simulations have been carried out (CMIP5 2013).

The temporal and spatial resolutions of GCMs are generally coarse, and daily time scales and spatial scales of more than 100 by 100 km are common, which are often unsuitable for urban hydrological purposes. Consequently, the resolutions need to be increased using downscaling, of which there are two main methods, as indicated in Figure 2. Dynamic downscaling is based on a model that covers part of the earth-atmosphere system and generally uses a GCM as boundary conditions. Hence not only precipitation but other atmospheric variables are resolved at higher resolutions. In statistical downscaling statistical relationships are established between climate model variables and observed precipitation.

### Dynamic downscaling

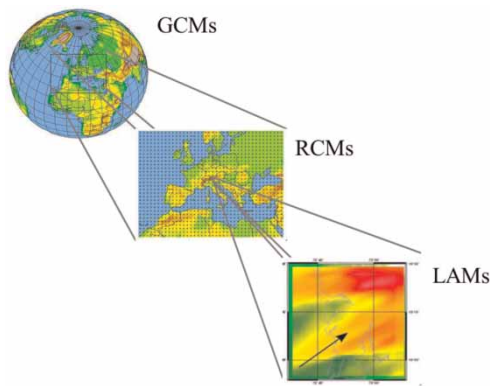
Models nested within GCMs are termed regional climate models (RCMs) or local area models (LAMs). RCMs typically have a spatial resolution between 12 by 12 km and 50 by 50 km while the term LAM is more often used to denote even higher resolutions. Repositories of RCM simulations exist for some regions, but most regions have so far been lacking from good RCM coverage. A global repository of RCM simulations covering all land areas of the globe is now being established under the project COordinated Regional climate Downscaling Experiment (CORDEX 2013). The nesting principle of downscaling is illustrated in Figure 3.

Downscaling allows topographical features, land cover heterogeneity and local feedback mechanisms to be included in the simulations. RCMs typically have a numerical representation of convective rainfall, leading to better



**Figure 2** | Simplified chart of the main processes involved in modelling (urban) hydrological impacts due to climate change (after Ward *et al.* (2011)).





**Figure 3** | Spatial range of models from GCMs to RCMs and LAMs.

performance with respect to generating precipitation extremes (Rummukainen 2010). However, these do not explicitly model small-scale cloud processes, but use cumulus parameterization to represent the collective influence of clouds (e.g. rainfall, radiation budget) within a larger area (single grid). For climate modellers, the primary purpose of cumulus parameterization is not to produce accurate rainfall, but to release model instabilities (Arakawa 2010). Cumulus formation is an important cloud process that leads to rain storms and occurs at around 0.1–10 km horizontal scales. With city scale LAMs at spatial scales finer than perhaps 3 km, it is possible to represent the cumulus process explicitly by the model physics (Lo *et al.* 2008; Pathirana *et al.* submitted).

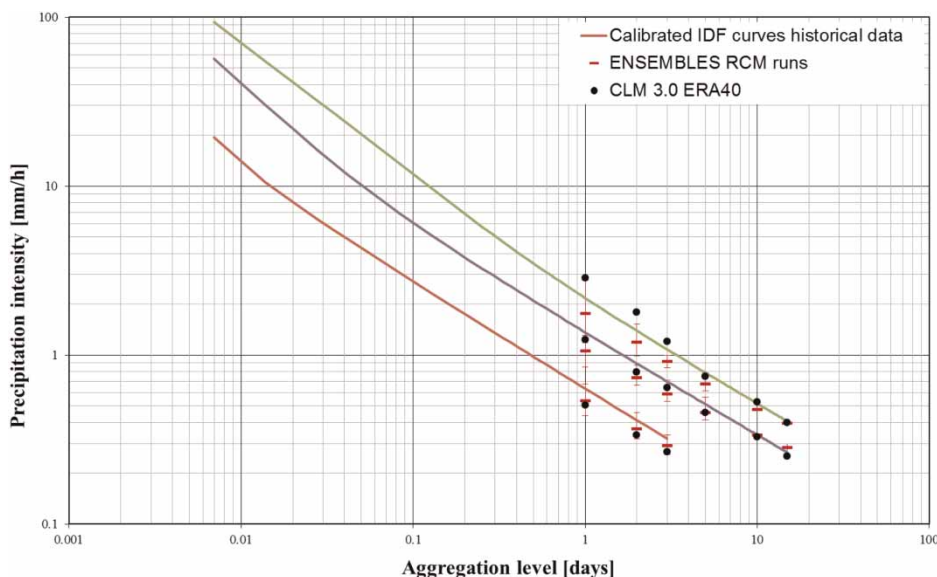
Validation of GCM/RCM/LAM results for local conditions is required before these models can be used as

input for local climate change impact studies. This is commonly undertaken by comparison with statistics obtained from long-term historical rainfall series. Statistical tests can be applied to the initial set of available climate model runs and, after testing, rejected runs can be removed. These are generally the ones that are inconsistent with the current or past climate observations. However, modellers have to be careful with such rejections for several reasons, including natural variability, the limited length of the available time series, differences in spatial scales, and the influence of climate oscillations. Hence, removal of simulations is likely to lead to an underestimation of the overall uncertainty of climate change projections because it is usually only the outlying simulations that are removed.

