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Review of trend analysis and climate change projections of extreme precipitation and floods in Europe

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Abstract

This paper presents a review of trend analysis of extreme precipitation and hydrological floods in Europe based on observations and future climate projections. The review summaries methods and methodologies applied and key findings from a large number of studies. Reported analyses of observed extreme precipitation and flood records show that there is some evidence of a general increase in extreme precipitation, whereas there are no clear indications of significant trends at large-scale regional or national level of extreme streamflow. Several studies from regions dominated by snowmelt-induced peak flows report decreases in extreme streamflow and earlier spring snowmelt peak flows, likely caused by increasing temperature. The review of likely future changes based on climate projections indicates a general increase in extreme precipitation under a future climate, which is consistent with the observed trends. Hydrological projections of peak flows show large impacts in many areas with both positive and negative changes. A general decrease in flood magnitude and earlier spring floods are projected for catchments with snowmelt-dominated peak flows, which is consistent with the observed trends. Finally, existing guidelines in Europe on design flood and design rainfall estimation are reviewed. The review shows that only few countries have developed guidelines that incorporate a consideration of climate change impacts.

Keywords: Floods; Extreme precipitation; Trends; Climate projections; Guidelines.

1. Introduction

The risk of destructive flooding has posed a threat to human settlements across Europe throughout recorded history (Bradzil et al., 2006; Macdonald, 2012) and has prompted hydrologists and engineers to develop tools for quantifying the risks such as flood frequency analysis. Standard statistical procedures for frequency analysis of extreme precipitation and floods are based on the assumption of stationarity, and historical records of extreme events are used to estimate extreme value statistics. Several European nations have developed specific methods and guidelines for use of flood frequency methods (Castellarin et al., 2012). In a changing environment, however, the assumption of stationarity might not be applicable due to changes in climate, in hydrological regime (e.g. land use changes, urbanisation, and wetland draining), and in river infrastructure. The impacts of these changes on extreme precipitation and flood frequency characteristics should be quantified and incorporated in design guidelines and standards. This includes detection and attribution of past changes or trends and projection of future changes. Improved knowledge of the likely future risk profiles also plays an important role in decision making when considering, for example, societal adaptation to future climate change (Hall et al., 2012; Bormann et al., 2012).

Changes in extreme precipitation and flood statistics has become a very active research area, and numerous studies have been published in recent years that analyse trends in historical time series of extreme precipitation and flood discharge (see review in Section 2). Investigation of possible climate change is a primary driver for these studies. With respect to changes under a future climate, climate modelling studies have shown that an increase in heavy precipitation is likely in most parts of the world in the 21st century (IPCC, 2012). As river flow is the integrated response of many driving processes, including meteorological forcing (temperature, precipitation, evaporation), morphologic properties of the catchment (slope, elevation), geologic characteristics (groundwater in aquifers, runoff characteristics), and anthropogenic activities (water withdrawal for irrigation or drinking, dams for flood mitigation or hydropower production, and land-use changes), such impacts on floods are challenging to assess. The projected increases in heavy precipitation as well as projected increases in temperature are expected to have an impact on flood frequency. To quantify these impacts a large number of studies have been conducted using projections from climate models as input to hydrological modelling (see review in Section 3).

While water resources management issues in Europe are complex and often predicated on local political, socio-economic, geophysical and climatic conditions (EEA, 2012), it is generally agreed that a risk-based approach to flood management is desirable. Consequently, the European Commission adopted the Flood Directive (Directive 2007/60/EC) (EC, 2007) to '*establish a framework for the assessment and management of flood risk, aiming at the reduction of the adverse consequences for human health, the environment, cultural heritage and economic activity associated with floods in the Community'*. The Directive requires member states to identify areas at risk of flooding and to take into consideration '*long term developments including impacts of climate change on the occurrence of floods*' (EC, 2007). However, the Directive does not prescribe actual guidelines for how best to estimate these potential impacts of climate change on flood risk.

As a first response to this gap between the requirements of the Flood Directive and the technical knowledge required to implement it, this paper presents a review of studies on detection of past trends based on observations and on likely future trends based on climate projections for extreme precipitation and hydrological floods in Europe. The review is based on a survey conducted as part of the COST Action ES0901 European Procedures for Flood Frequency Estimation (FloodFreq) and summarises results from review reports that have been prepared by 19 country members of the FloodFreq COST Action (see overview of contributing countries and organisations in Table 1). We have also included studies reported in a recent publication by the International Association of Hydrological Sciences (IAHS) on changes in flood risk in Europe (Kundzewicz, 2012). The following two sections (Sections 2 and 3) summarise, respectively, the studies on trend analysis of observed data and on projections of likely changes derived from climate model data. Each section includes a review of the methods applied and a summary of the key findings. In Section 4, existing guidelines in Europe on design flood and design rainfall estimation that have incorporated a consideration of climate change impacts are reviewed. Finally, a discussion and conclusions are presented in Section 5.

2. Trend analysis

The studies reviewed on trend analysis of extreme precipitation and floods are summarised in Table 2. The summary includes information about (i) study location and extent (i.e. European-wide, larger regions covering several countries, nationwide, smaller regions covering several catchments within a geographical coherent area, and river basins or catchments); (ii) the hydrological variable considered, i.e. precipitation or river discharge, including temporal resolution, number of stations, and length of the time series included in the analysis, as available; (iii) trend detection method(s) applied; (iv) summary of key findings, and (v) references.

Trend analyses from 46 studies representing 22 countries in Europe have been reviewed, see Figure 1. The review includes nationwide studies of extreme precipitation from Bulgaria, the Czech Republic, Denmark, Germany, Greece, Sweden and the UK, and of extreme streamflow from Austria, Finland, France, Germany, Lithuania, Poland, Slovenia, Switzerland and the UK. In addition, studies on changes in extreme precipitation and streamflow at a European scale and larger regional studies of extreme streamflow for the Alps (Austria, France, Germany, Italy, Slovenia and Switzerland), the Baltic countries (Lithuania, Latvia and Estonia) and the Nordic countries (Norway, Sweden, Denmark, Finland and Iceland) are included in the analysis. With respect to extreme precipitation, most studies are based on daily rainfall extremes, whereas some studies also report results on trend analysis of high-resolution rainfall extremes (down to 1-10 minutes). For extreme streamflow the reported studies are mainly based on daily discharge values, and in some cases on instantaneous peak flow values. River stage values have been analysed in one of the reviewed studies. In most studies, extreme value indices analysed have been derived using annual maximum or peak over threshold series, considering both annual and seasonal extremes.

2.1 Methods

Methods applied for analysing trends include both descriptive analyses and statistical tests. A simple descriptive approach is to compare distributions of extreme precipitation or discharge time series sampled from different sub-periods (e.g. Pashiardis, 2009; Madsen et al., 2009). A related method is to use a moving window approach in which the estimated extreme value distributions are analysed within each time window and compared (Ntegeka and Willems, 2008; Brunetti et al., 2001).

Different statistical tests have been applied for testing of trends in extreme precipitation and discharge time series (see e.g. Yue et al., 2012). These tests can be grouped into (i) at-site tests that are applied to a single time series, (ii) field significance tests that are applied to multiple time series to test their joint statistical significance, and (iii) regional consistency tests that are used for testing the spatial coherency of trends within a region.

