Hydrology Research

Hydrology Research Vol 53 No 6, 840 doi: 10.2166/nh.2022.137

Nordic contributions to stochastic methods in hydrology

Dan Rosbjerg [a,*], Kolbjørn Engeland [b], Eirik Førland [c], Ali Torabi Haghighi [d], Ali Danandeh Mehr [d] and Jonas Olsson [e]

[a] Department of Environmental Engineering, Technical University of Denmark, DK-2800, Kongens Lyngby, Denmark
[b] The Norwegian Water Resources and Energy Directorate, P.O. Box 5091, Majorstua, N-0301, Oslo, Norway
[c] The Norwegian Meteorological Institute, P.O. Box 43 Blindern, N-0313, Oslo, Norway
[d] Water, Energy, and Environmental Engineering Research Unit, University of Oulu, P.O. Box 4300, Oulu F-90014, Finland
[e] Swedish Meteorological and Hydrological Institute, SE-601 76, Norrköping, Sweden
*Corresponding author. E-mail: daro@dtu.dk

DR, 0000-0003-2204-8649; KE, 0000-0003-1081-8570; ATH, 0000-0002-6649-7406; ADM, 0000-0003-2769-106X; JO, 0000-0001-5907-4061

ABSTRACT

The paper presents prominent Nordic contributions to stochastic methods in hydrology and water resources during the previous 50 years. The development in methods from analysis of stationary and independent hydrological events to include non-stationarity, risk analysis, big data, operational research and climate change impacts is hereby demonstrated. The paper is divided into four main sections covering flood frequency and drought analyses, assessment of rainfall extremes, stochastic approaches to water resources management and approaches to climate change and adaptation efforts. It is intended as a review paper referring to a rich selection of internationally published papers authored by Nordic hydrologists or hydrologists from abroad working in a Nordic country or in cooperation with Nordic hydrologists. Emerging trends in needs and methodologies are highlighted in the conclusions.

Key words: climate change impacts, flood and drought frequency, rainfall extremes, water resources management

HIGHLIGHTS

- Historical development in use of stochastic methods.
- From stationarity to climate change impacts.
- From univariate to multivariate problems.
- From local to regional problems.

INTRODUCTION

In 1971, 50 years ago, stochastic approaches to hydrological problems were relatively sparse in the Nordic region. By inspiration from the international literature and increasingly more frequent international cooperation combined with actual needs, a fruitful period was initiated, resulting in many important contributions to stochastic methods in hydrology from the region.

In this review, the focus is on the scientific contributions from the Nordic and Baltic countries. We have therefore concentrated the efforts on studies, where at least one of the authors has a Nordic or Baltic affiliation. The literature was screened by searching in abstracts databases (e.g. Scopus) combined with key references from the author team's own knowledge. It should be noted that stochastic approaches are used to solve practical needs for society. Therefore, a large amount of 'grey' literature exists in form of technical reports, which only exceptionally have been considered this review.

The main purpose/aim of this paper is to provide a broad review of the development of stochastic methods by focusing on stochastic modelling of floods, droughts, rainfall extremes, water resources management (WRM) and climate change impacts. The first publications emerged in the 1970s and the development during time is indicated in Figure 1 by the number of referenced publications distributed on decades. In the first two decades, the activity was modest followed by a factor 4 in the next two. After 2010, the activity is again significantly multiplied revealing a strongly growing interest in the subject and the need for further development. In the conclusions, we summarize emerging trends in approaches and methods applied by the scientific community as a response to societal needs.

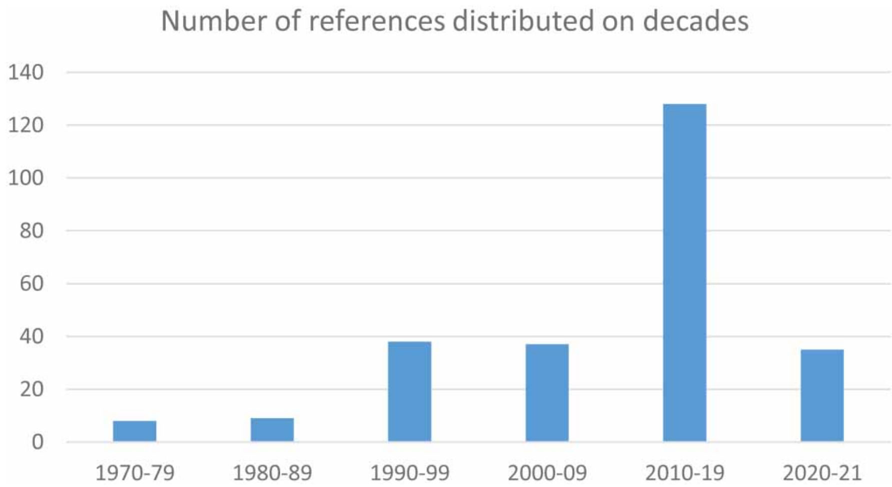

Figure 1 | Number of references from 1970 to 2021 distributed on decades.

FLOOD FREQUENCY AND DROUGHT ANALYSES

Estimation of flood magnitudes of low annual exceedance probability or large return periods is needed for design purposes to reduce the potential risk from flood hazards. Design flood estimates are used for dam safety, area planning, bridges and levees, etc. As flood frequency analysis is a crucial part of risk management, approaches and methods for design flood estimation are published in national guidelines and reports, i.e. in the 'grey literature'. Several of these approaches are summarized in Castellarin *et al.* (2012). In this review, the focus will be on the scientific publications.

Two basic approaches for statistical analysis of floods can be identified: (1) statistical flood frequency analysis based on flood data and (2) precipitation–runoff approaches where statistical analysis of extreme precipitation and possibly snowmelt and catchment moisture content are used to derive the statistical distribution of floods. Examples from both approaches will be reviewed. Since design flood estimates are used to plan land use and design infrastructure to sustain floods for the coming 50–100 years, climate change impact on floods is in recent years extensively addressed in the literature by analysing past trends and linking floods to large-scale weather patterns and flood-generating processes, as well as assessing future projections of floods. The latter is addressed in a separate section on climate change and adaptation efforts.

Most studies aim to estimate the design flood specified as a T-year flood (Q_T). Alternatively, as suggested in Rasmussen & Rosbjerg (1989), the design flood can be determined by specifying the probability that a flood is exceeding a given value in a period of L years, R_L, where L is the lifetime of a structure. In Rasmussen & Rosbjerg (1991a) it is further demonstrated that using the distribution of R_L might be more relevant than using the distribution of the T-year flood for design purposes, since this probability can directly be used in risk assessments. Jiang *et al.* (2019) and Haghighatafshar *et al.* (2020) argue that the probability over lifetime is more relevant to use in a non-stationary context, where the annual exceedance probability of floods varies with time.

To characterise flooding, most studies use flood discharge (m^3/s). However, other processes than high discharges might cause large inundations. In Nordic climate, ice-jams might cause severe flooding. Pagneux *et al.* (2010) therefore propose to use inundation extent as a key variable to analyse magnitude and frequency of flooding events. Using flood discharge will underestimate the flood risk in areas where ice-jams create large flooding.

Statistical flood frequency analysis

At locations with streamflow measurements, statistical flood frequency analysis involves fitting a distribution function to either an annual maxima series (AMS) or a series of peaks-over-threshold (POT). The latter is often denoted partial duration series (PDS) in hydrology. The POT approach is based on extracting flood peaks above a predefined threshold. To estimate a T-year flood, both the distribution of the flood magnitudes and the frequency of exceedances need to be assessed.

POT and AMS

The first challenge when using the POT approach is to select the threshold. In Rosbjerg & Madsen (1992), a threshold level based on a frequency factor is recommended, whereas Madsen *et al.* (1997a) used the 2% percentile. Alternatively, a threshold resulting in a predefined average number of events per year can be used. Madsen *et al.* (1997a) recommend a minimum of 1.64 floods per year to get more precise design flood estimates from POT than from AMS.

The second challenge is to account for the dependence between flood peaks. In Rosbjerg (1977b, 1985, 1987), the dependency is accounted for when estimating the annual exceedance probability. In Rosbjerg & Madsen (1992), another approach is used by selecting only independent flood peaks. The independence is achieved by following the recommendation by USWRC (1976) that subsequent flood peaks should be separated by at least 5+In(A) days, where A is the catchment area in square miles, and in addition the inter-event discharge should decrease by at least 75% of the lowest of two succeeding flood peaks. A third challenge when using the POT approach is to account for seasonal variations in floods. However, in Rasmussen & Rosbjerg (1991b) it is shown that for most data sets it is not necessary to account for these variations to estimate a T-year flood.

The annual maximum approach is based on extracting the largest flood each year and fit a suitable distribution. AMS is less systematically evaluated in the Nordic–Baltic scientific literature, nevertheless it is used in several operational guidelines (Castellarin *et al.* 2012). Madsen *et al.* (1997a) compared the AMS and POT approaches and showed that for most applications in hydrology, the POT approach provides the smallest estimation uncertainty for design floods.

Estimation of statistical parameters

In both POT and AMS approaches, it is required to choose a suitable distribution for the flood magnitude and an estimation method for the distribution parameters. Usually, ordinary moments, L-moments or probability weighted moment are used to estimate the distribution parameters (e.g. Rosbjerg *et al.* 1992); however, in some studies, the maximum likelihood approach is also applied (e.g. Engeland *et al.* 2004). In more recent years, Bayesian approaches using the Markov Chain Monte Carlo (MCMC) method for estimation is increasingly being applied (e.g. Steinbakk *et al.* 2016; Kobierska *et al.* 2018). When a reasonable prior information is available, the Bayesian method is a good choice (Kobierska *et al.* 2018). The Bayesian approach allows to easily include non-stationarities, calculate uncertainties for design flood estimates and account for uncertainty sources in these estimates.

Flood frequency distributions

The generalized extreme value (GEV) distribution or the Gumbel distribution is most commonly used for the annual maximum approach. The GEV distribution has three parameters, whereas the Gumbel distribution, a special case of the GEV distribution, has two parameters. In Kobierska *et al.* (2018), several distributions are compared, and for Norwegian flood data, it is found that the GEV distribution is the best choice. The exponential distribution or the generalized Pareto (GP) distribution are the corresponding choices for the POT approach. In Rosbjerg *et al.* (1992), these two distributions are compared using a simulation-based approach. The results show that the exponential distribution generates the smallest estimation uncertainty for data sampled from the GP distribution if the shape parameter is slightly negative.

Design floods

Since the design flood x_T is an estimate and thus a random variable, the associated uncertainty can be estimated as well. The classical approach is based on assuming that x_T is normally distributed. In Rasmussen & Rosbjerg (1989), Taylor series approximations are used to analytically estimate the uncertainty of the T-year design flood. The approach is further developed in Rasmussen & Rosbjerg (1991a), where a Bayesian formulation of the estimation problem is suggested. However, since x_T might have a skewed distribution, other approaches that account for the skewness have come into use. In Engeland *et al.* (2004), bootstrapping is applied, whereas Steinbakk *et al.* (2016) and Kobierska *et al.* (2018) use a Bayesian approach.

The uncertainty in the estimates of x_T originates from both the observation uncertainty and the sample uncertainty (Petersen-Øverleir & Reitan 2009; Steinbakk *et al.* 2016). Rosbjerg & Madsen (1998) analysed a wide range of methods to account for sampling uncertainty and concluded that, in general, a reasonable safety margin can be obtained by adding one standard deviation to the estimated design value. For gauging stations where the flood magnitudes mainly are based on a rating curve, high flood observation may introduce estimation biases for return levels, since the estimation is based on combining two highly skewed distributions. The sampling uncertainty, however, is dominating (Steinbakk *et al.* 2016).

Regional flood frequency analysis

Regional flood frequency analysis is used to estimate design floods at locations with no streamflow measurements. The most common approach is based on an index-flood procedure (Madsen & Rosbjerg 1997a, 1997b; Madsen *et al.* 1997b; Kjeldsen &

Rosbjerg 2002; Kjeldsen *et al.* 2002; Yang *et al.* 2010; Hailegeorgis & Alfredsen 2017). The first step of this approach is to define homogeneous regions. For each region a regression analysis between an index flood (i.e. the mean or median flood) is performed, and later all flood data within a region are applied to establish one growth curve. In Gottschalk & Krasovskaia (2002), the regional curve is established by calculating regional L-moments as weighted averages of the L-moments estimated at each streamflow station for annual maxima (AM) data. The weights are proportional to the record length of each time series. In Madsen & Rosbjerg (1997a), POT data are used to establish an index-flood model, where the shape parameter of the GP distribution is constant within a region, and the location parameter and flood rate are site specific. In Madsen & Rosbjerg (1997b), the model is further developed by introducing generalized least-squares (GLS) regression to estimate the parameters of the regional model combined with a Bayesian approach to estimate a posterior model that combine local data with the regional model at each location with observations. In Thorarinsdottir *et al.* (2018), a fully Bayesian approach to regional flood frequency analysis of AM data is developed, where all parameters in the GEV distribution depend on catchment characteristics. No best model is selected. Instead, a sample of models is established based on the posterior model probability, and the posterior distribution of design floods is achieved by sampling from both models and the posterior parameter distribution. The benefit of this approach is that it is not necessary to define homogeneous regions prior to model estimation. The uncertainty by applying the following different regional estimation methods is analysed by Rosbjerg & Madsen (1995): (i) A standard index-flood approach; (ii) a station-year approach; (iii and iv) two quantile regression approaches and (v) the US Water Resources Council (USWRC 1981) method based on a regional average of the logarithmic skewness. The index-flood and station-year methods were shown to provide the smallest uncertainty. Gottschalk (1989) estimates the empirical exceedance probabilities of regional extremes by combining order statistics with the equivalent number of independent stations based on the spatial correlation of floods.

Historical and paleo-data

To analyse trends in flooding, both historical data (Kjeldsen *et al.* 2014; Retsö 2015; Engeland *et al.* 2018; Xiong *et al.* 2020) and paleo-data in the form of lake sediments (Bøe *et al.* 2006; Støren *et al.* 2010, 2012; Rimbu *et al.* 2016; Johansson *et al.* 2020) are useful, since they increase the length of flood records with 100–10,000 years. In Kjeldsen *et al.* (2014) and Engeland *et al.* (2018, 2020) the historical and paleo-data are used to improve the design flood estimates by combining the flood information from both streamflow gauges and historical/paleo-information. The Bayesian inference provides a theoretical framework for combining the different flood data, when estimating distribution parameters and the magnitudes of design floods. In Bøe *et al.* (2006), Johansson *et al.* (2020), Støren *et al.* (2010), Støren *et al.* (2012), Rimbu *et al.* (2016) and Engeland *et al.* (2020) the paleo-data are used to investigate the connection between flood occurrences and large-scale climate variations through the Holocene period (approximately the last 10,000 years). The studies show that both precipitation and temperature explain variations in flood frequency when colder periods imply larger floods in catchments, where snowmelt is an important flood generating process.

Multivariate extremes

In many statistical approaches, several aspects of floods are modelled. One direction is to model the relationship between peak flood and flood volume as a bivariate distribution (Brunner *et al.* 2016, 2018a; Filipova *et al.* 2018). In Jiang *et al.* (2019), this approach is extended to a four-dimensional model by modelling floods of duration 1, 3, 7 and 15 days. These approaches use copulas to model the dependency. In Filipova *et al.* (2018), catchment properties and flood-generating processes (rain and snow melt) are used to explain the copula parameters. In Jiang *et al.* (2019), the dependency structure and the marginal distribution are shown to depend on urbanization and reservoir capacity, and the estimated design floods are found to be more sensitive to non-stationarity in the marginal distributions than in the dependency structure.

Instead of modelling floods of different duration as a multivariate extreme, a parallel to intensity–duration–frequency (IDF) models for precipitation has been developed for floods. They are known as runoff–duration–frequency (qdf) models. In Breinl *et al.* (2021), a parametric qdf-model is fitted to all durations simultaneously without considering the possible dependency between floods of different durations. Then, the duration dependence is explained by catchment properties.

Flood hydrographs might also be needed. In Brunner *et al.* (2018a), an approach for modelling synthetic flood hydrographs is introduced, and in Brunner *et al.* (2018b), a regionalization approach is established, where it is shown that the flood peak is relatively easy to regionalize, whereas regionalizing the shape of the flood hydrograph is more challenging, since it depends on flood type as well as catchment properties.

Flooding can also be caused by large waves and/or storm surges. In Harstveit & Jenssen (2003), the relationship between extreme floods and winds is explored.