Synoptic-scale RCMs can have poor accuracy in simulating precipitation extremes and tend to underestimate precipitation extremes for durations shorter than 1 day to 1 week, see Figure 4. This complicates urban impact analyses and consequently statistical downscaling methods are often used either instead of or as a supplement to dynamic downscaling for urban impact analysis.

### Statistical downscaling

There is a need to adapt the results of RCM/GCM simulations so that they can be meaningfully used at the more detailed scales that are needed for urban drainage models. This can be done using statistical methods, which also offer a potential way to assess the uncertainties and biases



**Figure 4** | Comparison of RCM output of precipitation extremes to observed values (Willems *et al.* 2012).

in RCM/GCM urban rainfall extremes (Maraun *et al.* 2010). The main shortcomings of statistical downscaling include that the methods typically only consider precipitation rather than the entire set of climatic variables, that validation is by definition difficult, and that some properties must be assumed to be invariant in either time or space. To overcome these shortcomings several different downscaling methods can be used. It is also recommended to validate as many steps as possible in the downscaling methods. Due to the lack of accurate long-term spatial rainfall statistics, spatial downscaling and bias correction of rainfall intensities at given temporal scales are difficult to separate, and hence they are often combined, see Figure 5.

There is a range of statistical downscaling techniques, aimed at downscaling daily precipitation. These are based on fitting changes in the distribution of daily values and/or the proportion of wet days. A review of these methods including applications is given in Willems *et al.* (2012). The following sections will focus on downscaling to higher resolutions. In general three types of methods have been reported in the literature: empirical transfer functions, resampling methods, and stochastic modelling. Each of these methods and examples of applications are presented below.

### Empirical transfer functions

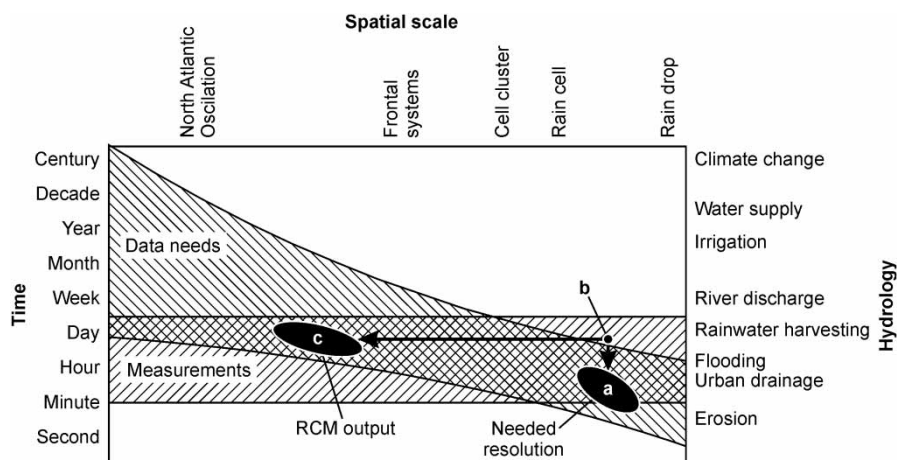
Empirical transfer function methods make use of empirical relationships between rainfall at the small urban hydrological impact scale and the statistics of coarse scale climate model output variables, such as sea level pressure, geopotential height, zonal wind velocity, specific or relative humidity

and temperature. The transfer function is derived from historical (observed or estimated) values at both the coarse and small scale, and is applied to the projections from the climate models to generate small scale values. The transfer function can take many forms such as a regression relation, equations based on rainfall time scaling laws, generalized linear models and artificial neural network models (Olsson *et al.* 2004; Coulibaly *et al.* 2005; Sharma *et al.* 2011).

Some apply bias correction to the climate model output, prior to the statistical downscaling. This bias correction step requires that observations are available at the same temporal and spatial scales as the climate model output. Gridded historical rainfall data can be obtained from interpolation of rain gauge data and/or from radar data, but the accuracy of the latter is often much lower than that of the rain gauge observations. This is why bias correction and spatial downscaling are often combined by matching the gridded climate model rainfall output with point rainfall observations (Nguyen *et al.* 2010). This can be done by quantile mapping (Rosenberg *et al.* 2010; Yang *et al.* 2010). An advanced version of this method has been recently developed by Olsson *et al.* (2012) by making the transfer function dependent on climate model process variables characterizing the weather situation such as cloud cover and precipitation type.