The most widely used at-site test is the Mann-Kendall test (Blöschl et al., 2012; Bocheva et al., 2009; Kyselý, 2009; Sadri et al., 2009; Korhonen and Kuusisto, 2010; Petrow and Merz, 2009; Petrow et al., 2009; Bormann et al., 2011; Meilutyte-Barauskiene and Kovalenkovienė, 2007; Meilutyte-Barauskiene et al., 2010; Jurko, 2009; Hannaford and Marsh, 2008; Reihan et al., 2007; Reihan et al., 2012; Wilson et al., 2010; Guintoli et al., 2012). The modified Mann-Kendall test is recommended for auto-correlated data (e.g. Korhonen and Kuusisto, 2010; Petrow and Merz, 2009; Petrow et al., 2009). In this case trends can be quantified using the non-parametric linear Sen’s slope estimator (Sen, 1968), and if data are found to be auto-correlated, a pre-whitening procedure (e.g. Wang and Swail, 2001; Yue et al, 2003) can be applied to remove autocorrelation from the time series prior to applying the Mann-Kendall test. Regression analysis has been applied to extreme precipitation series (Gregersen et al., 2013ab; Bengtsson, 2011; Nastos and Zerefos, 2008; Van den Bessalar et al., 2013; Zolina, 2012; Osborn et al., 2000; Jones et al., 2013) and flood discharge series (Bormann et al., 2011; Strupczewski et al., 2009; Jurko, 2009; Robson et al., 1998; Hannaford and Marsh, 2008). These studies include regression analysis on both the observed time series and sample statistics. For instance, Strupczewski et al. (2009) applied linear regression analysis to the mean and the variance of annual maximum flow series, whereas Galiatsatou and Prinos (2007) applied polynomial regression of the estimated location and scale parameter of the fitted Gumbel distribution. Other applications of at-site trend tests that have been applied include Pettitt's change point test and non-parametric sign test (Castellarin and Pistocchi, 2011); and normal scores regression and Spearman's correlation tests (Robson et al., 1998). A general framework for selection of tests was developed by Renard (2006) (see Lang et al., 2006), considering autocorrelation, distribution type, type of change (step change or trend), and length of the data series. Parametric tests based on the likelihood ratio of alternative hypotheses (LR tests) seem to be the most powerful, especially for extreme value data, provided that the distributional assumptions (e.g. Generalized Extreme Value or Generalized Pareto distributions) are fulfilled. Galiatsatou and Prinos (2007) used an LR test for testing the significance of the polynomial trends of estimated distribution parameters.

Field significance tests have been applied in some nationwide and regional studies (in France, Renard , 2006; Germany, Petrow and Merz, 2009; Petrow et al., 2009; in the Alps, Bard et al., 2012; and in the Nordic countries, Wilson et al., 2010). Several methods that account for inter-site dependence have been proposed to test the joint significance of the multiple time series, including (i) an equivalent (or effective) number of stations (Matalas and Langbein, 1962), (ii) a bootstrap procedure (Douglas et al., 2000; Burn and Hag Elnur, 2002), (iii) a Gaussian copula methodology (Renard and Lang, 2007), and (iv) the false discovery rate (FDR) (Benjamini and

Hochberg, 1995; Ventura et al., 2004). In the study by Renard et al. (2008) the bootstrap procedure was recommended, as it is easier to apply and requires no parametric assumption about marginal and joint distributions of the data. The FDR procedure is significantly more powerful for detecting changes affecting only a limited part of the sites, but is less powerful for detecting weaker generalized changes. In Petrow and Merz (2009) and Petrow et al. (2009) field significance was evaluated by the bootstrap method of Douglas et al. (2000), using a slightly modified approach in which field significance of upward and downward trends are assessed separately (Yue et al., 2003). Wilson et al. (2010) used the bootstrap procedure described by Burn and Hag Elnur (2002).

Renard et al. (2008) compared different methods for testing regional consistency of changes in hydro-climatic regions. These include (i) univariate tests (e.g. Mann-Kendall test) of regional indices, i.e. variables defined over the entire region (e.g. the regional mean value of the date of occurrence of the annual maximum flood), (ii) the regional average Mann-Kendall test proposed by Douglas et al. (2000) and Yue and Wang (2002), and (iii) a semi-parametric approach based on a normal score transformation and multivariate Gaussian distribution. Renard et al. (2008) applied these methods for testing trends of extreme streamflow in hydro-climatic regions in France. Sadri et al. (2009) applied the regional Mann-Kendall test to extreme precipitation data in Denmark.

2.2 Key findings

Some studies report increases in extreme precipitation based on observed daily values (in the western part of the Czech Republic in the winter, Kyselý, 2009; in some regions in France, Pujol et al., 2007; in Germany in the winter, Zolina, 2012; in north-eastern Italy, Brunetti et al., 2001; and in the UK in the autumn, winter and spring, Osborn et al., 2000, Jones et al. 2013). Studies for Germany and the UK report decreases in extreme precipitation in summer (Zolina, 2012; Osborn et al., 2000, Jones et al. 2013). Analyses in southern Sweden indicated no trend in daily maximum precipitation over the previous 90 years (Bengtsson, 2011). Bocheva et al. (2009) found a significant increase in the frequency of extreme daily precipitation in Bulgaria, and Nastos and Zerefos (2008) also found an increase in the frequency of extreme precipitation in Greece, although not statistically significant. In the study by Zolina (2012) a general increase of extreme winter precipitation over Europe was found, whereas for summer precipitation a decrease was observed at many locations in western and central Europe. Van den Bessalar et al. (2013) found a general increase in extreme precipitation in autumn, winter and spring in northern Europe, but smaller increases were observed in southern Europe. The findings of the two European-wide studies are, in general, consistent with the nationwide studies on daily precipitation, although differences in sub-regional and local patterns are found. With respect to short-duration rainfall (from 5-10 min up to 24 hours) some studies report changes , and these studies generally report increases (e.g. in Brussels, Belgium, Ntegeka and Willems, 2008; in Nicosia, Cypress, Pashiardis, 2009; and in Denmark, Madsen et al., 2009, Sadri et al., 2009). In the analysis of short-duration rainfall extremes from 15 stations in Sweden, Hernebring (2006) only found an increasing trend at one station (Malmö).

With respect to changes in observed extreme streamflow, the general conclusion is that there are no clear national or larger-scale regions in Europe which uniformly exhibit statistically significant increases in flood discharges in recent years. However, for smaller regions increases are apparent, e.g. in the northern part of Austria (Blöschl et al., 2012), in northeast France (Renard, 2006; Guintoli et al., 2012); in some regions in Germany (Petrow and Merz, 2009; Petrow et al., 2009; Bormann et al., 2011; Hattermann et al., 2012); in alpine basins in Switzerland (Castellarin and Pistocchi, 2011) and generally in glacier regimes in the Alps (Bard et al., 2012); and in maritime-influenced catchments in northern and western UK (Hannaford and Marsh, 2008). In many cases, individual stations in a country or within larger regions may have both positive and negative trends or no evident trend (e.g. spring peak flows in Finland, Korhonen and Kuuisisto, 2010; annual and seasonal maximum flows in the Nordic region, Wilson et. al., 2010; and in Slovenia, Jurko, 2009). Several studies report decreases in peak discharges (e.g. in the Baltic region, except western parts of Latvia and Lithuania, Reihan et al., 2007, 2012; in the Pyrenees, Renard, 2006; in mountainous areas in Slovenia, Jurko, 2009; and for some stations in Poland, Strupczekski et al., 2009; and Turkey, ARTEMIS, 2010). In addition, many studies undertaken in areas where snowmelt makes an important contribution to peak flows report an earlier spring snowmelt peak (e.g. in Finland, Korhonen and Kuuisisto, 2010; more generally throughout the Nordic region, Wilson et al., 2010; in the Alps, Renard, 2006, Bard et al., 2012; in Lithuania, Meilutytė-Barauskienė and Kovalenkovienė, 2007; and throughout the Baltic region, Reihan et al., 2012). In a European-wide study by Stahl et al. (2012) of 7-day annual maximum flows a general pattern of negative trends in southern and eastern Europe and positive trends elsewhere was found. It should be noted, however, that their results are not directly comparable with the other results reported in Table 2, which are based on extreme daily or instantaneous peak flows. In general, use of different indices for the trend analyses makes direct comparisons of results problematic. For instance, Petrow and Merz (2009) found opposite trends at the same gauging sites when using peak-over-threshold and annual maximum data.