Precipitation–runoff approaches

Precipitation–runoff approaches for design flood estimation has mainly been developed and applied in Norway, Sweden and Finland. Traditionally, an event-based approach based on a simplified Hydrologiska Byråns Vattenbalansavdelning (HBV) model known as PQRUT (Filipova *et al.* 2016) is applied in Norway. The design flood is calculated using a design rainfall event and saturated initial conditions. The design rainfall is symmetric and should represent the *T*-year precipitation for all durations in the compound design event. In Filipova *et al.* (2016), the parameters of the PQRUT model is regionalized based on catchment characteristics. Filipova *et al.* (2019) further develop the traditional PQRUT approach by introducing a distribution of initial conditions that is combined with the design storm. In Lawrence *et al.* (2014), a stochastic semi-continuous approach known as SHADEX (Paquet *et al.* 2013) is applied and evaluated for Norwegian catchments. This approach uses a seasonal dependent mixture distribution of extreme precipitation based on a seasonal threshold and exponential distributions (Blanchet *et al.* 2015) as well as the probabilities for the precipitation amounts before and after the peak precipitation event. A hydrological model using standard precipitation (and temperature) data is used to establish a continuous simulation. In a first step, flood peaks and the corresponding rainfall events are identified. Subsequently, new precipitation values are systematically sampled for each precipitation event, and new flood peaks are calculated using the hydrological model with initial conditions from the continuous simulation. Thousands of simulations are carried out for each flood event. The seasonal dependent probability of each sampled precipitation event is used to establish an empirical distribution for extreme floods. In the end, SHADEX offers the possibility to analyse the underlying factors driving large floods, i.e. the importance of snow melt and soil moisture, as well as the seasonality of extreme floods (Lawrence *et al.* 2014).

Slightly different approaches are used for design flood estimation in Sweden (Bergström *et al.* 1992; Harlin & Kung 1992; Lindström & Harlin 1992; Harlin *et al.* 1993) and in Finland (Veijalainen & Vehviläinen 2008). In Sweden, the approach uses a 14-day design precipitation event with the largest precipitation amounts on day 9 and constructed so that they roughly contain the largest amounts experienced over 1- to 14-day periods of the 100 years of observations available in Sweden. Such sequences were defined for five regions in Sweden. This design precipitation sequence is systematically inserted into a 10-year climatological record, where a statistical 30-year snowpack has replaced the initial snowpack. In Finland, some modifications to the Swedish approach are introduced by using a 40-year climatological record, where the design precipitation represents a 1,000–10,000 precipitation event and depends on season (Veijalainen & Vehviläinen 2008). A significant advantage of this approach over event-based methods is that the catchment response to extreme precipitation sequences over a range of catchment conditions corresponding to differing saturation states and contributions from snowmelt is sampled during the simulation process. This approach, however, does not provide a probability of the estimated flood magnitudes.

In Gottschalk & Weingartner (1998), an analytic expression for the flood frequency distribution is derived by combining frequency analysis of rainfall volumes with a beta distribution for the runoff coefficient. As pointed out in Filipova *et al.* (2019), both the SHADEX approach and the stochastic version of PQRUT described above can also be considered as derived distribution approaches, since they aim at sampling from the flood distribution.

Detection of systematic variations and trends

A key topic in research has been to identify trends in observed floods and linking trends to changes in river regulations, land use and/or climatic drivers.

Most approaches for detecting trends in floods are based on analysing either POT or AM flood series. Both POT and AM series are used to analyse trends in flood sizes, whereas POT series are also used to analyse trends in flood occurrence (e.g. Mangini *et al.* 2018). Many studies find trends that are more significant in flood occurrence than in magnitudes (e.g. Wilson *et al.* 2014; Mangini *et al.* 2018). Changes in flood statistics can be detected by comparing the empirical and theoretical distributions for different sub-periods (e.g. Sarauskiene & Kriaučiūnienė 2011). To detect the most likely time for a change point in flood statistics, a Cumulative Sum of Departures of Modulus Coefficient (CSDMC) (Chen *et al.* 2013) or the Pettitt-test (Zhang *et al.* 2014) can be applied. For analysing more gradual changes, the non-parametric Mann–Kendall test is used to identify significance of trends (e.g. Meilutytė-Barauskienė & Kovalenkovienė 2007), whereas the Sen's slope method is used to quantify the trends in flood data (e.g. Bian *et al.* 2020). Trends can be also identified in the moments of the flood data (Chen *et al.* 2019), in parameters of the statistical distribution (e.g. Kallache *et al.* 2011;

Zhang *et al.* 2014) or in the flood quantiles (e.g. Dahlke *et al.* 2012). In Kallache *et al.* (2011), the trends are modelled as linear functions, whereas in Zhang *et al.* (2014), generalized additive models (GAMs) are used to allow for more flexible and non-linear trends. In Yan *et al.* (2017), trends are detected by using a two-component mixture distribution, where both the mixture coefficient and the parameters depend on time. Hisdal *et al.* (2006) point out that due to the large natural variability in floods, detected trends are sensitive to the period that is analysed. Thus, too short flood time series might lead to wrong conclusions.

Variations and trends in flood statistics can be linked to changes in climate and weather like large-scale weather patterns, precipitation, temperature or the underlying flood generating processes (i.e. snowmelt and heavy rain). Several studies link frequency of floods to large-scale circulation patterns, using data outside the Nordic and Baltic regions. Krasovskaia *et al.* (1999) show that the frequency of floods in Costa Rica depends on the El Niño/Southern Oscillation (ENSO) index, whereas the magnitude does not. Ward *et al.* (2014) perform a global study showing that ENSO influences the annual flood in river basins covering one-third of the land surface, and in Ward *et al.* (2016), it is shown that ENSO influences even more the flood duration.

Several studies link non-stationarity in floods to changes in temperature and precipitation. Due to the importance of snow accumulation and snowmelt in large parts of the Nordic region, the interactions between changes in temperature, precipitation and floods are complex. In a review of European trend studies, Madsen *et al.* (2014) conclude that even if there is an increase in extreme precipitation, no clear trends in floods are detected. However, smaller and earlier snowmelt floods are observed due to increasing temperatures. In a pan-European study, Blöschl *et al.* (2019) identified two opposite trends in the Nordic and Baltic regions. In areas where the floods are driven by snowmelt (i.e. northern and eastern areas), floods tend to decrease, whereas in areas where the floods are driven by rain (in the western areas), they tend to increase due to increasing precipitation. Similar results are found in national studies. In the Baltic region, a decrease in the spring flood caused by snowmelt is identified (Sarauskiene & Kriaučiūnienė 2011), whereas no trends are found when analysing annual maximum floods (Meilutytė-Barauskienė & Kovalenkovienė 2007). In Norway, Vormoor *et al.* (2016) analysed trends in the flood-generating processes and detected a transition where in some regions rainfall floods become more frequent and snowmelt floods is decreasing. Slightly different conclusions are drawn in Krasovskaia & Gottschalk (1993). They find that floods are more frequent and slightly larger during warm and/or wet years. In Dahlke *et al.* (2012), the importance of catchment properties in terms of glacier-covered areas is demonstrated. Similar changes in climate forcing may cause fundamentally different responses of the hydrological systems and flood magnitudes. The floods increased in the glaciated catchment, whereas it decreased in the snow-free ones.

Trends and variations in floods can be linked to changes in land use, in particular urbanization. Bian *et al.* (2020) demonstrate that urbanization explains most of the changes in floods for a semi-urban catchment in Qinhuai River Basin, Southeast China.

Definition and modelling of droughts

Several approaches are used to define drought events. The earliest studies use the annual minimum flows over accumulation periods from 1 to 15 days (e.g. Gottschalk & Perzyna 1989). As a direct parallel to POT, pits under threshold (PUT), where the minimum value of a low flow sequence below a selected threshold is used in several studies (e.g. Pacheco *et al.* 2006). To make drought analysis relevant for WRM, drought events can be defined using a threshold level approach (Zelenhasic & Salvai 1987; Tallaksen *et al.* 1997). This approach defines drought events as periods when the streamflow is below a predefined threshold. These drought events can be characterized by volume, duration and the minimum flow. Tallaksen *et al.* (1997) point out that using this approach might result in many minor and mutually dependent droughts, when streamflow is oscillating around the threshold. Applying a moving average filter to the original streamflow observations prior to extracting drought events is a simple and efficient way to eliminate such droughts (Tallaksen *et al.* 1997; Fleig *et al.* 2006a). Alternative approaches are pooling dependent droughts based on inter-event times and volume (Madsen & Rosbjerg 1995) and the sequent peak algorithm (Tallaksen *et al.* 1997). The threshold level approach can be extended to specifying seasonal thresholds to account for seasonal variations in climate and runoff generating processes (Fleig *et al.* 2006b). This can be particularly useful in a Nordic climate, where summer and winter droughts are caused by different processes (Fleig *et al.* 2006b). Winter droughts are caused by precipitation stored as snow, whereas precipitation deficits and evapotranspiration losses cause summer droughts. Quesada-Montano *et al.* (2018) propose to use consistent definitions of flood and drought events based on the threshold level method. Then, a joint analysis of drought/flood durations, volumes and trends can be carried out.

Another set of drought indices is based on defining droughts as anomalies from the climatology, e.g. at a monthly time scale. One approach to analyse anomalies is to extend the threshold level approach explained above to a continuous seasonal variation in thresholds (Fleig *et al.* 2006b) Another approach is to use the standardized streamflow index (SSI), where the monthly streamflows are translated into a probability either by using empirical or parametric distributions (Tijdeman *et al.* 2020).

The difference between the traditional drought indices and the anomaly-based indices is discussed in Stahl *et al.* (2020). They state that the threshold-based approach more easily can be linked to low flow events, impacts on ecosystems and triggering of management actions, whereas the anomaly-based approach more frequently is used for monitoring. They demonstrate that the severity of specific drought events depends on the drought definition and points out that the anomaly-based indices are increasingly used and that a more systematic comparison is needed.

Statistical modelling of droughts

Statistical modelling of extreme droughts follows similar procedures as extreme value modelling of floods. Both annual maximum droughts and POT (e.g. Engeland *et al.* 2004) are used. Engeland *et al.* (2004) show that using the maxima from block sizes of 2 years might be useful, if there are many years with minor droughts. Also, for the POT method, minor droughts and a few major droughts might cause problems when fitting a distribution. Kjeldsen *et al.* (2000) and Hisdal *et al.* (2002) show that applying a threshold to remove minor droughts from the POT dataset is useful. In Clausen & Pearson (1997), annual maximum deficit volumes were used to assess the exceedance probability of a drought event in New Zealand in 1993/4. Gottschalk & Perzyna (1989, 1993) and Pacheco *et al.* (2006) incorporate streamflow recession characteristics to improve local fits of probability functions to low flows and show that in particular the length of the dry spells is a key factor to define homogeneous regions.

For predicting droughts of long return periods, the standard extreme value distributions like the GEV, Gumbel, generalized logistic (GL), GP, exponential, log Pearson type II and gamma distributions are used. The Tweedie distribution is also suggested as a distribution to use for drought indices (Stagge *et al.* 2015).

Both Clausen & Pearson (1997) and Kjeldsen *et al.* (1999) apply the index-flood approach for regional modelling of droughts. Clausen & Pearson (1997) analyse annual maximum droughts for New Zealand, and they show that a baseflow index is a key covariate for predicting the mean annual drought deficit volume in ungauged catchments. Kjeldsen *et al.* (1999) apply regional peak over threshold approach with a two-component exponential distribution in Zimbabwe, where L-moment diagrams are used to identify homogeneous regions. In Tallaksen & Hisdal (1997), the catchment-specific weight coefficients of empirical orthogonal functions (EOFs) are used to define homogeneous regions.

Gottschalk & Perzyna (1993) interpolate low flow distribution along a river by interpolating the recession characteristics, and in Pacheco *et al.* (2006) these interpolated distributions are used to regionalize low flow statistics in Costa Rica. Yu *et al.* (2014) further develop this approach by accounting for dependencies between the recession parameters and dry spell durations in the derived distributions.

Drought modelling by severity–area–frequency curves is developed in Hisdal & Tallaksen (2003). The model establishes the probabilities of an area to experience a severe drought. Due to limited amount of data, a simulation-based approach is used to establish these curves. Such approach is useful for water resource management, where droughts are handled at a regional level.

Trends in droughts

Several research papers are motivated by detecting trends in droughts. Hisdal *et al.* (2001) study trends in droughts all over Europe using both annual maximum and peak over threshold data. The Mann–Kendall test is used to assess the significance. They find some trends within the period 1962–1990. Increasing drought-deficit volumes were found in Spain, the eastern part of Eastern Europe and large parts of the UK, whereas decreasing drought deficit volumes occurred in large parts of Central Europe and the western part of Eastern Europe. Changes in precipitation or artificial influences might explain these trends. Wilson *et al.* (2010) find a tendency towards large water deficit in south-eastern Norway. Yu *et al.* (2018) used PUT data to analyse non-stationarities in the Loess Plateau in China and found that non-stationarities are caused by changes in recession duration and can be linked to changes in land use, particularly check dams, forest cover and grass land cover.

ASSESSMENT OF RAINFALL EXTREMES

Extreme rainfall can be viewed in terms of virtually all scales in time and space. We can talk about an extremely high 1-min intensity as well as an extremely wet year; we can talk about an extreme rainfall observed in a specific point as well as over a 50,000 km^2 area. Generally, when considering extreme rainfall in a societal context, e.g. for infrastructural design, the focus is on short-duration extremes, at sub-daily time scales, within a small, local area, where a single rainfall gauge adequately represents that. This is the focus of the following review, although daily and areal extremes are also covered to some extent.

Local, sub-daily rainfall extremes are best observed using rainfall gauges with a short time step, generally a tipping-bucket or weighing type gauge. Examples of single gauges that have been operational for many decades, up to a century, exist in all Nordic countries. In terms of national sub-daily observations, the main Nordic networks are described in Table 1.

An additional key source of high-resolution rainfall is weather radar, which has a high resolution in time and space. Through the BALTRAD initiative, composites with near-full coverage of the study domain are generated at resolutions 15 min and 2 km × 2 km from a network of C-band radars since the early 2000 s (Michelson *et al.* 2000). However, radar-observed rainfall is affected by a range of uncertainty sources limiting the space–time accuracy, especially of high intensities (e.g. Schleiss *et al.* 2020). Besides C-band radars, Denmark furthermore has a network of X-band radars with even higher-resolution, and single X-band radars also exist in Finland and Sweden (e.g. Thorndahl & Rasmussen 2012). New opportunities for high-resolution rainfall observation include attenuation in commercial microwave link networks (e.g. van de Beek *et al.* 2020) and private weather stations online (citizen science).

In a hydrological engineering context, the observations are commonly processed to estimate IDF (or depth–duration–frequency; DDF) statistics. IDF statistics provide the rainfall intensity or depth associated with a specific combination of duration (i.e. accumulation period) and frequency (i.e. return period). The estimation typically includes the following steps: (1) extraction of extreme values from a time series, either AM or PDS (a.k.a. POT); (2) fitting of a theoretical frequency distribution, typically GEV to AM values or GP to PDS values and (3) fit a generalized equation that estimates intensity or depth as a function of duration and return period. Also, high percentiles of empirical frequency distributions from rainfall observations are sometimes used to quantify extremes, e.g. in climate analyses.

Pioneering work in the field of rainfall extremes include Rosbjerg (1977a), who investigated event arrival assuming a Poisson process and established relations between return periods based on AM and PDS, respectively. In Sweden, Dahlström (1979) proposed a national model for sub-daily return levels with dependence on summer mean temperature and total precipitation. In the city of Lund, Sweden, a network of 12 tipping-bucket gauges was established and was operational from 1979 to 1981. The observations were used to characterize small-scale dynamic and aerial rainfall properties (Bengtsson & Niemczynowicz 1986). A key concept in rainfall extremes is Probable Maximum Precipitation (PMP), i.e. the greatest depth of precipitation for a given duration meteorologically possible for a design watershed or a given storm area at a particular location at a particular time of year, with no allowance made for long-term climatic trends (WMO 2009). Førland & Kristoffersen (1989) applied PMP in Norway using both meteorological and statistical methods.

Since the mid-1990s, when ~15 years of observations from the national gauge network were available, substantial and significant research and development with respect to short-duration extremes have been performed in Denmark. Arnbjerg-Nielsen *et al.* (1994) derived IDF and DDF statistics, including uncertainty, and investigated differences between the used 56 stations as well. Another statistical analysis of Danish data, including geographical variations, was performed by Harremoës & Mikkelsen (1995) as the first in a three-part paper sequence. In the second part, the uncertainty in IDF statistics was divided into sampling variability and regional variability, where the latter was found to be statistically significant

Table 1 | Rain gauge networks with short time steps in the Nordic countries

Country	Number of gauges	Time step	Operated since	Operator
Denmark	109[a]	1 min	1979	DMI/SVK
Finland	108[b]	10 min	2001	FMI
Norway	74[a]/60[b]	1 min/10 min	1968/1994	MET Norway
Sweden	130[b]	15 min	1995/96	SMHI

[a]Tipping bucket gauges.
[b]Weighing gauges.

(Mikkelsen *et al.* 1995). In the final third part of the paper, a method for estimating the spatial inter-site correlation structure was developed and applied (Mikkelsen *et al.* 1996). The evidence of spatial variability found in these studies spawned several further investigations focusing on regionalization, see the section *Regionalization* for key papers in this effort.