### Resampling methods and weather typing

In the resampling or weather typing methods the downscaling is performed by relating weather patterns of the climate model to observed patterns. For a given event (e.g. day) in the climate model, the most similar situation (analogue



**Figure 5** | Statistical downscaling of RCM outputs down to the scale required for urban hydrological impact studies. Both temporal downscaling (a–b) and spatial downscaling (b–c) are required (adapted from Willems *et al.* (2012)).

event or day) is sought in the historical rainfall series, and the precipitation from that event/day is used as the down-scaled rainfall. Weather types identified based on pressure fields are most often used to define analogue events.

Willems & Vrac (2011) further advanced the weather typing method by accounting for the fact that precipitation changes not only depend on changes in weather type, but also on temperature changes. For the different weather types, rainfall probability distributions were changed as a function of the change in temperature distributions.

Instead of using climate analogues from the past, climate analogues from other locations can also be considered. In this approach, denoted climate matching or space-for-time methods, locations are selected for which it is expected, based on the results of climate model outputs, that future climate conditions will be similar. This method has been tested by Arnbjerg-Nielsen (2012), assuming the future climate in Denmark in 2100 might become similar to the present climate in northern France and Germany.

### Conditional probability-based or stochastic modelling

Conditional probability-based or stochastic modelling methods use stochastic rainfall models with parameters conditioned on the coarse scale climate model outputs. The stochastic models can be weather or rainfall generators such as those discussed in the 'Stochastic rainfall generators' section (Semenov & Barrow 1997; Schreider *et al.* 2000). They can be conditioned on global climatic variables such as atmospheric circulation or weather types (Fowler *et al.* 2005). A comparison of different types of rainfall generators for this purpose can be found in Sunyer *et al.* (2012).

Another option for this type of statistical downscaling is to directly use coarse scale rainfall from the climate models and to apply to these a spatial and/or temporal rainfall disaggregation method. Onof & Arnbjerg-Nielsen (2009) followed a two-step approach where first a rainfall generator is applied to capture the storm structure at the hourly time scale, and in a second step rainfall disaggregation is applied to bring hourly rainfalls down to a 5-minute temporal scale.

## IMPLICATIONS FOR URBAN DRAINAGE DESIGN

### Climate change impacts on urban runoff

When the impact on urban runoff is studied (e.g. through runoff peak flows, floods, surcharge frequencies, and combined sewer overflow frequencies and volumes), the

projected impacts are uncertain, not only due to the uncertainties in the climate projections, but also due to uncertainties in the hydrological and hydraulic models. Care is required when predicting the impacts of more extreme conditions. The hydrological and hydraulic models are often calibrated and validated against historical time series of limited lengths, which may have included only a few extreme events. Extension of the model simulations to future conditions should therefore be made with caution, especially when considering system performance under extreme events that might become more common under future climate change conditions. Examples of propagations of climate change impacts based on single design events can be found in Niemczynowicz (1989), Waters *et al.* (2003), and Grossi & Bacchi (2008). Examples of propagations of continuous simulations of precipitation time series can be found in Semadeni-Davies *et al.* (2008), Arnbjerg-Nielsen & Fleischer (2009), Olsson *et al.* (2009), Schreider *et al.* (2000), and Willems (2011).

### Flexible and sustainable adaptation

In most cases the impact analyses of urban runoff indicate that in regions where climate change occurs a systematic adaptation effort should be undertaken to minimize the impacts on the performance of the drainage systems. This need is further amplified by a range of other drivers, including increased urbanization, wealth, and drainage boundary conditions such as increased risk of extreme sea surges and fluvial flooding (Tait *et al.* 2008; Olsson *et al.* 2010; Huong & Pathirana 2011; Pedersen *et al.* 2012). Some of these studies suggest that, regardless of the importance of climate change impacts, systematic adaptation can mitigate the impacts to an acceptable level through implementation of reasonable measures (Semadeni-Davies *et al.* 2008; Zhou *et al.* 2012).