As discussed by several authors (e.g. Svensson et al., 2006; Chen and Grasby, 2009; Hannaford et al., 2013), a specific difficulty in detecting trends is that several signals can overlap. Decadal and interdecadal variability are difficult to quantify when the series is too short (e.g a few decades). Use of long historical series and regional data sets provide the basis for detecting trends with higher confidence. In the analysis of trends in extreme streamflow, change in the meteorological forcing is just one of several potential attributes. In this context, Merz et al. (2012) advocated for a renewal of the statistical analysis of time series for a sound attribution of trends, considering evidence of consistency (relationship between cause and effect), evidence of inconsistency (failure to explain a trend without a specific driver), and provision of a confidence measure. Some of the studies listed in Table 2 include analyses of the causes of the observed trends and attribute the changes to drivers such as climate change, land-use change, river developments, etc. Petrow and Merz (2009) and Petrow et al. (2009) showed that the spatial and seasonal coherence of the trends of flood series in Germany suggested that the observed changes are climate-driven and can be related to changes in atmospheric circulation patterns. Bormann et al. (2011) showed that at some gauge locations in Germany increasing trends in discharge may be compensated by river training resulting in an opposite trend in river stage. In the study of Alpine catchments in Switzerland, Castellarin and Pistocchi (2011) showed that the increase in flood discharge can be explained in terms of temperature increases. The trends towards earlier spring floods in the Baltic countries have also been related to increasing temperature (Meilutyte-Barauskiene and Kovalenkovienė, 2007; Reihan et al., 2007; Reihan et al., 2012). In the analysis of extreme precipitation in Belgium, Ntegeka and Willems (2008) found multi-decadal oscillations that can be partly explained by atmospheric circulation patterns, and a departure from this oscillation with trends towards more extreme precipitation in recent decades may be an indication of climate change. Gregersen et al. (2013b) showed that the temporal variations in the frequency of extreme rainfall events in Denmark can be partly explained by atmospheric circulation patterns, average summer precipitation, and average summer temperature.

3. Climate change projections

The studies reviewed on climate change projections of extreme precipitation and floods are summarised in Table 3. The summary includes information about (i) study location; (ii) climate change projections applied, i.e. global climate models (GCM), regional climate models (RCM), and climate forcing scenarios analysed; (iii) bias correction and/or statistical downscaling method(s) applied; (iv) hydrological modelling approach, i.e. type and name of hydrological model(s) applied and information on simulation approach, as available; (v) variable considered, i.e. extreme precipitation (for given durations) or floods; (vi) summary of key findings, including projection horizon, and (vii) references.

Climate change projections from 33 studies representing 13 countries in Europe have been reviewed, see Figure 2. The review includes studies on projections of extreme precipitation for Belgium, Cyprus, the Czech Republic, Denmark and Sweden. Hydrological projections for changes in peak flows and in flood frequency have also been developed for catchments in several countries and are reported here for Belgium, Denmark, Finland, France, Germany, Lithuania, Norway, Poland, Slovakia, Sweden, and the UK. In addition, two European-wide studies are included in the review.

3.1 Methods

Assessment of climate change impacts on flood frequency requires a methodology comprising of a series of linked models and analyses. The basis for the impact assessment is climate change projections from large-scale GCMs. The GCM model runs are based on various climate forcing scenarios, which include the IPCC SRES scenarios (e.g. Nakićenović et al., 2000) and the newer RCP (Representative Concentration Pathways) scenarios (Meinshausen et al., 2011). Output from GCMs, typically having grid cell sizes of 100 – 250 km, is generally too coarse for direct analyses of changes in extreme precipitation and floods, and further processing is required. This processing takes the form of a dynamical downscaling using a RCM and/or some form of statistical processing (including statistical downscaling and bias correction) to obtain suitable data for use in further analyses and modelling. For evaluating the impact on river flooding, downscaled climate data are used as input to hydrological modelling.

A large proportion of the more recent analyses of changes in extremes are derived from RCM projections, including RCM simulations from the PRUDENCE project (Christensen et al., 2007) and the ENSEMBLES project (van der Linden and Mitchell, 2009). There have also been other regional, national and international projects that have focused on generating dynamically downscaled RCM projections (e.g. the EU FP6 project CECILIA, 2012). In some studies, climate change impacts on precipitation extremes have been interpreted directly from RCM outputs (e.g. Kyselý and Beranová, 2009; Kyselý et al., 2011; Hadjinicolaou et al., 2011; Hanel and Buishand, 2011; Arnbjerg-Nielsen, 2012). However, most studies have applied statistical downscaling and/or bias correction of the RCM (or GCM) output for the impact assessment studies.

The most widely-used approaches for statistical downscaling from both GCM and RCM model output are the ‘delta change’ or ‘perturbation’ methods (e.g. Reynard et al., 2001). In the most basic application of this technique, estimates of monthly relative changes in average precipitation are derived by comparing monthly values from climate model output between a reference and a future period. These change factors are then used to derive a time series of precipitation for the future by multiplication of the observed time series (for temperature an additive rather than a relative change is usually applied to the observed series). A considerable number of the studies reviewed that have considered climate change impacts on flood frequency have used this simple approach (e.g. Reynard et al., 2001; Prudhomme et al., 2003; Kay et al., 2006; Kriaučiūnienė et al., 2008, Reynard et al., 2010; Veijalainen et al., 2010) or have combined or compared it with other approaches (e.g. Lawrence and Haddeland, 2011; Sunyer et al., 2010). The methodology has been expanded to include change factors for other statistics such as precipitation variance (Sunyer et al., 2012) and precipitation quantiles (Olsson et al., 2009; Willems and Vrac, 2011), and this development is of particular relevance for projecting changes in extreme precipitation and flood frequency.

A related class of downscaling methods that have been applied are based on generating time series of climate data rather than perturbing observed time series. This includes use of stochastic rainfall models or weather generators, application of weather typing and resampling methods, and use of climate analogues. When used for downscaling from climate models, stochastic rainfall generators (e.g. Semenov et al., 1998; Brissete et al., 2007; Burton et al., 2008) are set up using probability distribution functions conditioned on outputs from the climate model, typically based on projected changes in different rainfall statistics. Comparisons between different rainfall generators and with change factor based perturbation methods indicate that certain rainfall generators are more suitable for evaluating changes in extremes than simple change factor methods (Sunyer et al., 2012). Weather typing (and related resampling) is also used for downscaling precipitation (e.g. Enke et al., 2005; Boé et al., 2006; Willems and Vrac, 2011) and is based on the concept of grouping days with synoptic similarity to define a finite set of weather types. Downscaling with this method takes the general form of identifying the relevant weather type for each day simulated by the climate model based on e.g. simulated pressure and temperature. The precipitation for that day is then selected from an observed precipitation series for a day having similar conditions. However, there are many variations of this approach (e.g. the resampling method of Orlowsky et al., 2008). A general limitation of many weather type approaches is that they do not allow for precipitation values that exceed those found in the observations. Alternative formulations include relating future precipitation to both weather type and to temperature (e.g. Willems and Vrac, 2011) and use of analogue data from other locations with observed precipitation series.

The methodologies described above involve the use of quantities derived from changes in climate model output from a reference to a future period. An alternative approach is bias correction where differences between RCM output for the control period and the observed time series are used to correct RCM output for the future period. Several methods for bias correction have been applied, such as a simple correction of the mean (e.g. Graham et al., 2007), empirical adjustment methods that correct the mean and the standard deviation (Engen-Skaugen, 2007; Leander and Buishand, 2007), distribution-based corrections using gamma functions (e.g. Piani et al., 2010) or double-gamma functions (Yang et al., 2010), and methods based on quantile-quantile mapping (e.g. Déqué, 2007). The application of these techniques should also include a strategy for adjusting the number of rainy days.

With respect to evaluating impacts on flash flood hazard resulting from extreme precipitation (e.g. urban flooding), the focus is on changes in short-term extreme precipitation statistics or on intensity-duration-frequency (IDF) relationships (e.g. see review of Willems et al., 2012). In some studies, projections of IDF relationships have been further applied to assess the impact on urban drainage systems (e.g. Olsson et al., 2009; Willems et al., 2010).

For evaluating climate change impacts on the frequency of river flooding, hydrological models are applied that use projections of rainfall and other climate data (e.g. temperature and, in some cases, potential evapotranspiration). Many of the hydrological models applied in the climate change studies reported in Table 3 are lumped and semi-distributed conceptual models such as HBV (Bergström, 1995; Sælthun, 1995), NAM (Nielsen and Hansen, 1973), PDM (Moore, 2007), GR4J (Perrin et al., 2003), SWIM (Krysanova et al., 1998), VHM (see overview in Taye et al., 2011), and WSFS (Vehviläinen,1994). Distributed, grid-based models such as ASGi, (Becker and Braun, 1999), CLASSIC (Crooks et al., 2000; Reynard et al., 2001), G2G (Bell et al., 2007), LARSIM (Ludwig and Bremicker, 2006), LISFLOOD (DeRoo et al., 2000), and

MIKE SHE (Graham and Butts, 2006) have also been used in climate change impact analyses of flooding. In most cases, the grid-based distributed models include surface flow routing, such that climate change impact on flood runoff can, in principle, be estimated at each point in the model grid. For more detailed flood risk assessment studies hydrodynamic models have been applied, such as the MIKE 11 model (Havnø et al., 1995). In addition to gridded, distributed hydrological models, land surface climate models and integrated hydrological and meteorological models, such as CLSM (Koster et al., 2000; Ducharne et al., 2000) and SIM (Habets et al., 2008) have been used for evaluating climate change impacts on flooding (Ducharne et al., 2010).