A fair number of studies have focused on properties of the methods used in IDF analysis, including parameter values and estimation methods. (Madsen *et al.* 1997a) performed a theoretical study to identify the optimal combination of IDF/DDF-approach (AM/GEV and PDS/GP) and parameter estimation method (maximum likelihood, moments and probability weighted moments). The optimal combination was found to depend on the shape parameter. Ragulina & Reitan (2017) compared GEV shape parameters for daily time series in Norway with estimates for other international regions. In another international (global) study of daily observations, PCA was used to develop and evaluate a relationship between wet-day mean precipitation and high percentiles, e.g. 95% (Benestad *et al.* 2012).

As demonstrated above, the Fennoscandian countries apply different methods to establish national IDF statistics. The latest available estimates for present climate are seen in Table 2.

IFD curves are typically used in design of urban drainage systems. Traditionally, this has been done on a regulatory basis by requesting certain *T*-year design values depending on construction type. Alternative design methods using economic optimality have recently attracted more attention (e.g. Rosbjerg 2017).

Regionalization

Locally estimated IDF statistics based on observations from one single gauge will inevitably become highly uncertain. More data, and thus less uncertainty, can be included by pooling observations from nearby gauges according to the station-year method (e.g. Buishand 1991). However, the extremes will be statistically different at some distance depending on differences in the rainfall regime caused by, e.g. temperature and topography. Therefore, many investigations have focused on developing methods for estimating IDF statistics at a given location, even if ungauged.

As previously mentioned, a lot of work on regionalization has been performed in Denmark. Madsen *et al.* (1994) concluded that spatial homogeneity could not be justified and used the Bayesian theory to perform regional PDS modelling with both exponential and generalized Pareto distributions. The approach was shown to significantly reduce uncertainties as compared with using at-site data (Madsen *et al.* 1995). In Madsen *et al.* (1998), least-squares regression related PDS model parameters to climatic and physiographic characteristics. A clear dependence on mean annual rainfall was found as well as a metropolitan effect in the Copenhagen area. The approach was further developed and evaluated in Madsen *et al.* (2002). Gregersen *et al.* (2013a, 2017) used generalized linear modelling to assess the value of spatial and temporal explanatory variables for the IDF estimation and found mean summer temperature and precipitation particularly useful. Recently, non-stationarity has been introduced in the regionalization for Denmark due to indications of increasing extremes (Arnbjerg-Nielsen 2006). Gregersen *et al.* (2017) extended the method of Gregersen *et al.* (2013a) to allow for non-stationarity also considering more parameters. Madsen *et al.* (2017) related PDS parameters to daily gridded rainfall statistics, including non-stationarity as an additional source of uncertainty.

In Norway, Dyrrdal *et al.* (2015) used a Bayesian hierarchical model to characterize the spatial variation of hourly precipitation extremes including uncertainty. A range of physiographical and climatic covariates was used to estimate GEV parameters based on generalized linear modelling. For estimation of sub-daily rainfall, Førland & Dyrrdal (2018a) divided Norway into seven regions. Olsson *et al.* (2019) performed a clustering of locally estimated GEV parameters to divide Sweden into four regions. For each region, DDF statistics including uncertainty were estimated by the station-year

Table 2 | Available IDF statistics in the Nordic countries

Country	Information	References
Denmark	IDF curves for 2-, 10- and 100-year events and maps of 2- and 100-year return levels for durations of 1 and 24 h	Madsen *et al.* (2017)
Finland	IDF statistics on return levels for durations 6 h–1 month; interactive graph for IDF values of durations 5–60 min	Aaltonen *et al.* (2008), FMI (2021)
Norway	IDF statistics for arbitrary locations	NCCS (2021)
Sweden	IDF statistics for sub-daily rainfalls	SMHI (2021)

method. The regionalization of Swedish DDF statistics by Dahlström (1979), based on summer temperature and precipitation as covariates, has been further developed into an updated, generalized model and applied to other European countries as well (Svensson *et al.* 2020; Dahlström 2021). Recently, a consistent GEV analysis of sub-daily rainfall extremes in the Nordic–Baltic region was made by Olsson *et al.* (2022). Interpolated $1° \times 1°$ fields with estimated depths for selected return periods and durations were produced and made public in open access.

Fractals and scale invariance

The fractal theory contains a concept of self-similarity or scale invariance that proved useful in, for example, analysis of rainfall extremes. One key manifestation of this concept is power laws, i.e. statistical log-log linearity. In this context, a well-known power law is Jennings' scaling law of global rainfall maximum depths vs. duration (Jennings 1950; WMO 1994).

Olsson *et al.* (1993) investigated 1-min observations from Lund, Sweden, and found evidence of scale invariance (or scaling). The scaling properties were dependent on intensity level (i.e. multiscaling or multifractal) as well as aggregation time scale interval. Daily observations in two contrasting climates, monsoon (China) and temperate (Sweden) were analysed by Svensson *et al.* (1996). A multifractal behaviour was found with properties depending on both time scale, climate and rainfall-generating mechanism.

Multifractal statistical properties imply that the process can be described by a random cascade model, which can be viewed as a gradual zoom-in to higher resolutions (in time or space) with associated redistribution of the considered quantity (rainfall depth, in this case). Olsson (1998) developed a random cascade model for temporal rainfall disaggregation, where redistribution parameters are dependent on rainfall volume and position in the rainfall sequence. In Güntner *et al.* (2001), the model was evaluated in two different climates (UK, Brazil) with particular focus on extremes as well as parameter transferability in time and space. The model has later been further developed and used for various applications related to extreme rainfall, e.g. soil erosion (Jebari *et al.* 2012).

Areal extremes

Despite their obvious importance for society, areal rainfall extremes have so far received rather limited attention in the study domain. This is probably related to limited availability of appropriate empirical data, i.e. observations with a high spatial resolution (e.g. a dense gauge network) and accurate intensity. Improved accuracy in radar-based rainfall products is expected to spawn more investigations and development focusing on areal extremes from now on.

A concept relating point-scale to areal extremes is areal reduction factors (ARFs), where a point-scale intensity is reduced to estimate the associated mean intensity within a surrounding area (e.g. review by Svensson & Jones 2010). Bengtsson & Niemczynowicz (1986) estimated ARFs using 1-min observations from 12 gauges in Lund, Sweden in a small-scale investigation. Recently, Thorndahl *et al.* (2019) estimated storm-centred ARFs from Denmark's 15 years of radar data. A generic relationship was developed between ARF, duration (1 min–1 day) and area (0.1–100 km^2).

In Norway, estimation of larger-scale, daily areal extremes has been the focus. Førland & Kristoffersen (1989) applied the growth-factor method (NERC 1975) to characterize large-scale extreme events in catchments up to 5,250 km^2. Skaugen *et al.* (1996) developed a method to simulate areal extremes by means of fractionally divided rainy areas in catchments up to 48,000 km^2. Dyrrdal *et al.* (2016) used the GEV distribution to describe areal extremes from a gridded 1 km × 1 km dataset of daily precipitation. The GEV shape parameter was found to depend on the precipitation-generating mechanism.

Atmospheric circulation

A category of investigations has focused on identifying and analysing relationships between rainfall extremes and the large-scale atmospheric circulation, often represented by climatic patterns or indices. These efforts aim to understand the physical causes and large-scale spatial dynamics behind the extremes, including analyses of temporal variability and trends, which are relevant for assessing climate variability and change.

Hellström (2005) related extreme and non-extreme daily precipitation in Sweden to weather types as well as atmospheric variables. Extremes were found to be associated with the cyclonic weather type as well as higher vertical velocity and specific humidity. Gustafsson *et al.* (2010) analysed moisture trajectories associated with summer extremes in Sweden and concluded that Europe and the Baltic act as important source regions. Azad & Sorteberg (2017) investigated moisture fluxes over the North Atlantic Ocean in connection with extreme precipitation events at the Norwegian west coast. Almost all events proved to be generated by atmospheric rivers, i.e. narrow plumes of intense high-level moisture.

In some investigations, climatic teleconnection patterns have been used for establishing links to rainfall extremes. The East Atlantic (EA) pattern was found to be a significant explanatory variable in the model of Gregersen *et al.* (2015) for short-duration extremes in Denmark. Irannezhad *et al.* (2017) investigated spatio-temporal changes in a suite of precipitation indices in Finland during 1961–2011 as well as their relation to teleconnection patterns. Significant correlations to several patterns were found, including EA, Scandinavia and Polar patterns. Marshall *et al.* (2020) studied the spatio-temporal variability of precipitation extremes in Artic Fennoscandia during 1968–2017. In addition, distinct relationships with several teleconnection patterns were evident, with both seasonal and geographical dependencies.

STOCHASTIC APPROACHES TO WRM

Hydrosystems are typically designed and operated based on the stochastic nature of triggering water cycle components. Therefore, different aspects of WRM, such as water supply and demands, groundwater issues or coping with extreme events, must be treated stochastically for making a sustainable decision (Smith 1973). In addition to the stochastic nature of hydrologic elements, a complex network of demands, supplies and stakeholders, which involves economic and social factors, leads to stochastic approaches capable of considering uncertainties germane to each component (Dralle *et al.* 2017). In this section, we briefly review some of the studies that have utilized stochastic methods to solve different issues in WRM. The studies are classified into five main WRM categories of (i) water supply, allocation and demand; (ii) droughts and floods; (iii) reservoirs and hydropower plants; (iv) groundwater management and (v) risk assessment and data assimilation (DA).

Water supply, allocation and demand

Water distribution between different beneficiaries is a challenging task in WRM due to the stochastic features of available resources and uncertainties of users' demand (Gaivoronski *et al.* 2012b). The problem gets more complicated in arid and semi-arid regions suffering from water scarcity. Several stochastic methods have been used to tackle water supply, allocation and demand problems. The associated research relies on both classic and data-driven techniques and covers different issues from both quantitative and qualitative perspectives.

From a quantitative point of view, Knudsen & Rosbjerg (1977) demonstrated that the general dynamic programming could be utilized for optimal scheduling of water supply considering the cost of operation. Selek *et al.* (2013) applied a consecutive high dimensional stochastic non-linear mixed-integer method to assess water distribution systems under water-demand uncertainties and develop an optimal control policy. Sveinsson (2014) showed that stochastic synthetic time series could be beneficial to estimate an irrigation system's performance under uncertainties of water deliveries. The author also highlighted the potential use of stochastics models for water supply and demand forecasting. Sechi *et al.* (2019) implemented the stochastic quasi-gradient optimization technique to optimize multi-user and multi-reservoirs in water supply systems and develop a robust pumping decision strategy in water supply systems. Most recently, Golmohamadi & Asadi (2020) suggested a multi-stage stochastic approach to schedule a time-oriented agricultural demand. Hatsey & Birkie (2020) showed that failure in pumping systems could be simulated via stochastic models.

Water quality has always been a targeted concern in WRM. Access to high-quality water is vital for human health and is an essential component of sustainable social and economic development and the protection of the environment. The WRM literature has witnessed several stochastic approaches to solve water quality issues. Some examples include the use of (i) stochastic data-driven models, such as artificial neural network, support vector machine and decision tree-based models to predict the concentration of phosphate (Latif *et al.* 2021), (ii) stochastic model predictive control to optimize the energy-demanding aeration process for nitrogen removal (Stentoft *et al.* 2019), (iii) stochastic mobility model to monitor contamination in water distribution networks (Du *et al.* 2016) and (iv) stochastic failure process to assess the aggregated risk of multiple contaminant hazards in groundwater wells (Enzenhoefer *et al.* 2015).

Management of droughts

Droughts and floods are of paramount importance stochastic natural events that can be considered benchmarks for WRM (Van Loon *et al.* 2016; Quesada-Montano *et al.* 2018). These events may significantly affect the quality and quantity of water resources and pose a great challenge for WRM in many regions. The relevant literature shows different approaches implemented to forecast, monitor and alleviate their negative impacts. Regarding groundwater vulnerability, Amundsen & Jensen (2019) considered drought events as a stochastic threat and showed that an increase in the probability of drought might yield counteracting effects. The authors recommended a drought-based policy for optimal groundwater extraction and thus dynamic groundwater management. Brunner & Tallaksen (2019) conducted a ground-breaking study on the probability of multi-year droughts across Europe. The authors demonstrated that the proneness of European catchments to droughts could be realized by applying phase randomization and a flexible four-parameter kappa distribution in the stochastic simulation of historical streamflow records. It is worth mentioning that statistical justification for persistent droughts is often tricky in typical stochastic approaches. This can result in a dramatically underestimated risk of failure when forecasting the reliability of reservoirs. The Hurst phenomenon offers a consistent basis to remedy this. The Hurst coefficient and Monte Carlo simulation can be used to quantify the amount of persistence in a time series for reservoir operation (Cox *et al.* 2006). Similarly, stochastic regression models and spectral analysis were also suggested to simulate teleconnections between large-scale atmospheric circulation patterns and catchment hydrology to predict extreme weather events (Räsänen & Kummu 2013).

Reservoirs and hydropower plants

Energy and water resources are strongly tied; energy is necessary to deliver water, and water is required to generate energy (Pereira-Cardenal *et al.* 2016). Both amounts of water and the associated generated energy in hydropower deal with the stochastic behaviour of key hydrological variables, such as precipitation, streamflow and groundwater (Li *et al.* 2019). Therefore, standalone stochastic methods and, in some cases, their hybridized version with optimization techniques, such as stochastic dynamic programming (SDP), water value method and stochastic time series modelling, have been frequently applied to optimal design and operation of reservoirs (e.g. Sveinsson 2014; Davidsen *et al.* 2015a; Pereira-Cardenal *et al.* 2015). For instance, Pereira-Cardenal *et al.* (2015) applied the water value method and power market models through SDP to minimize the cost of hydropower and maximize irrigation profit. In another study, Pereira-Cardenal *et al.* (2016) demonstrated that SDP could also be used to attain optimum water allocation by considering the inflow, reservoir capacity, hydropower generation and irrigation. Bauer-Gottwein *et al.* (2016) showed that SDP could be applied to solve multi-objective optimization problems in reservoir systems. The SDP combined with the hybrid linear programming optimization technique was applied for cost-optimal water quantity and quality management and water allocation. Reservoir releases, groundwater pumping, wastewater treatments and water curtailments have been considered by Davidsen *et al.* (2015b). In a more recent study, SDP was utilized to estimate the value of water and, therefore, simulate and forecast hydropower generation (Pérez-Díaz *et al.* 2020). Hydrological and meteorological forecasting could support reservoir operation for drought management, flood warning and water allocation (Gelati *et al.* 2011; Acharya *et al.* 2020). Optimization techniques (e.g. the shuffled complex evolution (SCE) algorithm) can be applied for reservoir operation (Le Ngo *et al.* 2007, 2008). A Bayesian probabilistic forecasting model was used to assess the uncertainty of the flood limiting water level control for reservoir operation in real-time dynamic (Liu *et al.* 2015). A compound model has been applied to optimize the reservoir rule curve; for this purpose, a simulation was coupled with a genetic algorithm and inner linear programming (Taghian *et al.* 2014).

Regarding stochastic time series models, several studies are available in the literature. For example, a Markov-switching model using exogenous inputs and autoregressive models was applied to forecast monthly inflow to perform stochastic optimization of reservoir release (Gelati *et al.* 2011). Grey-box is another robust stochastic modelling technique used for runoff prediction and quantification of the associated uncertainties in urban drainage systems (Löwe *et al.* 2013). In case of a shortage of historical measurements, generation of high-resolution stochastic time series of key hydrological variables was recommended by Sveinsson (2014). The author showed that synthetic but high-resolution time series could be used to assess the probability distribution of the variables and predict short-term operation rules and hydropower generation, which are crucial for securing WRM. The climate change impacts on these time series were also considered in recent studies (Pereira-Cardenal *et al.* 2014; Sørup *et al.* 2017). Sechi *et al.* (2019) used the stochastic quasi-gradient method to optimize and simulate a pumping system's often conflicting water deficit and energy consumption.

Groundwater management

Groundwater resources constitute nearly 30% of the Earth's fresh water and are critical to supporting aquifers' long-term viability and protecting their nearby surface waters. Likewise, surface and atmospheric water resources, several studies have used stochastic methods to cope with quantitative and qualitative groundwater management issues. Examples include (but are not limited to) the use of (i) a risk-cost minimization model based on groundwater value to develop a decision support system and find alternatives in order to reduce the contamination in drinking water (Rosén *et al.* 1998), (ii) a discrete-time stochastic model to tackle the problem of managing groundwater under random recharge in a single-cell aquifer (Krishnamurthy 2017), (iii) a meta-analytical method based on a stochastic simulation of water/solute transport to assess the impact of land use change on groundwater quality and (iv) applying multi-objective optimization for well field management and operation (Dorini *et al.* 2012; Hansen *et al.* 2012, 2013).

Risk assessment

The complicated interaction between different risk-related mechanisms in WRM cannot be easily modelled to characterize the system response under different risk control settings. Flood management is usually addressed from a risk viewpoint to quantify the hazard and depth of inundation and to consider the susceptibility to flooding (Oliver *et al.* 2019; Andaryani *et al.* 2021; Darabi *et al.* 2021). Various stochastics techniques have been used to assess the risk in WRM and related concerns, particularly for extreme events during floods and droughts. For example, Jonsdottir *et al.* (2005) applied a stochastic simulation model to produce synthetic runoff records with an acceptable length that can be used to estimate occasional droughts and associated risk. Gaivoronski *et al.* (2012a) showed that coupled cost optimization and risk management models could support the water resources manager to minimize the risk of wrong decisions in WRM. Furthermore, the resilience of the water resources system can be assessed through stochastic programming (Najafi *et al.* 2020).