Urban planners and designers of urban drainage infrastructure can use the projected changes in extreme rainfall and other key inputs to start accounting for the effects of future climate change. Sections of the urban drainage system with insufficient capacity to convey future design flows can be upgraded over the next few decades as part of a programme of routine and scheduled replacement and renewal of ageing infrastructure. Optimization methods for climate change adaptation are currently emerging (Zhou *et al.* 2012). However, current urban drainage practices are increasingly being challenged. In Australia, a persistent drought period has recently led to increased demand for retaining the precipitation in urban areas through



implementation of water sensitive urban design (WSUD) principles for urban water management (Wong & Brown 2009; Beecham 2012). Also in areas with less stress the potential amenity value of retaining water within the city leads to alternative paradigms for urban drainage objectives and interplay with other disciplines as described by Geldof & Stahre (2004), Fryd *et al.* (2010), and Zhou *et al.* (2013). Case study projects that meet both urban drainage criteria for climate change adaptation and other objectives are often collected and recorded in national repositories to inspire other stakeholders to consider multifunctional use of urban spaces. Examples of such repositories are UKCIP (2013) and ClimateChangeAdaptation (2013).

The large uncertainties associated with climate change should not be an argument for delaying impact investigations or adaptation actions. Instead, uncertainties should be accounted for, and flexible and sustainable solutions should be sought (Refsgaard *et al.* 2013). An adaptive approach has to be established that provides flexibility and reversibility but also avoids closing off options. This is different from the traditional engineering approach, which can be static and is often based on design rules set by engineering communities without much public debate. An adaptive approach involves active learning that recognizes that flexibility is required as understanding increases. Essentially two paradigms are being questioned. First, the recent focus on optimization of infrastructure has led to reduced investment and to reduced operational costs. This in turn has led to ageing and deteriorating infrastructure with lower service levels. Secondly, the concept of urban drainage as a well-defined and relatively static scientific discipline is being challenged. The implications of urban drainage design decisions are intricately connected to other decisions about the well-being of the city in the same way that decisions about the well-being of the city have a major influence on the ability of the urban drainage system to deliver the essential services in an affordable and efficient way.

## DISCUSSION AND OUTLOOK

This paper has described the most advanced methods for analysing climate change impacts on precipitation extremes in urban areas. However, there are still a number of shortcomings in these methods. When predicting future precipitation extremes, two major issues arise. Climate models provide an assessment of anthropogenic impacts only. What about the natural changes that will occur concurrently? Secondly, what are the assumptions behind the

climate models and how do these assumptions influence the projections?

Analyses of long historic records sometimes indicate non-stationary behaviour even before anthropogenic influences can reasonably be accounted for (Ntegeka & Willems 2008; Cappelen & Wang 2012), and in some studies co-variables that explain the variations have also been identified (e.g. Grimm & Tedeschi 2009; Kamruzzaman *et al.* 2012; Gregersen *et al.* 2013). If the non-stationarity is not taken into account in the analysis, differences in detected trends might be found when the tests are applied to different periods.

The climate model simulations are carried out assuming a constant climate except for anthropogenic impacts. The feedback mechanisms between natural and anthropogenic changes are not known, and also the problem of attributing observed changes to anthropogenic activity is in its infancy. So the combination of calculated climate change impacts due to anthropogenic activities and natural variations is difficult to assess and no fully satisfactory methods have yet been identified.

Caution must therefore be exercised when interpreting climate change scenarios. Consideration of an ensemble approach, where several climate forcing scenarios, climate models, initial states and statistical downscaling techniques are considered, allows the uncertainty associated with each aspect to be assessed. At the same time, it must be recognized that the total uncertainty of climate projections is likely to be larger than that exhibited by an ensemble of models, because the models share the same level of process understanding and sometimes even the same parameterization schemes and code. Whatever methods are adopted, the resulting change should not be interpreted as an exact number but only as being indicative of the expected magnitude of future change.

The majority of GCM simulations available are all based on relatively low climate change scenarios, leading to calculated global surface temperature increases of 2–3 °C (Solomon *et al.* 2007). For scenarios with emissions leading to higher temperature increases, very little information is available, in spite of the fact that no policies have yet been implemented that justify an anthropogenic impact of only 3 °C.

## CONCLUSIONS

Much literature has become available on the impacts of climate change on precipitation extremes and urban drainage

systems, but there are still large gaps in our understanding. The scientific level of understanding of how climate change will impact urban drainage systems remains limited for two reasons. The first reason is our lack of understanding of how to quantify the impacts given our understanding of climate change. The second reason is our lack of understanding of how the urban drainage sector should react to the challenges that large changes in precipitation extremes will generate. Together with other drivers they indicate the need for rapid action and for increased flexibility, robustness and resilience in our cities. Climate change may well be the driver that ensures that changes in urban drainage paradigms are identified and suitable solutions implemented. Design and optimization of urban drainage infrastructure that considers climate change impacts and co-optimizes this with other objectives for a habitable city will become increasingly important in the future.

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