The review indicates that there are numerous alternative approaches for assessing climate change impacts on extreme precipitation and flood frequency using climate model projections. The various alternative climate forcing scenarios, climate projections from available GCMs and RCMs, methods for statistical downscaling and bias correction, and hydrological models can produce differing projections for the impact variable of interest. The importance of considering a range of alternatives at each step of the climate change impacts modelling chain was first highlighted by Wilby and Harris (2006). Several of the flood frequency analyses reported in Table 3 consider a number of climate projections to produce a distribution of outcomes, as recommended by Dankers and Feyen (2009) rather than relying on a single climate projection. Besides the inclusion of different climate model projections, ensemble methods representing alternative downscaling techniques (e.g. Beldring et al., 2008; Willems and Vrac, 2011; Sunyer et al., 2012) are also represented in the studies reported in Table 3. It appears that less attention has been given to the potential contribution of hydrological modelling approaches as a potential source of uncertainty in the projections. This issue comprises a number of different factors, including the role of model structure and complexity, model parameter uncertainty, and model calibration procedures. Wilby (2005) considered uncertainty arising from model structure, the model calibration period and the non-uniqueness of model parameter sets due to equifinality in the optimisation process and found that these sources of uncertainty can dominate the climate change impacts modelling chain in some catchments. Similarly, Bastola et al. (2011) noted that hydrological model uncertainty is ‘remarkably high’ in their analysis of climate change impacts, which included the application of four different rainfall-runoff models and two alternative methods for assessing parameter uncertainty. Lawrence and Haddeland (2011) compared the relative contributions of emission scenarios, GCMs, downscaling methods and hydrological parameterisation in four catchments dominated by differing types of flood regimes resulting from various combinations of rainfall vs. snowmelt. They concluded that uncertainty associated with hydrological modelling is relatively higher in the two catchments with combined rainfall-snowmelt flood regimes. In addition, Brigode (2013) have recently evaluated the potential role of hydrological model parameter instability in the chain of uncertainty sources in climate change impact studies. They suggested that the use of a calibrated hydrological model under non-stationary conditions requires model structures and calibration procedures, which produce robust parameterisations suitable for such analyses. Refsgaard et al. (2014) presented a validation framework and guiding principles for testing the capability of hydrological models to project climate change impacts.

Most of the reported studies assume stationary conditions within a given time window (typically 30 years) for the current and future climate and compare the estimated extreme value characteristics from the two periods. For changes in precipitation extremes, change factors are often then calculated for seasonal or monthly precipitation statistics (e.g. Olsson, et al., 2009; Hadjinicolaou et al., 2011; Arnbjerg-Nielsen, 2012) or IDF curves (e.g. Willems and Vrac, 2011; Olsson, et al., 2012). Arnbjerg-Nielsen (2012) has also further used a stochastic rainfall generator to produce 100 years of synthetic data to enable a possibly more robust comparison of the empirical distribution functions for the two periods. For changes in extreme discharges, the published work considers changes in flood statistics, such as the magnitude of the spring flood (Kriauciuniene et al., 2008), the average annual flood (e.g. Lawrence and Haddeland, 2011), or most often the change in the discharge magnitude with a given return period based on flood frequency analysis (e.g. Prudhomme et al., 2003; Dankers and Feyen, 2008; Veijalainen et al., 2010; Hattermann et al., 2011; Lawrence and Hisdal, 2011). Flood frequency analysis is typically performed using either block maxima (i.e. annual peak flow series) or peak over threshold (i.e. partial duration series) approaches for the control and the future periods, and the change in the magnitude of a flood with a given return period is then calculated.

More recently, the dynamic pattern of changes in flood frequency in response to transient climate model simulations have been reported by Bergström et al. (2010) (see Lawrence et al. (2012) for a description in English), and Kay and Jones (2012). Both of these studies applied a moving 30-year window over the simulated output. Kay and Jones (2012) also applied a non-linear trend analysis on the derived time series and introduced a test for its statistical significance. Such transient impact studies represent a more detailed investigation and illustrate both the development and the variability in the pattern of change over time. They are, however, not based on a full non-stationary frequency model. Most existing work on non-stationary extreme value models attempts to introduce time-varying parameters into well-known extreme value models such as the Generalised Extreme Value (GEV) distribution (e.g. Hanel and Buishand, 2011). Such approaches have potentially much to offer in the analysis of changes in flood frequency in response to changing climatic conditions, although our review indicates that traditional stationary flood frequency analysis dominates the methods currently used.

3.2 Key findings

The studies reporting projections of changes in extreme precipitation point, in general, towards increases. The projected changes include increases in rainfall intensity of up to 30% by 2100 in Brussels (Willems and Vrac, 2011; Willems et al., 2012), increases up to 30-50% in the 50 and 100-year daily precipitation in the Czech Republic (Kyselý and Beranová, 2009; Kyselý et al., 2011, Hanel and Buishand, 2011), and small increases in maximum daily precipitation in Cyprus by 2050 (Hadjinicolaou et al., 2011). Studies in Denmark similarly report projected increases in daily precipitation extremes of up to a factor of 2 for the 100-year event for a station north of Copenhagen (Sunyer et al., 2012), and a national study of projections for shorter duration (1 to 24 hours) intensities indicate increases of 10-50% over the next 100 years (Arnbjerg-Nielsen, 2012). Increases in short-duration precipitation extremes have also been reported for Sweden (20-60% in Kalmar, Olsson et al., 2009; 10-20% in Stockholm, Olsson et al., 2012). These projections are, in general, consistent with the reported results described above of trends in observed extreme precipitation that show recent increases at many locations in Europe.

With respect to hydrological projections of changes in flood frequency at the catchment scale, both positive and negative changes in extreme discharge are projected. Increases in peak discharges are projected for sub-basins in the Scheldt and Meuse in Flanders (Boukhris and

Willems, 2008; Willems et al., 2010), for catchments in Denmark (Sunyer et al., 2010; Madsen et al., 2013), for Bavaria and Baden-Württemberg (Hennegriff et al., 2006) and Saxony-Anhalt (Hattermann et al., 2011) in Germany, for western, mid-northern and all of coastal Norway (Lawrence and Hisdal, 2011), for the Hron catchment in Slovakia (Hlavcova et al., 2007), in coastal, southern areas in Sweden (Bergström et al., 2012), and in many catchments within the UK (Reynard et al., 2001; Prudhomme et al., 2003; Kay et al.; 2006; Reynard et al., 2010; Kay and Jones, 2012). In addition, studies considering likely changes in seasonal inflows to lakes in Finland (Veijalainen et al., 2010) and to Lake Vänern in Sweden (Bergström, et al, 2010; Olsson, et al., 2011) indicate possible increases under a future climate. For other areas only small increases (e.g. southern Finland, Veijalainen et al., 2010; parts of Norway, Lawrence and Hisdal, 2011) or no significant change in flood discharge (e.g. for the Seine and Somme in France, Ducharne et al., 2010) are projected. There are also many regions for which a likely decrease in flood discharge has been projected, including much of Finland (Veijalainen et al., 2010), the Nemunas catchment in Lithuania (Kriaučiūnienė et al., 2008), the Wełna and Orla catchments in Poland (Osuch et al., 2012), and inland catchments in Norway (Lawrence and Hisdal, 2011) and in Sweden (Bergström et al., 2012). Kay et al. (2006) also project decreases in flood magnitude for the catchments in south and east England.