Data assimilation

DA is a powerful tool for WRM by contributing to real-time hydrological modelling and forecasting (Vrugt *et al.* 2006; Ridler *et al.* 2014a; He *et al.* 2019). The most commonly used approach in DA is the ensemble Kalman filter (EnKF) that has been widely applied for different purposes, such as the interaction of groundwater and surface water (He *et al.* 2019), integrated hydrological modelling (Rasmussen *et al.* 2015; Zhang *et al.* 2015; Ridler *et al.* 2018), reservoir water level measurement (Pereira-Cardenal *et al.* 2011), modelling of river hydrodynamics (Schneider *et al.* 2018), flood forecasting (Butts *et al.* 2007), groundwater modelling (Drécourt *et al.* 2006), soil moisture and groundwater interaction (Zhang *et al.* 2016), risk assessment (Borup *et al.* 2015) and downscaling satellite soil moisture (Ridler *et al.* 2014b) and forecasting flows and overflows in urban drainage systems (Lund *et al.* 2019).

APPROACHES TO CLIMATE CHANGE AND ADAPTATION EFFORTS

IPCC (2021) states that the frequency and intensity of heavy precipitation events have increased over a majority of land regions with good observational coverage since 1950, and that the increase in frequency and intensity will continue under future global warming.

Historic trends in heavy rainfall

Evidence that extreme rainfall intensity is increasing at the global scale has strengthened considerably in recent years (Westra *et al.* 2014). Myhre *et al.* (2019) concluded that increase in the frequency of heavy rainfall events is the main reason for an increase in total precipitation, and that the increase of intensity is less significant. For Europe and the USA, Benestad *et al.* (2019), however, found positive trends in rain intensity over the period 1961–2020 at most locations with observation series longer than 50 years.

Daily rainfall

For Northern and Central Europe, a high number of studies have detected changes in heavy daily rainfall, all adding to the debate on anthropogenic climate change and its potential impact on rainfall extremes (Gregersen *et al.* 2015). For most parts of Finland, Irannezhad *et al.* (2017) indicated significant increases in the frequency and intensity of precipitation extremes during 1961–2011. Sorteberg *et al.* (2018) found mainly positive trends for Norway, when studying changes in the highest measured daily precipitation for the summer season during 1968–2017. Over the Nordic–Baltic region (Finland, Sweden, Norway, Denmark, Estonia, Latvia and Lithuania), Dyrrdal *et al.* (2021) found that for a majority of stations, there had been a statistically significant increase in the intensity of annual maximum 1-day precipitation during the last 50 years, and also for a majority of the long-term stations (from 1901 to till date). Their results also indicated that the annual maximum 1-day precipitation events now occur somewhat later in the year compared to the beginning of the last century.

In addition to the general observed increase in heavy rainfall, it is also important to understand natural variations imposed on the past (and future) changes in heavy rainfall. In an analysis of return periods, Heino *et al.* (1999) found that there were high frequencies of 'extraordinary' 1-day rainfalls in the Nordic countries in the 1930s and later in the 1980s. Based on smoothed series of daily rainfall extremes from Denmark and southern Sweden, Gregersen *et al.* (2015) 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. The magnitude of the extreme events also oscillates, but with a cycle of 15–30 years and with a smaller amplitude. Similarly, Førland & Dyrrdal (2018a) demonstrated that the positive trend in maximum 1-day rainfall is not monotonic; i.e. decadal variability is superposed on the long-term trend. The long-term centennial variability of heavy 1-day rainfall reveals high values in the 1930s and low values in the 1960 and 1970s. In addition, for the Nordic-Baltic region Dyrrdal *et al.* (2021) found that smoothed series of annual 1-day rainfall maxima have a cyclic development.

Willems *et al.* (2012) stated that trend testing has to account for temporal clustering of rainfall extremes. Thus, it is likely that the present high level of heavy rainfall events will be followed by decades with lower values (Førland & Dyrrdal 2018a). Consequently, rainfall design-estimates based on observations from the most recent decade(s) may tend to be biased compared to estimates for 30-year reference periods, e.g. 1971–2000.

Sub-daily rainfall

Arnbjerg-Nielsen (2006) studied 41 Danish sub-daily rainfall series with an observation period close to 20 years. A statistically significant trend was found for the 10-min maximum intensity towards more extreme and more frequently occurring rainstorms. For the 6-h maximum intensity and total event volume the trends were less pronounced. The findings were confirmed by comparison to physically based climate models and studies based on large regions.

A comparison of the two periods 1979–1997 and 1997–2005 showed a general increase in extreme rainfall characteristics for Denmark (Madsen *et al.* 2009). For the durations of 30 min to 3 h and return periods in the order of 10 years being typical for most urban drainage designs, the increase in intensity is in the order of 10%. The analysis revealed that the changes are not statistically significant compared with the uncertainties of the regional estimation model, but the increases in design intensities were large and may have significant consequences to the costs of engineering designs.

For Norway, Førland & Dyrrdal (2018b) concluded that during the last 50 years the frequency and intensity of sub-daily rainfall have increased at a majority of the measuring sites. This positive trend also affects rainfall design values using IDF estimates.

Modelling future local heavy rainfall

Global climate models (GCMs) are the most comprehensive and widely used models for simulating the response of the global climate system to large-scale changes in greenhouse gas emissions. GCMs are not designed to represent local precipitation statistics, but their ability to simulate large-scale features can be utilized to infer local precipitation changes through downscaling (Benestad *et al.* 2008; Benestad 2010; Olsson *et al.* 2015; Sunyer *et al.* 2015a, 2015b). There are two main approaches for downscaling GCM simulation: (1) dynamical downscaling (regional climate models), and (2) empirical-statistical downscaling (ESD).

Dynamical downscaling

Dynamical downscaling involves running an area-limited high-resolution regional climate model (RCM) with large-scale variables from a GCM as boundary conditions. The RCMs tend to be expensive to run and may not provide realistic local conditions at small spatial scales (Benestad & Haugen 2007). Several analyses have applied RCMs to study precipitation extremes. Olsson *et al.* (2012a) outlined a framework for downscaling precipitation from RCM projections to high resolutions in time and space required for urban hydrological climate change impact assessment. Their basic approach was use of the delta change approach, developed for both continuous and event-based applications. Benestad & Haugen (2007) used RCMs to study shifts in the frequency of complex extremes in Norway. Mayer *et al.* (2018) used the high-resolution EURO-CORDEX ensemble to estimate changes in future sub-daily rainfall in Norway by fitting the GEV distribution to annual maximum precipitation from the simulations. Both stationary and non-stationary methods were applied.

Empirical-statistical downscaling

In ESD, a wide range of models and approaches has been used, and this approach may be divided into several subcategories (Benestad *et al.* 2008): (a) linear models (e.g. regression or canonical correlation analysis), (b) non-linear models or (c) weather generators. The choice of ESD model type should depend on which climatic variable is downscaled, as different variables have different characteristics that make them more or less suitable in a given model. RCMs and ESD complement each other.

Benestad (2007) used ESD to establish (1) a relationship between coefficients in the frequency function of daily rainfall and (2) local projections of mean temperature and precipitation to infer changes in the 95th percentiles of future rainfall for 2050. In a later study, Benestad (2010) explored a new ESD-method for predicting the upper tail of the precipitation distribution. Skaugen *et al.* (2004) used time-slices of 20 years for 1-day precipitation for present and future climate as training data for a precipitation simulation model. This model was used to generate a time series of 1000 years to assess possible changes in the extreme precipitation regime due to climate change.

Sunyer *et al.* (2015a) explored three statistical downscaling approaches: A delta change method for extreme events, a weather generator (WG) combined with a disaggregation method and a climate analogue method. All three methods relied on different assumptions and used different outputs from the RCMs. The results of their study highlighted the need to use a range of statistical downscaling methods and RCMs to assess changes in extreme precipitation.

For Denmark, Sørup *et al.* (2016) modelled precipitation at 1 h temporal resolution on a 2-km grid using a WG. Precipitation time series used as input to the WG were obtained from a network of 60 tipping-bucket rain gauges irregularly placed in a 40 km × 60 km model domain. The WG simulated precipitation time series were comparable to the observation-based extreme precipitation statistics. The climate change signals from six different RCMs were used to perturb a WG. All perturbed WGs resulted in more extreme future precipitation at the sub-daily to multi-daily level, and these extremes exhibit a much more realistic spatial pattern than observed in RCM precipitation output. Overall, the WG produced robust results and is seen as a reliable procedure for downscaling RCM precipitation output for use in urban hydrology.

Climate model evaluation

RCMs and GCMs have shown severe problems with their sub-grid scale parameterizations of convective processes, which affect their ability to reproduce, for example, the diurnal cycle of rainfall intensity, the peak storm intensities and extreme hourly intensities. It is therefore questionable to which extent such RCMs are capable of describing short-duration extremes in the present and future climate (Berg *et al.* 2019). Westra *et al.* (2014) stated that present-day GCMs have limited ability to simulate sub-daily precipitation extremes correctly, as they do not explicitly resolve convective processes. This casts strong doubts on future projections of changes in sub-daily precipitation extremes derived from these models. However, the authors stressed that RCMs run at convection-permitting resolutions (CPRCMs) show promising improvements to key attributes of sub-daily rainfall.

Willems *et al.* (2012) made a critical review of methods for assessing climate change impacts on rainfall in urban areas and concluded that estimation of extreme, local and short-duration rainfall is highly uncertain. Downscaling results from GCMs or RCMs to urban catchment scales is needed because these models cannot accurately describe the rainfall process at suitable high temporal and spatial resolution for urban drainage studies. A review made by Arnbjerg-Nielsen *et al.* (2013) concluded that many limitations exist in our understanding of how to describe precipitation patterns in a changing climate for design and operation of urban drainage infrastructure

Gregersen *et al.* (2013b) compared temporal and spatial characteristics from three different high-resolution RCMs to sub-daily rainfall extremes estimated from observed data. All analysed RCM-derived rainfall extremes showed a clear deviation from the observed correlation structure for sub-daily rainfalls, partly because RCM output represents areal rainfall intensities and partly due to well-known inadequacies in the convective parameterization of RCMs. The paper takes the first step towards a methodology by which RCM performance and other downscaling methods can be assessed in relation to the simulation of short-duration rainfall extremes.

For Denmark, Sunyer *et al.* (2012) analysed five different statistical downscaling methods using results from four RCMs driven by different GCMs. Special focus was given to the changes of extreme events, since downscaling methods mainly differ in the way extreme events are generated. Sunyer *et al.* (2013) used both gauge data and gridded data to rank different RCMs according to their performance using two different metrics. A set of indices ranging from mean to extreme precipitation properties was calculated for all the data sets. The papers by Sunyer *et al.* (2012, 2013) highlighted the need to be aware of the properties of observational data chosen in order to avoid overconfident and misleading conclusions with respect to climate model performance, and to acknowledge the limitations and advantages of different statistical downscaling methods as well as the uncertainties in downscaling climate change projections for use in hydrological models.

Berg *et al.* (2019) evaluated summertime IDF-values of a subset of the EURO-CORDEX 0.11 ensemble against observations for several European countries for durations of 1–12 h. Most of the model simulations strongly underestimated 10-year rainfall depths for durations up to a few hours but performed better at longer durations. Projected changes were assessed by relating relative depth changes to mean temperature changes. A strong relationship with temperature was found across different sub-regions of Europe, emission scenarios and future time periods.

Olsson *et al.* (2012b) formulated and tested a stochastic model for downscaling short-term rainfall from RCM grid scale to local (i.e. point) scale using data from Stockholm, Sweden. The results suggested that the model might effectively reproduce observed IDF curves. Olsson *et al.* (2015) explored to what degree sub-hourly IDF statistics in an RCM converge to observed point statistics for Swedish stations, when gradually increasing the resolution from 50 to 6 km. At 50 km, the intensities were underestimated by 50–90%, but at 6 km they were nearly unbiased, when averaged over all locations and durations. In addition, the reproduction of short-term variability and less extreme maxima were overall improved with increasing resolution. At 6-km resolution, a parameterized RCM (RCA3) is in approximate agreement with hourly gauge observations in Sweden (Olsson *et al.* 2015). Recently, the first historical high-resolution (3 km × 3 km) CPRCM simulations over Fenno-Scandinavia have been made and analysed (Lind *et al.* 2020; Olsson *et al.* 2021). The results indicate a substantially improved representation of precipitation, compared with lower-resolution RCM simulation, in terms of both average properties (e.g. diurnal cycle) and extreme properties (e.g. IDF statistics). These results imply that we can anticipate a higher confidence in future precipitation changes estimated by CPRCM projections, which currently are being analysed.

Projections of future extreme precipitation

As temperatures increase, the atmosphere can hold more moisture and the potential for more frequent and intense rainfall is present. Most projections indicate that the greatest increases are likely to occur in short-duration storms lasting less than a day, potentially leading to an increase in the magnitude and frequency of flash floods (Westra *et al.* 2014). Thus, changes in extreme precipitation are expected to be one of the most important impacts of climate change in cities. Based on observations and climate models, Myhre *et al.* (2019) projected that on a global scale the most intense precipitation events observed today are likely to almost double in occurrence for each degree centigrade of further global warming. Changes to extreme precipitation of this magnitude are dramatically stronger than the more widely communicated changes to global mean precipitation.

For large parts of the Nordic countries, Benestad (2007, 2010) pointed towards an increase in the number of extreme precipitation events, except for the most extreme percentiles for which sampling fluctuations gave rise to high uncertainties. In projections for Denmark, Sunyer *et al.* (2012) found that three of the four studied RCMs showed an increase in extreme events in the future. The increases in extreme precipitation were higher for higher spatial resolutions and shorter temporal aggregations (Sunyer *et al.* 2013). In a later study, Sunyer *et al.* (2015a) assessed the changes and uncertainties in extreme precipitation at hourly scale over Denmark. The results of the three methods applied pointed towards an increase in extreme precipitation, but the magnitude of the change varied depending on the RCM used and the spatial location. In general, a similar mean change was obtained for the three methods.

For Sweden, Olsson *et al.* (2012b) concluded that the future increase of local-scale short-term rainfall extremes might be higher than the predicted increase of short-term extremes at the RCM grid scale. Olsson & Foster (2014) analysed extreme precipitation for durations between 30 min and 1 day in simulations with the RCA3-RCM for Sweden. The increase in extreme precipitation decreased with increasing duration, and at the daily scale, the percentage values are approximately halved.

For Norway, Hanssen-Bauer *et al.* (2017) found that events with heavy 1-day rainfall should be more intense and occur more frequently in all regions. By fitting the GEV distribution to annual maximum precipitation from the ensemble of EURO-CORDEX simulations, Mayer *et al.* (2018) found that also sub-daily extreme precipitation is projected to increase for most areas in Norway. The largest increase was found for higher return periods and shorter precipitation duration.

Cities are becoming increasingly vulnerable to flooding because of rapid urbanization, installation of complex infrastructure, and changes in the precipitation patterns caused by anthropogenic climate change (Willems *et al.* 2012). 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 (Arnbjerg-Nielsen *et al.* 2013). For urban floods, robust information on changes in extreme precipitation at high-temporal resolution is required to design climate change adaptation measures. Urban hydrological climate change impact assessment requires an assessment of how short-term local precipitation extremes, e.g. expressed as IDF statistics, are expected to change in the future.

Projections of future extreme precipitation are regularly updated. For the Fennoscandian countries the present recommended climate factors (change from present to future climate) are outlined in Table 3.

Table 3 | Recommended climate factors for IDF values up to year 2100

Country	Duration (h)	Return period (year)	Climate factor	References
Denmark	≤24	100	1.4	Spildevandskomitéen (2014)
Finland	≤24	All	1.2	Médus (2021)
Norway	≤1	100	1.5	Dyrrdal & Førland (2019)
	2–24		1.3–1.4	Dyrrdal & Førland (2019)
Sweden	≤24	All	1.2–1.4	Olsson *et al.* (2017)

Climate change impact on flooding

A last group of studies aims to predict the change in flood sizes in a future climate. A review of both modelling approaches and key findings is provided in Madsen *et al.* (2014). Most studies use a series of linked models and analyses. The basis is the climate change projections from a Global circulation model (GCM). The outputs from these models need downscaling using either or both RCMs and statistical downscaling to produce precipitation, temperature and other weather variables needed to run a hydrological model. The output from the hydrological models can then by analysed for a reference period and future periods to provide estimates of expected changes. There are many options at each of these steps (several GCMs combined with several RCMs combined with several statistical downscaling methods that again is combined with an ensemble of hydrological model or model parameters), resulting in an ensemble of projections. In Lawrence (2020), the uncertainty is attributed to each of these steps showing that the uncertainty in the statistical flood frequency analysis is of the same magnitude as the uncertainty originating from the different GCM/RCM combinations.

The output from the Nordic and Baltic studies shows that both increase and decrease in flood sizes can be expected. In Vormoor *et al.* (2014,) trends in seasonality and flood generating processes are analysed, demonstrating that a shift towards more rain floods is expected. In Lawrence (2020), it is shown that for Norway the expected change is linked to the flood generating processes, where a decrease in flood size can be expected in several inland catchments, where snow melt is the main flood generating process, whereas increase in flood sizes is expected in catchments where rain is the main flood generating process. Particularly in small catchments, an increase in flood sizes is expected (Tsegaw *et al.* 2020). Similar results are shown in Sweden (Bergström *et al.* 2012), Finland (Veijalainen *et al.* 2010) and the Baltic countries (Meilutytė-Barauskienė *et al.* 2010).

Climate change and droughts

When analysing climate change impact on droughts, a modelling chain that includes climate models, dynamical downscaling using a RCM, statistical downscaling and finally a hydrological model is used. In large-scale studies, the downscaling parts might be omitted. Expected changes in drought in Norway are analysed by Hisdal *et al.* (2006) and Wong *et al.* (2011) finding substantial increases in hydrological drought duration and drought affected areas in a future climate, especially in the southern and northernmost parts of the country. Reduced summer precipitation is a major factor that affects changes in drought characteristics in the south, while temperature increases play a more dominant role for the rest of the country. Chan *et al.* (2021) also finds increasing drought severity and frequency in Denmark in a future climate based on emission scenario RCP8.5. Samaniego *et al.* (2017) compare the uncertainty contribution from GCMs and hydrological models for projection of drought severity for continental catchments in a future climate. They show that the largest uncertainty contribution comes from the GCMs.

CONCLUSIONS

In the Nordic countries, the application of stochastic methods in hydrology was initiated in the 1970s and has been gradually growing since them. As seen in this review, Nordic contributions have been manifold, not just fulfilling local needs, but also playing an important role in the international arena. The stochastic methods have been essential for the development of modern hydrology. Today, Nordic researchers are breaking new avenues for development and application of methods to solve problems related to flooding, droughts, heavy precipitation, WRM, and climate change impacts on the water cycle.

We see some emerging trends in both the addressed problems and in the methods that are used. Some key trends we want to highlight are:

- *Non-stationarity*: At the beginning of the period, stationary approaches were completely dominant. However, gradually it has been recognized that we must also include climate variability and change in the analyses. This sets challenging demands and acts as a vehicle for the future development of stochastic hydrology.
- *Design*: New design criteria based social cost-benefit analyses and economic optimization should be developed to supplement traditional regulatory-based design.
- *Risk analysis*: There is an increasing demand from the society to address the risk related to WRM and extremes. New approaches are needed to connect hydrology to impacts and address the probability of adverse impacts.
- *Big data/crowd sourcing*: Automatic weather stations, radar mapping, smartphones and new measurement technologies, e.g. using satellites or drones, open up for new insights and approaches.
- *Machine learning*: Due to increasing computer power as well as new data sources, machine learning is becoming increasingly used for hydrological applications and statistical approaches can be seen as special cases of machine learning.

AUTHOR CONTRIBUTION

K.E. has acted as the main author of the section *Flood frequency and low flow analyses*, J.O. has acted as the main author of the section *Assessment of rainfall extremes*, A.D.M. and A.T.H. have acted as the main authors of the section *Stochastic approaches to WRM*, E.F. has acted as the main author of the section *Approaches to climate change and adaption efforts*, while D.R. has undertaken the overall coordination and editing of the paper.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

Aaltonen, J., Hohti, H., Jylhä, K., Karvonen, T., Kilpeläinen, T., Koistinen, J., Kotro, J., Kuitunen, T., Ollila, M., Parvio, A., Pulkkinen, S., Silander, J., Tiihonen, T., Tuomenvirta, H. & Vajda, A. 2008 Rankkasateet ja taajamatulvat (RATU) (Heavy precipitation and urban floods. *Finnish Environment Institute 31/2008*, p. 123. (In Finnish). Available from: https://helda.helsinki.fi/handle/10138/38381.

Acharya, S. C., Babel, M. S., Madsen, H., Sisomphon, P. & Shrestha, S. 2020 Comparison of different quantile regression methods to estimate predictive hydrological uncertainty in the Upper Chao Phraya River Basin, Thailand. *Journal of Flood Risk Management* **13** (1), e12585.

Amundsen, E. S. & Jensen, F. 2019 Groundwater management: waiting for a drought. *Natural Resource Modeling* **32** (4), e12209.

Andaryani, S., Nourani, V., Haghighi, A. T. & Keesstra, S. 2021 Integration of hard and soft supervised machine learning for flood susceptibility mapping. *Journal of Environmental Management* **291**, 112731.

Arnbjerg-Nielsen, K. 2006 Significant climate change of extreme rainfall in Denmark 10th International Conference on Urban Drainage. *Water Science and Technology* **54** (6–7), 1–8.

Arnbjerg-Nielsen, K., Harremoës, P. & Spliid, H. 1994 Non-parametric statistics on extreme rainfall. *Nordic Hydrology* **25** (4), 267–278.

Arnbjerg-Nielsen, K., Willems, P., Olsson, J., Beecham, S., Pathirana, A., Bülow Gregersen, I., Madsen, H. & Nguyen, V. T. 2013 Impacts of climate change on rainfall extremes and urban drainage systems: a review. *Water Science and Technology* **68** (1), 16–28.

Azad, R. & Sorteberg, A. 2017 Extreme daily precipitation in coastal western Norway and the link to atmospheric rivers. *Journal of Geophysical Research: Atmospheres* **122** (4), 2080–2095.

Bauer-Gottwein, P., Schneider, R. & Davidsen, C. 2016 Optimizing wellfield operation in a variable power price regime. *Groundwater* **54** (1), 92–103.

Benestad, R. E. 2007 Novel methods for inferring future changes in extreme rainfall over Northern Europe. *Climate Research* **34**, 195–210. doi:10.3354/cr00693.

Benestad, R. E. 2010 Downscaling precipitation extremes. *Theoretical and Applied Climatology* **100**, 1–21.

Benestad, R. E. & Haugen, J. E. 2007 On complex extremes: flood hazards and combined high spring-time precipitation and temperature in Norway. *Climatic Change* **85**, 381–406.

Benestad, R. E., Chen, D. & Hanssen-Bauer, I. 2008 *Empirical-Statistical Downscaling*. World Scientific Publishing Company, p. 228. https://doi.org/10.1142/6908.

Benestad, R. E., Nychka, D. & Mearns, L. O. 2012 Spatially and temporally consistent prediction of heavy precipitation from mean values. *Nature Climate Change* **2** (7), 544–547.

Benestad, R. E., Parding, K. M., Erlandsen, H. B. & Meghan, A. 2019 A simple equation to study changes in rainfall statistics. *Environmental Research Letters* **14**, 084017.

Bengtsson, L. & Niemczynowicz, J. 1986 Areal reduction factors from rain movement. *Hydrology Research* **17** (2), 65–82.

Berg, P., Christensen, O. B., Klehmet, K., Lenderink, G., Olsson, J., Teichmann, C. & Yang, W. 2019 Summertime precipitation extremes in a EURO-CORDEX 0.11° ensemble at an hourly resolution. *Natural Hazards and Earth System Sciences* **19**, 957–971. doi: 10.5194/nhess-19-957-2019.

Bergström, S., Harlin, J. & Lindström, G. 1992 Spillway design floods in Sweden: I. New guidelines. *Hydrological Sciences Journal* **37** (5), 505–519. doi:10.1080/02626669209492615.

Bergström, S., Andréasson, J., Veijalainen, N., Vehviläinen, B., Einarsson, B., Jónsson, S., Kurpniece, L., Kriaučiūnienė, J., Meilutyte ˙-Barauskiene ˙, D., Beldring, S., Lawrence, D. & Roald, L. 2012 Modelling climate change impacts on the hydropower system. In: *Climate Change and Energy Systems: Impacts, Risks and Adaptation in the Nordic and Baltic Countries, TemaNord2011:502* (Thorsteinsson, T. & Björnsson, H., eds). Nordic Council of Ministers, Copenhagen, pp. 113–146.

Bian, G., Du, J., Song, M., Zhang, X., Zhang, X., Li, R., Wu, S., Duan, Z. & Xu, C.-Y. 2020 Detection and attribution of flood responses to precipitation change and urbanization: a case sturj. *Hydrology Research* **51** (2), 351–365. doi:10.2166/nh.2020.063.

Blanchet, J., Touati, J., Lawrence, D., Garavaglia, F. & Paquet, E. 2015 Evaluation of a compound distribution based on weather pattern subsampling for extreme rainfall in Norway. *Natural Hazards and Earth System Sciences* **15**, 2653–2667. https://doi.org/10.5194/nhess-15-2653-2015.

Blöschl, G., Hall, J., Viglione, A., Perdigão, R. A. P., Parajka, J., Merz, B., Lun, D., Arheimer, B., Aronica, G. T., Bilibashi, A., Boháč, M., Bonacci, O., Borga, M., Čanjevac, I., Castellarin, A., Chirico, G. B., Claps, P., Frolova, N., Ganora, D., Gorbachova, L., Gül, A., Hannaford, J., Harrigan, S., Kireeva, M., Kiss, A., Kjeldsen, T. R., Kohnová, S., Koskela, J. J., Ledvinka, O., Macdonald, N., Mavrova-Guirguinova, M., Mediero, L., Merz, R., Molnar, P., Montanari, A., Murphy, C., Osuch, M., Ovcharuk, V., Radevski, I., Salinas, J. L., Sauquet, E., Šraj, M., Szolgay, J., Volpi, E., Wilson, D., Zaimi, K. & Živković, N. 2019 Changing climate both increases and decreases European river floods. *Nature* **573**, 108–111. https://doi.org/10.1038/s41586-019-1495-6.

Bøe, A.-G., Dahl, S. O., Lie, Ø. & Nesje, A. 2006 Holocene river floods in the upper Glomma catchment, southern Norway: a high-resolution multiproxy record from lacustrine sediments. *Holocene* **16** (3), 445–455. doi:10.1191/0959683606hl940rp.

Borup, M., Grum, M., Madsen, H. & Mikkelsen, P. S. 2015 A partial ensemble Kalman filtering approach to enable use of range limited observations. *Stochastic Environmental Research and Risk Assessment* **29** (1), 119–129.

Breinl, K., Lun, D., Müller-Thomy, H. & Blöschl, G. 2021 Understanding the relationship between rainfall and flood probabilities through combined intensity-duration-frequency analysis. *Journal of Hydrology* **602**. doi:10.1016/j.jhydrol.2021.126759.

Brunner, M. I. & Tallaksen, L. M. 2019 Proneness of European catchments to multiyear streamflow droughts. *Water Resources Research* **55** (11), 8881–8894.

Brunner, M. I., Seibert, J. & Favre, A.-C. 2016 Bivariate return periods and their importance for flood peak and volume estimation. *Wiley Interdisciplinary Reviews: Water* **3** (6), 819–833. doi:10.1002/wat2.1173.

Brunner, M. I., Sikorska, A. E. & Seibert, J. 2018a Bivariate analysis of floods in climate impact assessments. *Science of the Total Environment* **616–617**, 1392–1403. doi:10.1016/j.scitotenv.2017.10.176.

Brunner, M. I., Furrer, R., Sikorska, A. E., Viviroli, D., Seibert, J. & Favre, A.-C. 2018b Synthetic design hydrographs for ungauged catchments: a comparison of regionalization methods. *Stochastic Environmental Research and Risk Assessment* **32** (7), 1993–2023. doi:10.1007/s00477-018-1523-3.

Buishand, T. A. 1991 Extreme rainfall estimation by combining data from several sites. *Hydrological Sciences Journal* **36** (4), 345–365.

Butts, M., Falk, A. K. V., Xuan, Y. & Cluckie, I. D. 2007 Integrating meteorological and uncertainty information in flood forecasting: the FLOODRELIEF project. *IAHS Publication* **313**, 385–397.

Castellarin, A., Kohnová, S., Gaál, L., Fleig, A., Salinas, J. L., Toumazis, A., Kjeldsen, T. R. & Macdonald, N. 2012 *European Procedures for Flood Frequency Estimation: Review of Applied-Statistical Methods For Flood-Frequency Analysis in Europe*. NERC/Centre for Ecology and Hydrology, Lancaster, UK.

Chan, S. S., Seidenfaden, I. K., Jensen, K. H. & Sonnenborg, T. O. 2021 Climate change impacts and uncertainty on spatiotemporal variations of drought indices for an irrigated catchment. *Journal of Hydrology* **601**. doi:10.1016/j.jhydrol.2021.126814.

Chen, X., Zhang, L., Xu, C.-Y., Zhang, J. & Ye, C. 2013 Hydrological design of nonstationary flood extremes and durations in Wujiang river, South China: changing properties, causes, and impacts. *Mathematical Problems in Engineering*. doi:10.1155/2013/527461.

Chen, X., Ye, C., Zhang, J., Xu, C.-Y., Zhang, L. & Tang, Y. 2019 Selection of an optimal distribution curve for non-stationary flood series. *Atmosphere* **10** (1). doi:10.3390/atmos10010031.

Clausen, B. & Pearson, C. P. 1997 How extreme was the drought? *Nordic Hydrology* **28** (4–5), 297–306. doi: https://doi-org.ezproxy.uio.no/10.2166/nh.1998.23.

Cox, G., Smythe, C. & Koutsoyiannis, D. 2006 The Hurst phenomenon and Monte Carlo simulation to forecast reliability of an Australian reservoir. In *Proceedings of the 30th Hydrology and Water Resources Symposium*, Launceston, Australia. doi:10.13140/RG.2.1.2517.2721.

Dahlke, H. E., Lyon, S. W., Stedinger, J. R., Rosqvist, G. & Jansson, P. 2012 Contrasting trends in floods for two sub-Arctic catchments in northern Sweden – does glacier presence matter? *Hydrology and Earth System Sciences* **16** (7), 2123–2141. doi:10.5194/hess-16-2123-2012.

Dahlström, B. 1979 Regional Fördelning av Nederbördsintensitet – en Klimatologisk Analys (Regional Distribution of Precipitation Intensity – A Climatological Analysis), Report R18:1979, BRF, Stockholm, Sweden.

Dahlström, B. 2021 Cloud physical and climatological factors for the determination of rain intensity. *Water* **13** (16), 2292. doi:10.3390/w13162292.

Darabi, H., Rahmati, O., Naghibi, S. A., Mohammadi, F., Ahmadisharaf, E., Kalantari, Z., Torabi Haghighi, A., Soleimanpour, S. M., Tiefenbacher, J. P. & Tien Bui, D. 2021 Development of a novel hybrid multi-boosting neural network model for spatial prediction of urban flood. *Geocarto International*, 1–27. doi: 10.1080/10106049.2021.1920629.

Davidsen, C., Liu, S., Mo, X., Holm, P. E., Trapp, S., Rosbjerg, D. & Bauer-Gottwein, P. 2015a Hydroeconomic optimization of reservoir management under downstream water quality constraints. *Journal of Hydrology* **529**, 1679–1689.

Davidsen, C., Pereira-Cardenal, S. J., Liu, S., Mo, X., Rosbjerg, D. & Bauer-Gottwein, P. 2015b Using stochastic dynamic programming to support water resources management in the Ziya River Basin, China. *Journal of Water Resources Planning and Management* **141** (7), 04014086.

Dorini, G. F., Thordarson, F. Ö., Bauer-Gottwein, P., Madsen, H., Rosbjerg, D. & Madsen, H. 2012 A convex programming framework for optimal and bounded suboptimal well field management. *Water Resources Research* **48** (6), W06525.

Dralle, D., Karst, N., Müller, M., Vico, G. & Thompson, S. E. 2017 Stochastic modeling of interannual variation of hydrologic variables. *Geophysical Research Letters* **44** (14), 7285–7294.

Drécourt, J. P., Madsen, H. & Rosbjerg, D. 2006 Calibration framework for a Kalman filter applied to a groundwater model. *Advances in Water Resources* **29** (5), 719–734.

Du, R., Fischione, C. & Xiao, M. 2016 Flowing with the water: on optimal monitoring of water distribution networks by mobile sensors. In *IEEE INFOCOM 2016-The 35th Annual IEEE International Conference on Computer Communications*. pp. 1–9.

Dyrrdal, A. V. & Førland, E. 2019 *Climate Factors for Change in Sub-Daily Precipitation – Recommended Values for Norway (In Norwegian). Norwegian Centre for Climate Service, Report 5/2019*. Available from: https://klimaservicesenter.no/.

Dyrrdal, A. V., Lenkoski, A., Thorarinsdottir, T. L. & Stordal, F. 2015 Bayesian hierarchical modeling of extreme hourly precipitation in Norway. *Environmetrics* **26** (2), 89–106.

Dyrrdal, A. V., Skaugen, T., Stordal, F. & Førland, E. J. 2016 Estimating extreme areal precipitation in Norway from a gridded dataset. *Hydrological Sciences Journal* **61** (3), 483–494.