In addition to the studies reported above for individual catchments, countries and regions, European-wide projections of likely changes in future flooding have been made based on the LISFLOOD hydrological model (Dankers and Feyen, 2008; Rojas et al., 2012). Dankers and Feyen (2008) report a likely decrease in the 100-year return level in northeastern Europe, as well as in some rivers in central and southern Europe, and increases in many parts of western and eastern Europe. There are, however, discrepancies between the three model runs considered, which are based on a single GCM that was run under A2 and B2 SRES scenarios and dynamically downscaled at two differing horizontal resolutions. The more recent LISFLOOD simulations (Rojas et al., 2012) are based on a larger ensemble of GCM/RCM combinations. In addition, the RCM output is bias corrected using quantile mapping prior to hydrological model simulation. These results confirm the projected increases in the magnitude of the 100-year flood in western Europe. Increases are also projected for the British Isles and northern Italy, while decreases are indicated in some rivers in eastern Germany, Poland, southern Sweden and the Baltic countries. The decreases projected for southern Sweden, as well as some of the increases projected for inland rivers in Norway, are somewhat at odds with the projections reported based on national studies (e.g., Lawrence and Hisdal, 2011, Bergström et al., 2012; Lawrence et al., 2012). Although the reason for this difference is unclear, it may be related to the effects of river regulation on the data series used in the calibration of the LISFLOOD model.

There are several factors which will have an influence on the response of individual catchments to projected regional changes in temperature and precipitation, including the dominant flood generating mechanism. Important distinctions can be made between flooding in response to intense precipitation of short duration vs. longer periods of heavy rainfall and between flood regimes dominated by rainfall vs. snowmelt. Catchment size and topographic relief are also critical in determining the dominant processes producing peak flows. These factors contribute to the large differences across Europe in the reported projections for flood magnitudes under a future climate, which makes it especially difficult to draw general conclusions regarding the level of agreement between observed trends in peak discharge and projections of changes in flood magnitudes under a future climate. One exception amongst these factors is, however, the role of snowmelt in flood generation. Despite expected increases in extreme precipitation throughout Europe, many areas dominated by peak flows during the spring to early summer snowmelt season are projected to have decreased flood magnitudes under a future climate, reflecting a decline in snow storage during winter periods. In addition, peak flows are expected to occur earlier. These projections are consistent with the observed trend towards earlier snowmelt peaks and decreases in spring peak flows described in Section 2.2 and Table 2. Climate change projections, though, also indicate that many areas of Europe are likely to experience an increase in peak flood discharges. The regions and types of catchments in which increases are observed cf. Section 2.2 and Table 2 are generally consistent with the projected changes. Such catchments tend to exhibit peak flows in response to rainfall, rather than snowmelt, typically during the autumn-winter period under conditions of catchment saturation.

4. Design guidelines

Reviews of current guidelines in Europe for design flood and design rainfall that include the potential impacts of climate change are summarised in Table 4. These guidelines are typically derived from model-based assessment of future climate projections. In all reviewed cases, the guidelines exist in the form of relatively simple correction factors, where results obtained from analysis of historical data (e.g. 100-year design floods) are corrected using a percentage factor (often referred to as climate factor). Most guidelines provide correction factors corresponding to expected changes for one projection horizon, typically 2100, but some recommend different correction factors to be used for different time horizons.

Norway, the UK, two river basin authorities in Belgium, and two federal states in Germany have developed guidelines for directly adjusting design flood estimates for climate change impacts. In Belgium, the two main river authorities for the Flanders region (W&Z - Flanders Hydraulics, Flemish Environment Agency) have established guidelines for flood hazard mapping under current climate conditions and for high, mean, and low climate scenarios. In the high climate scenario, the peak flows (for return periods larger than 1 year) increase with about 30% by 2100 (Boukhris and Willems, 2008). In Germany, the two federal states of Bavaria and Baden-Württemberg have both introduced climate change factors. In Bavaria a factor of +15% is added to the 100-year estimate, whereas Baden-Württemberg have adopted climate factors varying between 0% and +75%, depending on the region and the return period (decreasing climate factors for increasing return periods) (Hennegriff et al., 2006). In Norway, climate factors of 0%, 20% and 40% increase of design flood estimates are recommended based on location (region and inland or coastal catchment), and prevailing flood season. For all catchments with a catchment area less than 100 km^2, a default increase of 20% is recommended, reflecting evidence that short-term extreme precipitation will increase throughout the country under a future climate, and that smaller catchments are most vulnerable to this increase (Lawrence and Hisdal, 2011). In the UK, statistical procedures for flood frequency analysis are currently based on assumptions of stationarity. However, procedures exist to adjust design flow estimates for the perceived impact of climate change. A climate factor of +20% is applied, as recommended by Defra (2006), to compensate for climate change with a time horizon until 2085. Subsequently, it should be investigated if this increase in design flow has a significant impact on design/management of the hydraulic structure being studied. More recently, research has been undertaken to derive more regional climate factors (Prudhomme et al., 2010), but these results have not yet found their way into official policy.

More specifically targeting urban drainage design, guidelines for adjusting design rainfall estimates have been developed for Belgium, Denmark, Sweden and the UK. In Belgium, IDF curves and design storms have been developed for high, mean, and low climate scenarios. Rainfall intensities increase with about 30% by 2100 in the high climate scenario (and between 0% and 30% for the other scenarios). In Denmark, Arnbjerg-Nielsen (2008) published climate factors for use with existing IDF curves in Denmark. The guidelines prescribe climate factors of +20%, +30% and +40% by 2100 when estimating design rainfall of 2, 10, and 100-year, respectively. While recognising that the effects might vary for different rainfall durations and geographical locations, these effects were considered secondary in relation to return periods, and thus, not considered. Note that the Danish guideline recommends increasing climate factors for increasing return periods, which is in contrast with the recommendations for design floods in Baden-Württemberg (Hennegriff et al., 2006). The Swedish Water & Wastewater Association (SWWA, 2011) published guidelines with a climate factor between +5% to +30% depending on the region. For the UK, Defra (2006) advices that peak rainfall should be increased by a factor of 10%, 20% and 30% for the time horizons 2055, 2085 and 2115, respectively.

5. Discussion and conclusions

The large number of studies reviewed in this paper show that non-stationarity in extreme precipitation and flood characteristics due to climatic changes is high on the research agenda in Europe. Numerous studies have been undertaken, including European-wide studies, larger regional studies covering several countries, nationwide studies as well as more local studies. The studies indicate that there is some evidence of a general increase in observed extreme precipitation, whereas there are no clear indications of significant increasing trends at larger-scale regional or national level of observed extreme streamflow. The most significant result regarding extreme streamflow is that several studies from regions dominated by snowmelt-induced peak flows report decreases in extreme streamflow and earlier spring snowmelt peak flows, likely caused by increasing temperature. For some regions in Europe apparent increases in extreme streamflow are found.

Regarding climate model projections most studies reviewed indicate an increase in extreme precipitation under a future climate, which is consistent with the observed trend of extreme precipitation. Hydrological projections of peak flows and flood frequency show both positive and negative changes. Large increases in peak flows are reported for some catchments, whereas a general decrease in flood magnitude and earlier spring floods are reported for catchments with snowmelt-dominated peak flows. The latter is consistent with the observed trends.

Although there is evidence in scientific literature of trends in observed extreme precipitation and flood discharge in recent years, and use of climate model projections shows a likely impact on these extremes in the 21st century throughout Europe, only few countries have developed guidelines for incorporating climate change. The EU Floods Directive (2007/60/EC) states that consideration should be given to the possible effects of climate change on flood hazard in flood risk assessment and management (Ch.II, Art.4.2 and Ch.VIII, Art.14.4). The potential effects of long-term environmental changes on flood risk, including climate change, are to be considered both in conjunction with preliminary flood risk mapping and development of flood risk management plans. The review has highlighted a gap between the need for considering effects of environmental change on extreme floods, as stipulated in the EU Floods Directive, and the actual paucity of published guidelines for how to incorporate these effects in flood frequency estimation.

It should be recognised that the process of producing scientific research is not always compatible with the social, legal and economic constraints under which end-users such as infrastructure owners and decision-makers operate. For example, changes to dam safety and flood protection standards cannot easily be accommodated at the same short timescales as those typically involved in producing scientific research. In addition, changes to design flood estimates might have severe economic consequences. For example, if changes in the 100-year design flood leads to significant changes in the delineation of flood hazard zones, this might result in an increase of insurance premiums for affected households and businesses. Changes in dam spillway design to accommodate changes in 10,000-year design floods might be very costly, and it would be right to be cautious before implementing and enforcing such changes.

The main scientific challenges for the future are to improve our knowledge of natural climate variability and to assess the impact of environmental changes on extreme floods. A more general non-stationary framework has to be developed (such as the models first proposed by Strupczewski et al., 2001a,b,c) and included into operational guidelines for flood risk mitigation. The question of uncertainty is of primary importance: we should be able to assess the significance of future changes on flood risk and propose some way to account for design values in a changing environment.

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Tables

Table 1 List of countries and organisations that have contributed to the survey.

Country	**Organisation(s)**
Belgium	KU Leuven, Hydraulics Division, Leuven
Bulgaria	National Institute of Meteorology and Hydrology, Bulgarian Academy of Sciences, Sofia
Cyprus	Dion Toumazis & Associates, Nicosia
Czech Republic	T. G. Masaryk Water Research Institute, Prague Faculty of Civil Engineering, Czech Technical University, Prague
Denmark	DTU Environment, Technical University of Denmark DHI, Hørsholm
Finland	Finnish Environment Institute, Freshwater Centre, Helsinki
France	Irstea, UR HHLY, Lyon
Germany	Helmholtz Centre Potsdam – GFZ German Research Centre for Geosciences, Section Hydrology, Potsdam
Greece	Department of Civil Engineering, University of Thessaly, Pedion Areos, Volos
Italy	GECO sistema srl – Cesena, Italy and Regione Emilia Romagna – Autorità dei Bacini Regionali Romagnoli, Forlì
Lithuania	Lithuanian Energy Institute
Norway	Norwegian Water Resources and Energy Directorate, Oslo
Poland	Department of Hydrology and Hydrodynamics, Institute of Geophysics, Polish Academy of Sciences
Slovakia	Department of Land and Water Resources Management, Faculty of Civil Engineering, Slovak University of Technology, Bratislava
Slovenia	Faculty of Civil and Geodetic Engineering, University of Ljubljana, Ljubljana
Spain	Department of Civil Engineering, Hydraulic and Energy Engineering, Technical University of Madrid, Madrid
Sweden	Swedish Meteorological and Hydrological Institute, Norrköping DHI, Göteborg
Turkey	Middle East Technical University, Civil Engineering Department, Ankara Dokuz Eylul University, Department of Civil Engineering, Izmir
UK	Centre for Ecology & Hydrology, Wallingford Department of Geography, University of Liverpool

Table 2 Summary of reviewed studies on trend detection of precipitation extremes and floods.

Country/region	**Data/variable**	**Methods**	**Key findings**	**Reference**
Alps	177 stations from 6 countries Daily discharge	Field significance test Semi-parametric regional consistency procedure	Higher spring snowmelt-related flows and increase in volume and peak of snowmelt flows for glacier regimes. An earlier start of the snowmelt season and increase in the duration of the snowmelt season.	Bard *et al.* (2012)
Austria	512 stations Annual and seasonal maximum discharge	Mann-Kendall test	Annual maxima: increasing trends, particularly north of the main Alpine ridge and with intermediate catchment size (< 500 km^2) Seasonal maxima: increasing trends for summer floods except in Tirol (decreasing), and for winter floods (except in Southeast)	Blöschl *et al.* (2012)
Baltic countries (Lithuania, Latvia, and Estonia)	70 stations Daily discharge (84 years of record)	Mann-Kendall test Sen's trend test	Trends towards earlier spring floods observed in all Baltic countries (because of warmer winters). A decrease in spring flood magnitude was detected for almost the whole region, except for some hydrological stations in the western parts of Latvia and Lithuania.	Reihan et al. (2007, 2012)
Belgium Uccle, Brussels	Extreme precipitation with durations between 10 min and one month 107-year rainfall series	Frequency analysis with moving window sizes of 5, 10 and 15 years	Statistically significant increase in extreme precipitation, partly explained by persistence in atmospheric circulation patterns over the North Atlantic during periods of 10 to 15 years.	Ntegeka and Willems (2008)
Bulgaria Nationwide study	90 stations Daily precipitation (1961-2005)	Mann-Kendall test	Significant increase in the frequency of extreme precipitation events.	Bocheva et al. (2009)
Cypress Nicosia	Extreme precipitation with durations between 5 min and 2 hours	Analysis of estimated IDF curves based on data from 1931-1970 and 1971-2007	Increase in extreme rainfall intensities observed.	Pashiardis (2009)

Czech Republic Nationwide study	175 stations Daily precipitation (1961-2005) Different extreme precipitation indices	Mann-Kendall test	Significant increase in extreme precipitation in winter in the western part of the country (20 - 30%).	Kyselý (2009)
Denmark Nationwide study	66 stations Extreme precipitation with durations between 1 min and 48 hours	Analysis of estimated IDF curves based on data from 1979-1997 and 1979-2006 Mann-Kendall test Regression analysis	Update of the regional IDF curves showed an increase of about 10% for durations between 30 min and 3 hours and return periods of about 10 years. This trend was also confirmed by a regional Mann-Kendall test. Regression analysis shows an increase of about 2% in the number of extreme events per year for rainfall durations between 10 min and 24 hours.	Arnbjerg-Nielsen (2006) Madsen et al. (2009) Sadri et al. (2009) Gregersen et al. (2013ab)
Europe	1158 synoptic rainfall stations in Europe 95th percentile of daily precipitation	Linear regression test	A general increase of extreme winter precipitation over Europe. An increase of extreme summer precipitation in eastern Europe, but a decrease at many locations in western and central Europe.	Zolina (2012)
Europe	478 stations in Europe Seasonal maxima of 1-day and 5-day precipitation amounts	Linear regression test	In northern Europe, increase of extreme precipitation in autumn, winter and spring. In southern Europe, small increase of extreme precipitation in all seasons.	Van den Bessalar *et al.* (2013)
Europe	441 discharge stations from 15 countries in Europe and simulated daily discharge from 8 hydrological models Annual 7-day maximum discharge	Kendall-Theil slope	Generally, negative trends in southern and eastern Europe and positive trends elsewhere. Indication of positive trends in rain-dominated regimes, and inconsistent or decreasing trends in snow-dominated regimes.	Stahl *et al.* (2012)
Finland Nationwide study	25 stations Daily discharge	Mann-Kendall test	Earlier timing of spring peak flow observed at more than one third of the sites. However, no trend observed in the magnitudes of spring peak flow.	Korhonen and Kuusisto (2010)
France	209 stations	Field significance test	No general change was found at the national scale but clear spatial patterns of positive and negative	Renard (2006)

Nationwide study	Annual maximum series of peak, volume and date	Semi-parametric regional consistency procedure	trends in peaks. Increased flood peaks were observed in Northeast, consistent with the trend in observed rainfall. A decreasing trend in high flow was observed in the Pyrenees. In the Alps, earlier snowmelt-related floods and increasing runoff due to glacier melting were observed.	Renard *et al.* (2008) Giuntoli *et al.* (2012)
France Mediterranean region	92 stations Daily precipitation (1945–2004)	Peak-over-threshold extreme value model with non-stationary parameters	Statistically significant increase of the occurrence and the intensity of extreme rainfall in three out of seven regions were detected.	Pujol et al. (2007)
Germany Nationwide study	5454 rainfall stations 95th percentile of daily precipitation	Linear regression test	A general increase of extreme winter precipitation, and a general decrease of extreme summer precipitation, except in southeastern Germany.	Zolina (2012)
Germany Nationwide study	150 stations Flood time series (1951-2002)	Mann-Kendall test Field significance test (Douglas et al., 2000)	Trends in floods were detected for a considerable number of catchments (both positive and negative trends). Catchments with significant trends were spatially clustered, suggesting that the observed changes in flood behaviour are climate-driven. Changes in circulation patterns were found to influence the changes in floods.	Petrow and Merz (2009) Petrow et al. (2009) Hattermann *et al.* (2012)
Germany Nationwide study	78 stations Discharge and river levels	Chi-squared test on two-way contingency tables of flood versus non-flood years (Pinter et al., 2006). Linear regression and Mann-Kendall test of annual maximum discharge	With respect to annual maximum discharge and flood frequency no significant trends could be identified consistently throughout the country. Significant trends in extreme discharge were identified at a number of stations (both positive and negative trends).	Bormann et al. (2011)
Greece Nationwide study	21 stations Daily precipitation (1957–2001)	Linear regression test of No. of days with precipitation above 50 mm	Increasing (but not significant) trend of the frequency of extreme precipitation	Nastos and Zerefos (2008)
Greece Thessaloniki	Daily precipitation (1958-2000)	Polynomial regression of estimated location and scale parameter in Gumbel distribution of annual maxima	No significant trends in the extreme value parameters were found.	Galiatsatou and Prinos (2007)
Italy North-eastern Italy	7 stations Daily precipitation	Frequency analysis using a 30-year moving window	Significant increase in extreme precipitation.	Brunetti et al. (2001)