Dyrrdal, A. V., Olsson, J., Toivonen, E., Arnbjerg-Nielsen, K., Poste, P., Aniskevica, S., Thorndahl, S., Førland, E., Wern, L., Maciulyte, V. & Mäkelä, A. 2021 Observed changes in heavy daily precipitation over the Nordic-Baltic region. *Journal of Hydrology: Regional Studies* **38**, 100965. https://doi.org/10.1016/j.ejrh.2021.

Engeland, K., Hisdal, H. & Frigessi, A. 2004 Practical extreme value modelling of hydrological floods and droughts: a case study. *Extremes* **7** (1), 5–30. doi:10.1007/s10687-004-4727-5.

Engeland, K., Wilson, D., Borsányi, P., Roald, L. & Holmqvist, E. 2018 Use of historical data in flood frequency analysis: a case study for four catchments in Norway. *Hydrology Research* **49** (2), 466–486. doi:10.2166/nh.2017.069.

Engeland, K., Aano, A., Steffensen, I., Støren, E. & Paasche, O. 2020 New flood frequency estimates for the largest river in Norway based on the combination of short and long time series. *Hydrology and Earth System Sciences* **24** (11), 5595–5619. doi:10.5194/hess-24-5595-2020.

Enzenhoefer, R., Binning, P. J. & Nowak, W. 2015 Stakeholder-Objective Risk Model (STORM): determining the aggregated risk of multiple contaminant hazards in groundwater well catchments. *Advances in Water Resources* **83**, 160–175.

Filipova, V., Lawrence, D. & Klempe, H. 2016 Regionalisation of the parameters of the rainfall-runoff model PQRUT. *Hydrology Research* **47** (4), 748–766. doi:10.2166/nh.2016.060.

Filipova, V., Lawrence, D. & Klempe, H. 2018 Effect of catchment properties and flood generation regime on copula selection for bivariate flood frequency analysis. *Acta Geophysica* **66** (4), 791–806. doi:10.1007/s11600-018-0113-6.

Filipova, V., Lawrence, D. & Skaugen, T. 2019 A stochastic event-based approach for flood estimation in catchments with mixed rainfall and snowmelt flood regimes. *Natural Hazards and Earth System Sciences* **19** (1), 1–18. doi:10.5194/nhess-19-1-2019.

Fleig, A. K., Tallaksen, L. M., Hisdal, H. & Demuth, S. A. 2006a Global evaluation of streamflow drought characteristics. *Hydrology and Earth System Sciences* **10** (4), 535–555.

Fleig, A. K., Tallaksen, L. M. & Hisdal, H. 2006b Drought indices suitable to study the linkages to large-scale climate drivers in regions with seasonal frost influence. *IAHS Publications* **308**, 169–174.

FMI 2021 *Climate Guide. Precipitation Return Levels for Durations 6 h to 1 Month is Presented at*. Available from: https://ilmasto-opas.fi/en/datat/sateiden-toistuvuustasot.

Førland, E. & Dyrrdal, A. V. 2018a *Trend Analyses for Short Duration Rainfall in Norway. In Sorteberg et al. (2018), Norwegian Centre for Climate Services. Report 1/2018*. Available from: https://klimaservicesenter.no/

Førland, E. & Dyrrdal, A. V. 2018b Regionalization of rainfall return values for single sites in Norway. In Sorteberg *et al.* (2018).

Førland, E. J. & Kristoffersen, D. 1989 Estimation of extreme precipitation in Norway. *Hydrology Research* **20** (4–5), 257–276.

Gaivoronski, A., Sechi, G. M. & Zuddas, P. 2012a Cost/risk balanced management of scarce resources using stochastic programming. *European Journal of Operational Research* **216** (1), 214–224.

Gaivoronski, A. A., Sechi, G. M. & Zuddas, P. 2012b Balancing cost-risk in management optimization of water resource systems under uncertainty. *Physics and Chemistry of the Earth, Parts A/B/C* **42**, 98–107.

Gelati, E., Madsen, H. & Rosbjerg, D. 2011 Stochastic reservoir optimization using El Niño information: case study of Daule Peripa, Ecuador. *Hydrology Research* **42** (5), 413–431.

Golmohamadi, H. & Asadi, A. 2020 A multi-stage stochastic energy management of responsive irrigation pumps in dynamic electricity markets. *Applied Energy* **265**, 114804.

Gottschalk, L. 1989 Regional exceedance probabilities. *Hydrology Research* **20** (4–5), 201–214. doi: 10.2166/nh.1989.0016.

Gottschalk, L. & Krasovskaia, I. 2002 L-moment estimation using annual maximum (AM) and peak over threshold (POT) series in regional analysis of flood frequencies. *Norsk Geografisk Tidsskrift* **56** (2), 179–187. doi:10.1080 %2f002919502760056512.
Gottschalk, L. & Perzyna, G. 1989 A physically based distribution function for low flow. *Sciences Journal* **34** (5), 559–573. doi:10.1080/02626668909491362.
Gottschalk, L. & Perzyna, G. 1993 Low flow distribution along a river. Extreme Hydrological Events. Proc. International Symposium, Yokohama, 1993, IAHS publication no. 213, 33-41.
Gottschalk, L. & Weingartner, R. 1998 Distribution of peak flow derived from a distribution of rainfall volume and runoff coefficient, and a unit hydrograph. *Journal of Hydrology* **208** (3–4), 148–162. doi:10.1016/S0022-1694(98)00152-8.
Gregersen, I. B., Madsen, H., Rosbjerg, D. & Arnbjerg-Nielsen, K. 2013a A spatial and nonstationary model for the frequency of extreme rainfall events. *Water Resources Research* **49** (1), 127–136.
Gregersen, I. B., Sørup, H. J. D., Madsen, H., Rosbjerg, D., Mikkelsen, P. S. & Arnbjerg-Nielsen, K. 2013b Assessing future climatic changes of rainfall extremes at small spatio-temporal scales. *Climatic Change* **118**, 783–797. https://doi.org/10.1007/s10584-012-0669-0.
Gregersen, I. B., Madsen, H., Rosbjerg, D. & Arnbjerg-Nielsen, K. 2015 Long term variations of extreme rainfall in Denmark and southern Sweden. *Climate Dynamics* **44** (11–12), 3155–3169.
Gregersen, I. B., Madsen, H., Rosbjerg, D. & Arnbjerg-Nielsen, K. 2017 A regional and nonstationary model for partial duration series of extreme rainfall. *Water Resources Research* **53** (4), 2659–2678. doi: 10.1002/2016WR019554.
Güntner, A., Olsson, J., Calver, A. & Gannon, B. 2001 Cascade-based disaggregation of continuous rainfall time series: the influence of climate. *Hydrology and Earth System Sciences* **5** (2), 145–164.
Gustafsson, M., Rayner, D. & Chen, D. 2010 Extreme rainfall events in southern Sweden: where does the moisture come from? *Tellus A: Dynamic Meteorology and Oceanography* **62** (5), 605–616.
Haghighatafshar, S., Becker, P., Moddemeyer, S., Persson, A., Sörensen, J., Aspegren, H. & Jönsson, K. 2020 Paradigm shift in engineering of pluvial floods: from historical recurrence intervals to risk-based design for an uncertain future. *Sustainable Cities and Society* **61**. doi:10.1016/j.scs.2020.102317.
Hailegeorgis, T. T. & Alfredsen, K. 2017 Regional flood frequency analysis and prediction in ungauged basins including estimation of major uncertainties for mid-Norway. *Journal of Hydrology: Regional Studies* **9**, 104–126. doi:10.1016/j.ejrh.2016.11.004.
Hansen, A. K., Madsen, H., Bauer-Gottwein, P., Falk, A. K. V. & Rosbjerg, D. 2012 Multi-objective optimization of the management of a waterworks using an integrated well field model. *Hydrology Research* **43** (4), 430–444.
Hansen, A. K., Franssen, H. J. H., Bauer-Gottwein, P., Madsen, H., Rosbjerg, D. & Kaiser, H. P. 2013 Well field management using multi-objective optimization. *Water Resources Management* **27** (3), 629–648.
Hanssen-Bauer, I., Førland, E., Haddeland, I., Hisdal, H., Lawrence, D., Mayer, S., Nesje, A., Nilsen, J. E. Ø., Sandven, S., Sandø, A. B., Sorteberg, S. & Ådlandsvik, B. 2017 *Climate in Norway 2100 – A Knowledge Base for Climate Adaptation. Norwegian Centre for Climate Services, Report 1/2017*.
Harlin, J. & Kung, C.-S. 1992 Parameter uncertainty and simulation of design floods in Sweden. *Journal of Hydrology* **137** (1–4), 209–230. doi:10.1016/0022-1694(92)90057-3.
Harlin, J., Lindstrom, G. & Bergstrom, S. 1993 New guidelines for spillway design floods in Sweden. *IAHS Publications* **213**, 237–244.
Harremoës, P. & Mikkelsen, P. S. 1995 Properties of extreme point rainfall I: results from a rain gauge system in Denmark. *Atmospheric Research* **37** (4), 277–286.
Harstveit, K. & Jenssen, L. 2003 The correlation between extreme wind and flood events in unregulated river basins. *Nordic Hydrology* **34** (5), 449–460. doi:10.2166/nh.2003.0017.
Hatsey, N. H. & Birkie, S. E. 2020 Total cost optimization of submersible irrigation pump maintenance using simulation. *Journal of Quality in Maintenance Engineering* **27** (1), 187–202.
He, X., Lucatero, D., Ridler, M. E., Madsen, H., Kidmose, J., Hole, Ø., Petersen, C., Zheng, C. & Refsgaard, J. C. 2019 Real-time simulation of surface water and groundwater with data assimilation. *Advances in Water Resources* **127**, 13–25.
Heino, R., Brazdil, R., Førland, E., Tuomenvirta, H., Alexandersson, H., Beniston, M., Pfister, C., Rebetez, M., Rosenhagen, G., Rösner, S. & Wibig, J. 1999 Progress in the study of climatic extremes in northern and central Europe. *Climatic Change* **42** (1), 151–118.
Hellström, C. 2005 Atmospheric conditions during extreme and non-extreme precipitation events in Sweden. *International Journal of Climatology: A Journal of the Royal Meteorological Society* **25** (5), 631–648.
Hisdal, H. & Tallaksen, L. M. 2003 Estimation of regional meteorological and hydrological drought characteristics: a case study for Denmark. *Journal of Hydrology* **281** (3), 230–247. doi:10.1016/S0022-1694(03)00233-6.
Hisdal, H., Stahl, K., Tallaksen, L. M. & Demuth, S. 2001 Have streamflow droughts in Europe become more severe or frequent? *International Journal of Climatology* **21** (3), 317–333. doi:10.1002/joc.619.
Hisdal, H., Tallaksen, L. M. & Frigessi, A. 2002 Handling non-extreme events in extreme value modelling of streamflow droughts. *IAHS Publications* **274**, 281–288.
Hisdal, H., Roald, L. A. & Beldring, S. 2006 Past and future changes in flood and drought in the Nordic countries. *IAHS Publications* **308**, 502–507.
IPCC 2021 Climate Change. In: *The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., Caud, N.,

Chen, Y., Goldfarb, L., Gomis, M. I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J. B. R., Maycock, T. K., Waterfield, T., Yelekçi, O., Yu, R. & Zhou, B., eds). Cambridge University Press, Cambridge and New York.

Irannezhad, M., Chen, D., Kløve, B. & Moradkhani, H. 2017 Analysing the variability and trends of precipitation extremes in Finland and their connection to atmospheric circulation patterns. *International Journal of Climatology* **37** (1–2), 801–817. doi:10.1002/joc.5059.

Jebari, S., Berndtsson, R., Olsson, J. & Bahri, A. 2012 Soil erosion estimation based on rainfall disaggregation. *Journal of Hydrology* **436**, 102–110.

Jennings, A. H. 1950 World's greatest observed point rainfalls. *Monthly Weather Review* **78** (1), 4–5.

Jiang, C., Xiong, L., Yan, L., Dong, J. & Xu, C.-Y. 2019 Multivariate hydrologic design methods under nonstationary conditions and application to engineering practice. *Hydrology and Earth System Sciences* **23** (3), 1683–1704. doi:10.5194/hess-23-1683-2019.

Johansson, F., Bakke, J., Støren, E. N., Paasche, Ø., Engeland, K. & Arnaud, F. 2020 Lake sediments reveal large variations in flood frequency over the last 6,500 years in south-western Norway. *Frontiers in Earth Science* **8**. doi:10.3389/feart.2020.00239.

Jonsdottir, H., Eliasson, J. & Madsen, H. 2005 Assessment of serious water shortage in the Icelandic water resource system. *Physics and Chemistry of the Earth, Parts A/B/C* **30** (6–7), 420–425.

Kallache, M., Rust, H. W., Lange, H. & Kropp, J. P. 2011 Extreme value analysis considering trends: Application to discharge data of the Danube river basin. In: *Extremis* (Kropp, J. & Schellnhuber, H. J., eds). Springer, Berlin, Heidelberg. doi:10.1007/978-3-642-14863-7.

Kjeldsen, T. R. & Rosbjerg, D. 2002 Comparison of regional index flood estimation procedures based on the extreme value type I distribution. *Stochastic Environmental Research and Risk Assessment* **16** (5), 358–373.

Kjeldsen, T. R., Lundorf, A. & Rosbjerg, D. 1999 Regional partial duration series modelling of hydrological droughts in Zimbabwean rivers using a two-component exponential distribution. *IAHS Publication* **255**, 145–153. doi:10.1080/15715124.2019.1597727.

Kjeldsen, T. R., Lundorf, A. & Rosbjerg, D. 2000 Use of a two-component exponential distribution in partial duration modelling of hydrological droughts in Zimbabwean rivers. *Hydrological Sciences Journal* **45** (2), 285–298. doi: 10.1080/02626660009492325.

Kjeldsen, T. R., Smithers, J. C. & Schulze, R. E. 2002 Regional flood frequency analysis in the Kwazulu-Natal province, South Africa, using the index-flood method. *Journal of Hydrology* **255** (1–4), 194–211. doi:10.1016/S0022-1694(01)00520-0.

Kjeldsen, T. R., Macdonald, N., Lang, M., Mediero, L., Albuquerque, T., Bogdanowicz, E., Brázdil, R., Castellarin, A., David, V., Fleig, A., Gül, G. O., Kriaučiūnienė, J., Kohnová, S., Merz, B., Nicholson, O., Roald, L. A., Salinas, J. L., Sarauskiene, D., Šraj, S., Strupczewski, W., Szolgay, J., Toumasis, A., Vanneuville, W., Veijalainen, N. & Wilson, D. 2014 Documentary evidence of past floods in Europe and their utility in flood frequency estimation. *Journal of Hydrology* **517**, 963–973. doi:10.1016/j.jhydrol.2014.06.038.

Knudsen, J. & Rosbjerg, D. 1977 Optimal scheduling of water supply projects. *Nordic Hydrology* **8** (3), 171–192.

Kobierska, F., Engeland, K. & Thorarinsdottir, T. 2018 Evaluation of design flood estimates – a case study for Norway. *Hydrology Research* **49** (2), 450–465. doi: 10.2166/nh.2017.068.

Krasovskaia, I. & Gottschalk, L. 1993 Frequency of extremes and its relation to climate fluctuations. *Hydrology Research* **24** (1), 1–12. doi: 10.2166/nh.1993.0001.

Krasovskaia, I., Gottschalk, L., Rodríguez, A. & Laporte, S. 1999 Dependence of the frequency and magnitude of extreme floods in Costa Rica on the southern oscillation index. *IAHS Publications* **255**, 81–89.

Krishnamurthy, C. K. B. 2017 Optimal management of groundwater under uncertainty: a unified approach. *Environmental and Resource Economics* **67** (2), 351–377.

Latif, S. D., Birima, A. H., Ahmed, A. N., Hatem, D. M., Al-Ansari, N., Fai, C. M. & El-Shafie, A. 2021 Development of prediction model for phosphate in reservoir water system based machine learning algorithms. *Ain Shams Engineering Journal*. https://doi.org/10.1016/j.asej.2021.06.009.

Lawrence, D. 2020 Uncertainty introduced by flood frequency analysis in projections for changes in flood magnitudes under a future climate in Norway. *Journal of Hydrology: Regional Studies* **28**. doi:10.1016/j.ejrh.2020.100675.

Lawrence, D., Paquet, E., Gailhard, J. & Fleig, A. K. 2014 Stochastic semi-continuous simulation for extreme flood estimation in catchments with combined rainfall-snowmelt flood regimes. *Natural Hazards and Earth System Sciences* **14** (5), 1283–1298. doi:10.5194/nhess-14-1283-2014.

Le Ngo, L., Madsen, H. & Rosbjerg, D. 2007 Simulation and optimisation modelling approach for operation of the Hoa Binh reservoir, Vietnam. *Journal of Hydrology* **336** (3–4), 269–281.

Le Ngo, L., Madsen, H., Rosbjerg, D. & Pedersen, C. B. 2008 Implementation and comparison of reservoir operation strategies for the Hoa Binh reservoir, Vietnam using the MIKE 11 model. *Water Resources Management* **22** (4), 457–472.