	(1920–1998)			
Lithuania Nationwide study	32 stations Daily discharge (1922-2003)	Mann-Kendall test	Decrease in spring flood magnitude and trend towards an earlier spring flood throughout the country.	Meilutyte-Barauskiene and Kovalenkovienė (2007) Meilutyte-Barauskiene et al. (2010)
Nordic countries (Norway, Sweden, Denmark, Finland, Iceland)	151 stations Extreme discharge data	Mann-Kendall test Field significance test (Burn and Hag Elnur, 2002)	No clear trend in annual maximum flow (neither autumn maximum flow nor spring maximum flow). Weak and strong trends towards an earlier spring flood at many stations in the region.	Wilson, et al. (2010)
Poland Nationwide study	39 stations Daily discharge (1921-1990 and 1951-2005)	Linear regression of mean and variance of annual maximum flow Non-stationary flood frequency analysis	In general, a decreasing trend is detected in both the mean and the variance of annual maximum flow series. The tendency is more pronounced in rivers with a high contribution of winter floods.	Strupczewski et al. (2001abc, 2009)
Slovenia Nationwide study	77 stations Daily discharge	Mann-Kendall test Linear regression test	Both significant negative and positive trends found for maximum flows (slightly more stations with negative trends). Negative trends were found for predominantly high mountain and karstic catchments.	Jurko (2009)
Sweden Nationwide study	15 stations Extreme precipitation with durations between 5 min and 24 hours	Analysis of estimated IDF curves for different periods	Most precipitation series show no trend in extreme value statistics. At one location (Malmö) an increase of 15-20% in the 1 and 2-year events for durations larger than 15 min was detected.	Hernebring (2006)
Sweden Southern Sweden	200+ stations Daily precipitation	Linear regression analysis	No trends found in annual maximum series of daily precipitation	Bengtson (2011)
Switzerland Alpine basins	17 stations Annual maximum discharge (91-140 years of record)	Pettitt's change point test Non-parametric sign test Sen's trend test	Significant changes in the frequency regime of annual maxima and increasing trends in the magnitude of annual flood peaks.	Castellarin and Pistocchi (2011)
Switzerland	83 discharge stations and 14 long historical flood series	Regional trend analysis	Flood-rich periods linked with changes in large scale atmospheric circulation	Schmocker-Fackel and Naef (2012)

Turkey Two catchments	2 stations Daily discharge	Linear regression tests Mann-Kendall test Spearman's correlation test	Significant negative trends found for annual maximum series at the two stations.	ARTEMIS (2010)
UK Nationwide study	890 stations Annual maximum and peak-over-threshold discharge data	Linear regression test Normal scores regression test Spearman's correlation test	Trends were analysed for the 40-year period 1941-1980, 50-year period 1941-1990, and for few long data series for 1870-1995. No significant trends in extreme streamflow were found.	Robson et al. (1998)
UK Nationwide study	87 stations Daily discharge (1969-2003)	Linear regression test Mann-Kendall test	Significant positive trends were identified in all flood indicators, primarily in upland, maritime-influenced catchments in northern and western areas of the UK. Recent increases in floods may be caused by a shift towards a more prevalent positive North Atlantic Oscillation since the 1960s.	Hannaford and Marsh (2008) Hannaford and Hall (2012)
UK Nationwide study	110 stations with daily rainfall 223 stations with 1, 2, 5 and 10 days seasonal and annual maxima	Linear regression test	More intense daily precipitation in winter, and less intense in summer. Increases in winter, spring and autumn extreme rainfall events, decrease in short duration summer rainfall events	Osborn *et al.* (2000) Jones *et al.* (2013)

Table 3 Summary of reviewed studies on projections of precipitation extremes and floods under future climate change.

Country/Region	**Climate projection (GCM, RCM, Scenario)**	**Bias correction / statistical downscaling method**	**Hydrological modelling approach**	**Hydrological quantities considered**	**Key findings (projection horizon)**	**Reference**
Belgium Flanders: 67 sub-basins in Scheldt and Meuse river basins	10 RCMs from PRUDENCE (A2, B2) Other SRES scenarios considered by ‘scaling’ from more than 20 GCMs	Quantile perturbations (Willems and Vrac, 2011)	Lumped conceptual models (NAM, PDM, VHM) for rainfall-runoff modelling Hydrodynamic modeling for flood hazard mapping (MIKE 11) Ensemble simulation approach	Streamflow with return periods larger than 1 yr.	Peak flows increase up to 30% under high climate scenarios by 2100 Flood hazard maps for low, medium, and high climate scenarios	Boukhris and Willems (2008) Willems et al. (2010)
Belgium Uccle, Brussels	Ensemble of 17 simulations with ECHAM5 GCM (A1B)	Quantile perturbations (Willems and Vrac, 2011) Weather typing based statistical downscaling	Reservoir-type approach for urban drainage modelling Ensemble simulation approach	Extreme precipitation with duration of 10 minutes to 15 days and storage requirements for urban drainage systems	Rainfall intensity found to increase by up to 30% by 2100 For high scenario 20-40% increased storage capacity required	Willems and Vrac (2011) Willems et al. (2012)
Cyprus	6 RCMs from ENSEMBLES (A1B)	Change in RCM extreme value statistics		Extreme daily precipitation	Small increase (1-3%) in extreme daily precipitation by 2050	Hadjinicolaou et al. (2011)
Czech Republic Nationwide study	24 RCMs from PRUDENCE (A2, B2)	Change in RCM extreme value statistics		Extreme daily precipitation	RCM ensemble shows a general increase in 50-year event up to about 50% in 2100	Kyselý and Beranová (2009)
Czech Republic Nationwide study	12 RCMs from ENSEMBLES	Change in RCM extreme value		Extreme daily precipitation	Increase in 100-year event by about 23 %	Kysely et al. (2011)

	(A1B)	statistics			in 2100 (average of 12 RCMs)	
Czech Republic Nationwide study	14 RCMs from ENSEMBLES (A1B)	Regional non-stationary index-flood model (Hanel et al., 2009)		Extreme precipitation for durations between 1 and 30 days	RCM ensemble shows a general increase in extreme precipitation by 2100, up to about 30% of 50-year daily precipitation	Hanel and Buishand (2011)
Denmark North-Eastern Sealand	4 RCMs from ENSEMBLES (A1B)	Mean correction (delta change method) Mean and variance correction (Sunyer et al., 2012) Three stochastic rainfall generators: Markov Chain (Brisette et al., 2007); LARS (Semenov et al., 1998); RainSim (Burton et al., 2008).	Distributed, physically-based hydrological model (MIKE SHE) Ensemble simulation approach	Extreme daily precipitation Flood frequency	Significant increase in daily precipitation extremes, up to a factor 2 for a 100-year event in 2100. Largest increases obtained with weather generator downscaling. Significant increases in flood statistics, up to more than a factor 2 for a 100-year event for some catchments.	Sunyer et al. (2010, 2012)
Denmark Southern Jutland	15 RCMs from ENSEMBLES (A1B)	Mean and variance correction (Sunyer et al., 2012) Weighted ensemble average changes in mean and variance used for statistical downscaling	Semi-distributed, conceptual rainfall-runoff model (NAM) MIKE 11 river model	Extreme daily precipitation Flood frequency	Extreme daily precipitation increases about 9% in 2050 and 15% in 2100. Similar changes are seen in the extreme catchment runoff statistics.	Madsen et al. (2013)
Denmark Nationwide study	HadAM3H/ HIRHAM4 RCM from PRUDENCE (A2)	Change in RCM extreme value statistics Stochastic rainfall generator		Extreme precipitation for duration between 1 and 24 hours	Increases in extreme rainfall intensities by 10 – 50% within the next 100 years.	Arnbjerg-Nielsen (2012)