Li, Q., Loy-Benitez, J., Nam, K., Hwangbo, S., Rashidi, J. & Yoo, C. 2019 Sustainable and reliable design of reverse osmosis desalination with hybrid renewable energy systems through supply chain forecasting using recurrent neural networks. *Energy* **178**, 277–292.

Lind, P., Belušić, D., Christensen, O. B., Dobler, A., Kjellström, E., Landgren, O., Lindstedt, D., Matte, D., Pedersen, R. A., Toivonen, E. & Wang, F. 2020 Benefits and added value of convection-permitting climate modeling over Fenno-Scandinavia. *Climate Dynamcs* **55**, 1893–1912. https://doi.org/10.1007/s00382-020-05359-3.

Lindström, G. & Harlin, J. 1992 Spillway design floods in Sweden: II. Applications and sensitivity analysis. *Hydrological Sciences Journal* **37** (5), 521–539. doi:10.1080/02626669209492616.

Liu, D., Li, X., Guo, S., Rosbjerg, D. & Chen, H. 2015 Using a Bayesian probabilistic forecasting model to analyze the uncertainty in real-time dynamic control of the flood limiting water level for reservoir operation. *Journal of Hydrologic Engineering* **20** (2), 04014036.

Löwe, R., Mikkelsen, P. S., Rasmussen, M. R. & Madsen, H. 2013 State-space adjustment of radar rainfall and skill score evaluation of stochastic volume forecasts in urban drainage systems. *Water Science and Technology* **68** (3), 584–590.

Lund, N. S., Madsen, H., Mazzoleni, M., Solomatine, D. & Borup, M. 2019 Assimilating flow and level data into an urban drainage surrogate model for forecasting flows and overflows. *Journal of Environmental Management* **248**, 109052.

Madsen, H. & Rosbjerg, D. 1995 On the modelling of extreme droughts. In: S. P. Simonovic, Z. Kundzewicz, D. Rosbjerg & K. Takeuchi, eds. *Modelling and Management of Sustainable Basin-Scale Water Resources Systems*, Vol. 231. IAHS Publication, Wallingford, pp. 377–385.

Madsen, H. & Rosbjerg, D. 1997a The partial duration series method in regional index-flood modeling. *Water Resources Research* **33** (4), 737–746. doi:10.1029/96WR03847.

Madsen, H. & Rosbjerg, D. 1997b Generalized least squares and empirical Bayes estimation in regional partial duration series index-flood modeling. *Water Resources Research* **33** (4), 771–781. doi:10.1029/96WR03850.

Madsen, H., Rosbjerg, D. & Harremoës, P. 1994 PDS-modelling and regional Bayesian estimation of extreme rainfalls. *Hydrology Research* **25** (4), 279–300.

Madsen, H., Rosbjerg, D. & Harremoöes, P. 1995 Application of the Bayesian approach in regional analysis of extreme rainfalls. *Stochastic Hydrology and Hydraulics* **9** (1), 77–88.

Madsen, H., Rasmussen, P. F. & Rosbjerg, D. 1997a Comparison of annual maximum series and partial duration series methods for modeling extreme hydrologic events, 1. At-site modelling. *Water Resources Research* **33** (4), 747–757.

Madsen, H., Pearson, C. P. & Rosbjerg, D. 1997b Comparison of annual maximum series and partial duration series methods for modeling extreme hydrologic events, 2. Regional modelling. *Water Resources Research* **33** (4), 759–769.

Madsen, H., Mikkelsen, P. S., Rosbjerg, D. & Harremoës, P. 1998 Estimation of regional intensity-duration-frequency curves for extreme precipitation. *Water Science and Technology* **37** (11), 29–36.

Madsen, H., Mikkelsen, P. S., Rosbjerg, D. & Harremoës, P. 2002 Regional estimation of rainfall intensity-duration-frequency curves using generalized least squares regression of partial duration series statistics. *Water Resources Research* **38** (11), 1239. doi:10.1029/2001WR001125.

Madsen, H., Arnbjerg-Nielsen, K. & Mikkelsen, P. S. 2009 Update of regional intensity-duration-frequency curves in Denmark: tendency towards increased storm intensities. 7th International Workshop on Precipitation in Urban Areas. *Atmospheric Research* **92** (3), 343–349.

Madsen, H., Lawrence, D., Lang, M., Martinkova, M. & Kjeldsen, T. R. 2014 Review of trend analysis and climate change projections of extreme precipitation and floods in Europe. *Journal of Hydrology* **519** (PD), 3634–3650. doi:10.1016/j.jhydrol.2014.11.003.

Madsen, H., Gregersen, I. B., Rosbjerg, D. & Arnbjerg-Nielsen, K. 2017 Regional frequency analysis of short duration rainfall extremes using gridded daily rainfall data as co-variate. *Water Science and Technology* **75**, 1971–1981. https://doi.org/10.2166/wst.2017.089.

Mangini, M., Viglione, A., Hall, J., Hundecha, Y., Ceola, S., Montanari, A., Rogger, M., Salinas, J. L., Borzì, I. & Parajka, J. 2018 Detection of trends in magnitude and frequency of flood peaks across Europe. *Hydrological Sciences Journal* **63** (4), 493–512. doi: 10.1080/02626667.2018.1444766.

Marshall, G. J., Jylhä, K., Kivinen, S., Laapas, M. & Dyrrdal, A. V. 2020 The role of atmospheric circulation patterns in driving recent changes in indices of extreme seasonal precipitation across Arctic Fennoscandia. *Climatic Change* **162** (2), 741–759.

Mayer, S., Dyrrdal, A. V. & Skaland, R. G. 2018 Projected changes in future short-duration extreme precipitation events using EURO-CORDEX simulations: Stationary and non-stationary analysis. In Sorteberg *et al.* (2018). *Norwegian Centre for Climate Services, Report* 1/2018. Available from: https://klimaservicesenter.no/.

Médus, E. 2021 (pers comm. with Erika Médus, Finnish Meteorological Institute).

Meilutytė-Barauskienė, D. & Kovalenkovienė, M. 2007 Change of spring flood parameters in Lithuanian rivers. *Energetika* **4** (2), 26–33. ISSN: 0235-7208.

Meilutytė-Barauskienė, D., Kriaučiūnienė, J. & Kovalenkovienė, M. 2010 *Impact of Climate Change on Runoff of the Lithuanian Rivers: Modern Climate Change Models, Statistical Methods and Hydrological Modelling*. LAP LAMBERT Academic Publishing, Saarbrucken, p. 55. ISBN: 9783838358338.

Michelson, D., Andersson, T., Koistinen, J., Collier, C. G., Riedl, J., Szturc, J., Gjertsen, U., Nielsen, A. & Overgaard, S. 2000 *BALTEX Radar Data Centre Products and Their Methodologies, Report RMK 90*. Swedish Meteorological and Hydrological Institute, Norrköping, Sweden.

Mikkelsen, P. S., Harremoës, P. & Rosbjerg, D. 1995 Properties of extreme point rainfall II: parametric data interpretation and regional uncertainty assessment. *Atmospheric Research* **37** (4), 287–304.

Mikkelsen, P. S., Madsen, H., Rosbjerg, D. & Harremoës, P. 1996 Properties of extreme point rainfall III: identification of spatial inter-site correlation structure. *Atmospheric Research* **40** (1), 77–98.

Myhre, G., Alterskjær, K., Stjern, C. W., Hodnebrog, Ø., Marelle, L., Samset, B. N., Sillmenn, J., Fisher, E., Schulz, M. & Stohl, A. 2019 Frequency of extreme precipitation increases extensively with event rareness under global warming. *Scientific Reports* **9**, 16063. https://doi.org/10.1038/s41598-019-52277-4.

Najafi, J., Peiravi, A. & Anvari-Moghaddam, A. 2020 Enhancing integrated power and water distribution networks seismic resilience leveraging microgrids. *Sustainability* **12** (6), 2167.

NCCS 2021 IDF-statistics for arbitrary locations in Norway are presented at. Available from: https://klimaservicesenter.no/ivf.

NERC 1975 *Flood Studies Report*, Vol. 1. Natural Environment Research Council, London, UK.
Oliver, J., Qin, X. S., Madsen, H., Rautela, P., Joshi, G. C. & Jorgensen, G. 2019 A probabilistic risk modelling chain for analysis of regional flood events. *Stochastic Environmental Research and Risk Assessment* **33** (4–6), 1057–1074. doi:10.1007/s00477-019-01681-3.
Olsson, J. 1998 Evaluation of a scaling cascade model for temporal rain-fall disaggregation. *Hydrology and Earth System Sciences* **2** (1), 19–30.
Olsson, J. & Foster, K. 2014 Short-term precipitation extremes in regional climate simulations for Sweden. *Hydrology Research* **45** (3), 479–489.
Olsson, J., Niemczynowicz, J. & Berndtsson, R. 1993 Fractal analysis of high-resolution rainfall time series. *Journal of Geophysical Research: Atmospheres* **98** (D12), 23265–23274.
Olsson, J., Gidhagen, L., Gamerith, V., Gruber, G., Hoppe, H. & Kutschera, P. 2012a Downscaling of short-term precipitation from Regional Climate Models for sustainable urban planning. *Sustainability* **4**, 866–887. doi:10.3390/su4050866.
Olsson, J., Willén, U. & Kawamura, A. 2012b Downscaling extreme short-term regional climate model precipitation for urban hydrological applications. *Hydrology Research* **43** (4), 341–351. https://doi.org/10.2166/nh.2012.135.
Olsson, J., Berg, P. & Kawamura, A. 2015 Impact of RCM spatial resolution on the reproduction of local, sub-daily precipitation. *Journal of Hydrometeorology* **16** (2), 534–547. doi:10.1175/JHM-D-14-0007.
Olsson, J., Berg, P., Eronn, A., Simonsson, L., Södling, J., Wern, L. & Yang, W. 2017 *Extreme Rainfall in Present and Future Climate (In Swedish), SMHI Klimatologi Report No. 47*.
Olsson, J., Södling, J., Berg, P., Wern, L. & Eronn, A. 2019 Short-duration rainfall extremes in Sweden: a regional analysis. *Hydrology Research* **50** (3), 945–960.
Olsson, J., Du, Y., An, D., Uvo, C. B., Sörensen, J., Toivonen, E., Belušić, D. & Dobler, A. 2021 An analysis of (sub-)hourly rainfall in convection-permitting climate simulations over southern Sweden from a user's perspective. *Frontiers in Earth Science* **9**, 681312. doi: 10.3389/feart.2021.681312.
Olsson, J., Dyrrdal, A. V., Toivonen, E., Södling, J., Aniskeviča, S., Arnbjerg-Nielsen, K., Førland, E., Mačiulytė, V., Mäkelä, A., Post, P., Thorndahl, S. L. & Wern, L. 2022 Sub-daily rainfall extremes in the Nordic-Baltic region. *Hydrology Research*. doi:10.2166/nh.2022.119.
Pacheco, A., Gottschalk, L. & Krasovskaia, I. 2006 Regionalization of low flow in Costa Rica. IAHS Publication, Wallingford **308**, 111–116.
Pagneux, E., Gísladóttir, G. & Snorrason, Á. 2010 Inundation extent as a key parameter for assessing the magnitude and return period of flooding events in southern Iceland. *Hydrological Sciences Journal* **55** (5), 704–716. doi:10.1080/02626667.2010.489281.
Paquet, E., Garavaglia, F., Gailhard, J. & Garçon, R. 2013 The SCHADEX method: a semi-continuous rainfall-runoff simulation for extreme flood estimation. *Journal of Hydrology* **495**, 23–37.
Pereira-Cardenal, S. J., Riegels, N. D., Berry, P. A. M., Smith, R. G., Yakovlev, A., Siegfried, T. U. & Bauer-Gottwein, P. 2011 Real-time remote sensing driven river basin modeling using radar altimetry. *Hydrology and Earth System Sciences* **15** (1), 241–254.
Pereira-Cardenal, S. J., Mo, B., Riegels, N. D., Arnbjerg-Nielsen, K. & Bauer-Gottwein, P. 2015 Optimization of multipurpose reservoir systems using power market models. *Journal of Water Resources Planning and Management* **141** (8), 04014100.
Pereira-Cardenal, S. J., Mo, B., Gjelsvik, A., Riegels, N. D., Arnbjerg-Nielsen, K. & Bauer-Gottwein, P. 2016 Joint optimization of regional water-power systems. *Advances in Water Resources* **92**, 200–207.
Pérez-Díaz, J. I., Guisández, I., Chazarra, M. & Helseth, A. 2020 Medium-term scheduling of a hydropower plant participating as a price-maker in the automatic frequency restoration reserve market. *Electric Power Systems Research* **185**, 106399.
Petersen-Øverleir, A. & Reitan, T. 2009 Accounting for rating curve imprecision in flood frequency analysis using likelihood-based methods. *Journal of Hydrology* **366** (1–4), 89–100. doi:10.1016/j.jhydrol.2008.12.014.
Quesada-Montano, B., Di Baldassarre, G., Rangecroft, S. & Van Loon, A. F. 2018 Hydrological change: towards a consistent approach to assess changes on both floods and droughts. *Advances in Water Resources* **111**, 31–35. doi:10.1016/j.advwatres.2017.10.038.
Ragulina, G. & Reitan, T. 2017 Generalized extreme value shape parameter and its nature for extreme precipitation using long time series and the Bayesian approach. *Hydrological Sciences Journal* **62** (6), 863–879.
Räsänen, T. & Kummu, M. 2013 Spatiotemporal influences of ENSO on precipitation and flood pulse in the Mekong River Basin. *Journal of Hydrology* **476**, 154–168.
Rasmussen, P. F. & Rosbjerg, D. 1989 Risk estimation in partial duration series. *Water Resources Research* **25** (11), 2319–2330.
Rasmussen, P. F. & Rosbjerg, D. 1991a Evaluation of risk concepts in partial duration series. *Stochastic Hydrology and Hydraulics* **5** (1), 1–16.
Rasmussen, P. F. & Rosbjerg, D. 1991b Prediction uncertainty in seasonal partial duration series. *Water Resources Research* **27** (11), 2875–2883.
Rasmussen, J., Madsen, H., Jensen, K. H. & Refsgaard, J. C. 2015 Data assimilation in integrated hydrological modeling using ensemble Kalman filtering: evaluating the effect of ensemble size and localization on filter performance. *Hydrology and Earth System Sciences* **19** (7), 2999–3013.
Retsö, D. 2015 Documentary evidence of historical floods and extreme rainfall events in Sweden 1400–1800. *Hydrology and Earth System Sciences* **19** (3), 1307–1323. doi:10.5194/hess-19-1307-2015.
Ridler, M. E., van Velzen, N., Hummel, S., Sandholt, I., Falk, A. K., Heemink, A. & Madsen, H. 2014a Data assimilation framework: linking an open data assimilation library (OpenDA) to a widely adopted model interface (OpenMI). *Environmental Modelling & Software* **57**, 76–89.
Ridler, M. E., Madsen, H., Stisen, S., Bircher, S. & Fensholt, R. 2014b Assimilation of SMOS-derived soil moisture in a fully integrated hydrological and soil-vegetation-atmosphere transfer model in Western D Denmark. *Water Resources Research* **50** (11), 8962–8981.

Ridler, M. E., Zhang, D., Madsen, H., Kidmose, J., Refsgaard, J. C. & Jensen, K. H. 2018 Bias-aware data assimilation in integrated hydrological modelling. *Hydrology Research* **49** (4), 989–1004.

Rimbu, N., Czymzik, M., Ionita, M., Lohmann, G. & Brauer, A. 2016 Atmospheric circulation patterns associated with the variability of River Ammer floods: evidence from observed and proxy data. *Climate of the Past* **12** (2), 377–385. doi:10.5194/cp-12-377-2016.

Rosbjerg, D. & Madsen, H. 1992 On the choice of threshold level in partial duration series. Nordic Hydrological Conference, Alta, NHP Report 30, edited by Østrem G., 604-615.

Rosbjerg, D. & Madsen, H. 1995 Uncertainty measures of regional flood frequency estimators. *Journal of Hydrology* **167** (1–4), 209–224. doi:10.1016/0022-1694(94)02624-K.

Rosbjerg, D. & Madsen, H. 1998 Design with uncertain design values. In: *Hydrology in A Changing Environment*, Vol. III. (Wheater, H. & Kirby, C., eds). John Wiley & Sons, Hoboken, pp. 155–163. ISBN: 978-0-471-98686-7.

Rosbjerg, D. 1977a Return periods of hydrological events. *Nordic Hydrology* **8** (1), 57–61.

Rosbjerg, D. 1977b Crossings and extremes in stationary dependent annual series. *Nordic Hydrology* **8** (5), 257–266.

Rosbjerg, D. 1985 Estimation in partial duration series with independent and dependent peak values. *Journal of Hydrology* **76** (1–2), 183–195.

Rosbjerg, D. 1987 On the annual maximum distribution in dependent partial duration series. *Stochastic Hydrology and Hydraulics* **1** (1), 3–16.

Rosbjerg, D. 2017 Optimal adaptation to extreme rainfalls in current and future climate. *Water Resources Research* **53** (1), 535–543. doi**:** 10. 1002/2016WR019718.

Rosbjerg, D., Madsen, H. & Rasmussen, P. F. 1992 Prediction in partial duration series with generalized Pareto-distributed exceedances. *Water Resources Research* **28** (11), 3001–3010.

Rosén, L., Wladis, D. & Ramaekers, D. 1998 Risk and decision analysis of groundwater protection alternatives on the European scale with emphasis on nitrate and aluminium contamination from diffuse sources. *Journal of Hazardous Materials* **61** (1–3), 329–336.

Samaniego, L., Kumar, R., Breuer, L., Chamorro, A., Flörke, M., Pechlivanidis, I. G., Schäfer, D., Shah, H., Vetter, T., Wortmann, M. & Zeng, X. 2017 Propagation of forcing and model uncertainties on to hydrological drought characteristics in a multi-model century-long experiment in large river basins. *Climatic Change* **141** (3), 435–449. doi:10.1007/s10584-016-1778-y.

Sarauskiene, D. & Kriaučiūnienė, J. 2011 Flood frequency analysis of Lithuanian rivers. In *8th International Conference on Environmental Engineering*. ICEE, pp. 666–671.

Schleiss, M., Olsson, J., Berg, P., Niemi, T., Kokkonen, T., Thorndahl, S., Nielsen, R., Ellerbæk Nielsen, J., Bozhinova, D. & Pulkkinen, S. 2020 The accuracy of weather radar in heavy rain: a comparative study for Denmark, the Netherlands, Finland and Sweden. *Hydrology and Earth System Sciences* **24**, 3157–3188. doi: 10.5194/hess-24-3157-2020.

Schneider, R., Ridler, M. E., Godiksen, P. N., Madsen, H. & Bauer-Gottwein, P. 2018 A data assimilation system combining CryoSat-2 data and hydrodynamic river models. *Journal of Hydrology* **557**, 197–210.

Sechi, G. M., Gaivoronski, A. A. & Napolitano, J. 2019 Optimising pumping activation in multi-reservoir water supply systems under uncertainty with stochastic quasi-gradient methods. *Water Resources Management* **33** (5), 1881–1895. doi: 10.1007/s11269-019-02219-6.

Selek, I., Bene, J. G. & Ikonen, E. 2013 Utilizing permutational symmetries in dynamic programming-with an application to the optimal control of water distribution systems under water demand uncertainties. *International Journal of Innovative Computing, Information and Control* **9** (8), 3091–3113.

Skaugen, T., Creutin, J. D. & Gottschalk, L. 1996 Reconstruction and frequency estimates of extreme daily areal precipitation. *Journal of Geophysical Research: Atmospheres* **101** (D21), 26287–26295.

Skaugen, T., Astrup, M., Roald, L. A. & Førland, E. 2004 Scenarios of extreme daily precipitation for Norway under climate change. *Hydrology Research* **35** (1), 1–13.

SMHI 2021 IDF statistics and climate factors for sub-daily rainfall for present and future climate are presented at. Available from: https://www.smhi.se/kunskapsbanken/meteorologi/statistik-for-extrem-korttidsnederbord-1.159736.

Smith, D. V. 1973 A hybrid model for irrigation planning using chance constrained programming and hydrologic simulation. *International Journal of Systems Science* **4** (4), 533–544.

Sorteberg, A., Lawrence, D., Dyrrdal, A. V., Mayer, S. & Engeland, K. 2018 *Climatic Changes In Short Duration Extreme Precipitation and Rapid Onset Flooding – Implications for Design Values. Norwegian Centre for Climate Services. Report 1/2018*. Available from: https://klimaservicesenter.no/.

Sørup, H. J. D., Christensen, O. B., Arnbjerg-Nielsen, K. & Mikkelsen, P. S. 2016 Downscaling future precipitation extremes to urban hydrology scales using a spatio-temporal Neyman–Scott weather generator. *Hydrology and Earth System Sciences* **20**, 1387–1403.

Sørup, H. J. D., Georgiadis, S., Gregersen, I. B. & Arnbjerg-Nielsen, K. 2017 Formulating and testing a method for perturbing precipitation time series to reflect anticipated climatic changes. *Hydrology and Earth System Sciences* **21**, 345–355. doi:10.5194/hess-21-245-2017.

Spildevandskomitéen 2014 *Updated Climate Factors and Dimensioning Rain Intensities (In Danish). IDA, Report no 30*. Available from: https://ida.dk/media/2994/svk_skrift30_0.pdf

Stagge, J. H., Tallaksen, L. M., Gudmundsson, L., Van Loon, A. F. & Stahl, K. 2015 Candidate distributions for climatological drought indices (SPI and SPEI). *International Journal of Climatology* **35** (13), 4027–4040. doi:10.1002/joc.4267.

Stahl, K., Vidal, J.-P., Hannaford, J., Tijdeman, E., Laaha, G., Gauster, T. & Tallaksen, L. M. 2020 The challenges of hydrological drought definition, quantification and communication: an interdisciplinary perspective. *IAHS Publications* **383**, 291–295.

Steinbakk, G. H., Thorarinsdottir, T. L., Reitan, T., Schlichting, L., Hølleland, S. & Engeland, K. 2016 Propagation of rating curve uncertainty in design flood estimation. *Water Resources Research* **52** (9), 6897–6915. doi: 10.1002/2015WR018516.

Stentoft, P. A., Munk-Nielsen, T., Vezzaro, L., Madsen, H., Mikkelsen, P. S. & Møller, J. K. 2019 Towards model predictive control: online predictions of ammonium and nitrate removal by using a stochastic ASM. *Water Science and Technology* **79** (1), 51–62.

Støren, E. N., Dahl, S. O., Nesje, A. & Paasche, T. 2010 Identifying the sedimentary imprint of high-frequency holocene river floods in lake sediments: development and application of a new method. *Quaternary Science Reviews* **29** (23–24), 3021–3033. doi:10.1016/j.quascirev.2010.06.038.

Støren, E. N., Kolstad, E. W. & Paasche, O. 2012 Linking past flood frequencies in Norway to regional atmospheric circulation anomalies. *Journal of Quaternary Science* **27** (1), 71–80. doi:10.1002/jqs.1520.

Sunyer, M. A., Madsen, H. & Ang, P. H. 2012 A comparison of different regional climate models and statistical downscaling methods for extreme rainfall estimation under climate change. 8th International Workshop on Precipitation in Urban Areas. *Atmospheric Research* **103**, 119–128.

Sunyer, M. A., Sørup, H. J. D., Christensen, O. B., Madsen, H., Rosbjerg, D., Mikkelsen, P. S. & Arnbjerg-Nielsen, K. 2013 On the importance of observational data properties when assessing regional climate model performance of extreme precipitation. *Hydrology and Earth System Sciences* **17**, 4323–4337. https://doi.org/10.5194/hess-17-4323-2013.

Sunyer, M. A., Gregersen, I. B., Rosbjerg, D., Madsen, H., Luchner, J. & Arnbjerg-Nielsen, K. 2015a Comparison of different statistical downscaling methods to estimate changes in hourly extreme precipitation using RCM projections from ENSEMBLES. *International Journal of Climatology* **35** (9), 2528–2539.

Sunyer, M. A., Hundecha, Y., Lawrence, D., Madsen, H., Willems, P., Martinkova, M., Vormoor, K., Bürger, G., Hane, M., Kriaučiūnienė, J., Loukas, A., Osuch, M. & Yücel, I. 2015b Inter-comparison of statistical downscaling methods for projection of extreme precipitation in Europe. *Hydrology and Earth System Sciences* **19**, 1827–1847. https://doi.org/10.5194/hess-19-1827-2015.

Sveinsson, Ó. G. B. 2014 Time series analysis of hydrologic data. In: S. Eslamian, ed. *Handbook of Engineering Hydrology*. CRC Press, Boca Raton, pp. 569–590.

Svensson, C. & Jones, D. A. 2010 Review of methods for deriving areal reduction factors. *Journal of Flood Risk Management* **3** (3), 232–245.

Svensson, C., Olsson, J. & Berndtsson, R. 1996 Multifractal properties of daily rainfall in two different climates. *Water Resources Research* **32** (8), 2463–2472.

Svensson, G., Berg, P., Dahlström, B., Hernebring, C. & Olsson, J. 2020 *Nederbördsstatistik för dimensionering av dagvattensystem – State of the art (Precipitation statistics for storm water system design – Sate of the art)*, Meddelande M148, Svenstk Vatten AB, Stockholm, Sweden.

Taghian, M., Rosbjerg, D., Haghighi, A. & Madsen, H. 2014 Optimization of conventional rule curves coupled with hedging rules for reservoir optimization. *Journal of Water Resources, Planning and Management* **140** (5), 693–698.

Tallaksen, L. M. & Hisdal, H. 1997 Regional analysis of extreme streamflow drought duration and deficit volume. *IAHS Publications* **246**, 141–150.

Tallaksen, L. M., Madsen, H. & Clausen, B. 1997 On the definition and modelling of streamflow drought duration and deficit volume. *Hydrological Sciences Journal* **42** (1), 15–33.

Thorarinsdottir, T. L., Hellton, K. H., Steinbakk, G. H., Schlichting, L. & Engeland, K. 2018 Bayesian regional flood frequency analysis for large catchments. *Water Resources Research* **54** (9), 6929–6947. doi:10.1029/2017WR022460.

Thorndahl, S. & Rasmussen, M. R. 2012 Marine X-band weather radar data calibration. *Atmospheric Research* **103**, 33–44.

Thorndahl, S., Nielsen, J. E. & Rasmussen, M. R. 2019 Estimation of storm-centred areal reduction factors from radar rainfall for design in urban hydrology. *Water* **11** (6), 1120.

Tijdeman, E., Stahl, K. & Tallaksen, L. M. 2020 Drought characteristics derived based on the standardized streamflow index: a large sample comparison for parametric and nonparametric methods. *Water Resources Research* **56** (10). doi:10.1029/2019WR026315.

Tsegaw, A. T., Pontoppidan, M., Kristvik, E., Alfredsen, K. & Muthanna, T. M. 2020 Hydrological impacts of climate change on small ungauged catchments – results from a global climate model-regional climate model-hydrologic model chain. *Natural Hazards and Earth System Sciences* **20** (8), 2133–2155. doi:10.5194/nhess-20-2133-2020.

USWRC 1976 *Guidelines for Determining Flood Flow Frequency, United States Water Resources Council*. Bull. 17, USWRC Hydrology Committee, Washington, DC.

USWRC. 1981 *Guidelines for Determining Flood Flow Frequency*. Bull. 17B, USWRC Hydrology Committee, Washington, DC.

van de Beek, R. C., Olsson, J. & Andersson, J. 2020 Optimal grid resolution for precipitation maps from commercial microwave link networks. *Advances in Science and Research* **17**, 79–85.

Van Loon, A. F., Stahl, K., Di Baldassarre, G., Clark, J., Rangecroft, S., Wanders, N., Gleeson, T., Van Dijk, A. I. J. M., Tallaksen, L. M., Hannaford, J., Uijlenhoet, R., Teuling, A. J., Hannah, D. M., Sheffield, J., Svoboda, M., Verbeiren, B., Wagener, T. & Van Lanen, H. A. J. 2016 Drought in a human-modified world: reframing drought definitions, understanding, and analysis approaches. *Hydrology and Earth System Sciences* **20**, 3631–3650.

Veijalainen, N. & Vehviläinen, B. 2008 The effect of climate change on design floods of high hazard dams in Finland. *Hydrology Research* **39** (5–6), 465–477. doi:10.2166/nh.2008.202.

Veijalainen, N., Lotsari, E., Alho, P., Vehviläinen, B. & Käyhkö, J. 2010 National scale assessment of climate change impacts on flooding in Finland. *Journal of Hydrology* **391** (3–4), 333–350. doi:10.1016/j.jhydrol.2010.07.035.

Vormoor, K., Lawrence, D., Heistermann, M. & Bronstert, A. 2014 Climate change impacts on the seasonality and generation processes of floods – projections and uncertainties for catchments with mixed snowmelt/rainfall regimes. *Hydrology and Earth System Sciences* **19** (2), 913–931. doi:10.5194/hess-19-913-2015.

Vormoor, K., Lawrence, D., Schlichting, L., Wilson, D. & Wong, W. K. 2016 Evidence for changes in the magnitude and frequency of observed rainfall vs. snowmelt driven floods in Norway. *Journal of Hydrology* **538**, 33–48. doi:10.1016/j.jhydrol.2016.03.066.

Vrugt, J. A., Gupta, H. V., Nualláin, B. & Bouten, W. 2006 Real-time data assimilation for operational ensemble streamflow forecasting. *Journal of Hydrometeorology* **7** (3), 548–565.

Ward, P. J., Eisner, S., Flörke, M., Dettinger, M. D. & Kummu, M. 2014 Annual flood sensitivities to el ninõ-southern oscillation at the global scale. *Hydrology and Earth System Sciences* **18** (1), 47–66. doi:10.5194/hess-18-47-2014.

Ward, P. J., Kummu, M. & Lall, U. 2016 Flood frequencies and durations and their response to el niño southern oscillation: global analysis. *Journal of Hydrology* **539**, 358–378. doi:10.1016/j.jhydrol.2016.05.045.

Westra, S., Fowler, H. J., Evans, J. P., Alexander, L. V., Berg, P., Johnson, F., Kendon, E. J., Lenderink, G. & Roberts, N. M. 2014 Future changes to the intensity and frequency of short-duration extreme rainfall. *Reviews of Geophysics* **52**, 522–555. doi:10.1002/2014RG000464.

Willems, P., Arnbjerg-Nielsen, K., Olsson, J. & Nguyen, V. T. V. 2012 Climate change impact assessment on urban rainfall extremes and urban drainage: methods and shortcomings. *Atmospheric Research* **103**, 106–118.

Wilson, D., Hisdal, H. & Lawrence, D. 2010 Has streamflow changed in the Nordic countries? - recent trends and comparisons to hydrological projections. *Journal of Hydrology* **394** (3–4), 334–346. doi:10.1016/j.jhydrol.2010.09.010.

Wilson, D., Hisdal, H. & Lawrence, D. 2014 Trends in floods in small Norwegian catchments -instantaneous vs. daily peaks. *IAHS Publications* **363**, 42–47.

WMO 1994 *Guide to Hydrological Practices*. WMO-No 168, WMO, Geneva, Switzerland.

WMO 2009 *Manual on Estimation of Probable Maximum Precipitation (PMP)*. WMO-No 1045, WMO, Geneva, Switzerland.

Wong, W. K., Beldring, S., Engen-Skaugen, T., Haddeland, I. & Hisdal, H. 2011 Climate change effects on spatiotemporal patterns of hydroclimatological summer droughts in Norway. *Journal of Hydrometeorology* **12** (6), 1205–1220.

Xiong, B., Xiong, L., Guo, S., Xu, C.-Y., Xia, J., Zhong, Y. & Yang, H. 2020 Nonstationary frequency analysis of censored data: a case study of the floods in the Yangtze River from 1470 to 2017. *Water Resources Research* **56** (8). doi:10.1029/2020WR027112.

Yan, L., Xiong, L., Liu, D., Hu, T. & Xu, C.-Y. 2017 Frequency analysis of nonstationary annual maximum flood series using the time-varying two-component mixture distributions. *Hydrological Processes* **31** (1), 69–89. doi:10.1002/hyp.10965.

Yang, T., Xu, C.-Y., Shao, Q.-X. & Chen, X. 2010 Regional flood frequency and spatial patterns analysis in the Pearl River delta region using L-moments approach. *Stochastic Environmental Research and Risk Assessment* **24** (2), 165–182. doi:10.1007/s00477-009-0308-0.

Yu, K.-X., Xiong, L. & Gottschalk, L. 2014 Derivation of low flow distribution functions using copulas. *Journal of Hydrology* **508**, 273–288. doi:10.1016/j.jhydrol.2013.09.057.

Yu, K.-X., Gottschalk, L., Zhang, X., Li, P., Li, Z., Xiong, L. & Sun, Q. 2018 Analysis of nonstationarity in low flow in the Loess plateau of China. *Hydrological Processes* **32** (12), 1844–1857. doi:10.1002/hyp.1162.

Zelenhasic, E. & Salvai, A. 1987 A method of streamflow drought analysis. *Water Resources Research* **23** (1), 156–168.

Zhang, Q., Gu, X., Singh, V. P., Xiao, M. & Xu, C.-Y. 2014 Stationarity of annual flood peaks during 1951–2010 in.the Pearl River basin, China. *Journal of Hydrology* **519** (PD), 3263–3274. doi:10.1016/j.jhydrol.2014.10.028.

Zhang, D., Madsen, H., Ridler, M. E., Refsgaard, J. C. & Jensen, K. H. 2015 Impact of uncertainty description on assimilating hydraulic head in the MIKE SHE distributed hydrological model. *Advances in Water Resources* **86**, 400–413.

Zhang, D., Madsen, H., Ridler, M. E., Kidmose, J., Jensen, K. H. & Refsgaard, J. C. 2016 Multivariate hydrological data assimilation of soil moisture and groundwater head. *Hydrology and Earth System Sciences* **20** (10), 4341–4357.

First received 20 December 2021; accepted in revised form 28 February 2022. Available online 23 May 2022