		Climate analogue				
Europe	HadAM3H/ HIRHAM4 RCM (A2, B2 at ~50 km and A2 at ~12 km)	RCM output regridded to 5 km with no bias correction or further downscaling	Combined grid-based water balance and 1D hydrodynamic routing models (LISFLOOD)	Flood frequency	Increases in 100-year flood magnitudes in many rivers, particularly in western and eastern Europe; decreases in northeastern Europe	Dankers and Feyen (2008)
Europe	12 simulations from ENSEMBLES representing 5 GCMs and 8 RCMs (A1B)	Bias correction with quantile mapping (Rojas et al.,2011)	Combined grid-based water balance and 1D hydrodynamic routing models (LISFLOOD)	Flood frequency	Increases in 100-year flood magnitudes in western Europe, the British Isles and northern Italy, and decreases in eastern Germany, Poland, south Sweden and the Baltic countries	Rojas *et al.* (2012)
Finland Nationwide study	15 GCMs (A2,B1) and 5 RCMs from ENSEMBLES (A1B)	Delta change method	Semi-distributed, conceptual rainfall-runoff model (WSFS) Ensemble simulation approach	Flood frequency	100-year floods decrease on average by 8–22% by 2100. Largest decrease in central Finland. Small increase in southern Finland. Increases in large central lakes.	Veijalainen et al.(2010)
France Seine and Somme catchments	8 GCMs (1 or 2 SRES scenarios each, 12 scenarios in total)	Dynamic downscaling and bias correction of distribution (Déqué, 2007) Weather typing (Boé et al., 2006) Perturbation method (Ducharne et al., 2007)	5 hydrological models, representing both lumped, conceptual and distributed, physically-based models (MODCOU, SIM, CLSM, EROS/GARDENIA, GR4J) Ensemble simulation approach	Flood frequency	10-year flood magnitudes do not change significantly; ±10% in most cases (2045-2065 and 2080-2100)	Ducharne et al. (2010)
Germany	ECHAM4/REMO	WettReg (Enke et	Two distributed	Flood frequency	15% increase in 100-	KLIWA (2011)

Bavaria and Baden-Württemberg	RCM (B2)	al., 2005) STAR (Orlowsky et al., 2008)	hydrological models (LARSIM and ASGi) Ensemble simulation approach		year flood in Bavaria and up to 75% in 2-year flood and up to 25% increase in 100-year flood in Baden-Württemberg (2021-2050).	Hennegriff et al. (2006)
Germany Saxony -Anhalt	ECHAM5/REMO RCM (A2, A1B,B1)	WettReg (Enke et al., 2005)	Semi-distributed, conceptual rainfall-runoff model (SWIM) Ensemble simulation approach; WettReg generated 20 realizations of each scenario	Flood frequency	Significant increases in flood frequency. Up to 60% increase in 50-year flood (2011–2040, 2041–2070 and 2071–2100)	Hattermann et al. (2011)
Lithuania Nemunas catchment	ECHAM5 and HadCM3 GCMs (A2, A1B, B1)	Regression relationships between large and local scale monthly means Delta change method	Lumped, conceptual rainfall-runoff model (HBV) Ensemble simulation approach	Flood frequency	Significant decreases in spring flood magnitude, between 25-60% (2011-2040, 2041-2070 and 2071-2100)	Kriaučiūnienė et al. (2008) Meilutytė-Barauskiene et al. (2010)
Norway Flaksvatn, Masi, Nybergsund, Viksvatn catchments	3 RCMS from HIRHAM, run from ECHAM/OPYC3 (B2) and HadAM3H (A2)	Delta change method Empirical adjustment method (Engen-Skaugen, 2007)	Lumped, conceptual rainfall-runoff model (HBV) Ensemble simulation approach Uncertainty in hydrological parameters included	Changes in mean annual flood	Large decreases in annual flood in the northernmost and the inland catchments; moderate increases in the southern and western catchments by 2100.	Lawrence and Haddeland (2011)
Norway Nationwide study	13 RCMs from ENSEMBLES (A1B) 4 RCMs from earlier projects (A2, B2)	Delta change method Empirical adjustment method (Engen-Skaugen, 2007)	Lumped, conceptual rainfall-runoff model (HBV) Ensemble simulation approach Uncertainty from	Flood frequency	Western Norway has the largest percentage increases in flood magnitude (up to 60% increase in 200-year flood by 2100). Catchments in inland	Lawrence and Hisdal (2011)

			hydrological parameters and flood frequency analysis included		regions are generally expected to have reduced flood magnitudes.	
Poland Wełna and Orla catchments	6 RCMs from ENSEMBLES (A1B)	Quantile mapping	Lumped, conceptual rainfall-runoff model (HBV)	Flood frequency	In western Poland, the simulation results for different RCM/GCMs indicate different directions of change or lack of statistically significant changes.	Osuch et al. (2012)
Slovakia Hron catchment	3 GCMs	Calculation of changes in short-term extreme precipitation totals based on projected changes in monthly temperature and specific humidity	Lumped, conceptual rainfall-runoff model developed at Slovak University of Technology	Maximum discharge for selected extreme precipitation events	Increases in discharge up to 80% in 2030 and up to 140% in 2075.	Hlavčová et al. (2007)
Sweden Kalmar	2 RCA3 RCMs (A2 and B2)	Scaling of distribution of rainfall intensities		30-min extreme precipitation	Extreme intensities will increase by 20–60% in 2100	Olsson et al. (2009)
Sweden Stockholm	3 RCA3 RCMs (A2,B2 and A1B)	Stochastic downscaling scheme		Extreme precipitation for durations between 30 min and 24 hours	5–10% increase in short-duration extreme intensities in the period 2011–2040and a 10–20% increase in the period 2071–2100	Olsson et al. (2012)
Sweden Lake Vänern	12 – 16 RCMs (mostly from ENSEMBLES) (A1B, also A2, B1)	Distribution based scaling (Yang et al., 2010)	Lumped, conceptual rainfall-runoff model (HBV)	Inflow to Lake Vänern	Higher winter inflows and reduced spring flood projected for near future periods and by 2100.	Bergström et al., (2010) Olsson et al. (2011)
Sweden Nationwide study	16 RCMs	Distribution based scaling (Yang et	Lumped, conceptual rainfall-runoff model	Flood frequency	In the central part of the country, floods	Bergström et al. (2012)

		al., 2010)	(HBV) Ensemble simulation approach		tend to decrease, mainly due to decreasing snowmelt floods in spring, while rain-fed floods in the south show the opposite tendency.	
UK River Severn and Thames	HadCM2 GCM	Delta change method	Distributed rainfall-runoff model (CLASSIC)	Flood frequency	50-year flood in the Severn and Thames increase by 20% and 16%, respectively by 2050.	Reynard et al. (2001)
UK 5 catchments	7 GCMs (A1, A2, B1, B2) GCMs perturbed using a climate sensitivity based rescaling approach	Delta change method	Lumped, conceptual rainfall-runoff model (PDM) Ensemble simulation approach	Flood frequency	Increase in flood magnitude for most scenarios by 2050.	Prudhomme et al. (2003)
UK 15 catchments	HadRM3H RCM(A2)	Delta change method	Lumped, conceptual rainfall-runoff model (PDM)	Flood frequency	Decrease in flood magnitude in south and east England, 50% increase in 50-year flood in north and west UK by 2100.	Kay et al. (2006)
UK 154 catchments	16 GCMs and 11 versions of HadRM3 RCM (A1B)	Delta change method	Lumped, conceptual (PDM) and distributed (CLASSIC) rainfall-runoff models Ensemble simulation approach	Flood frequency	The median of the ensemble show few catchments with changes in flood frequency above 20% by 2010. However, considering the large uncertainty in the ensemble the 20% change factor can no longer be considered precautionary.	Reynard et al. (2010)
UK	HadRM3 RCM	No statistical	Lumped, conceptual	Flood frequency	Upward trend in	Kay and Jones

Nationwide study	(A1B) Ensemble of three perturbed parameter simulations	downscaling of RCM	(PDM) and distributed (G2G) rainfall-runoff models Ensemble simulation approach		flood risk nationally	(2012)

A2, A1B, B1, B2: IPCC SRES scenarios (Nakićenović et al., 2000)
ECHAM4, ECHAM5: GCM developed by Max Planck Institute for Meteorology, Germany
HadCM2, HadAM3H, HadCM3: GCM developed by Met Office Hadley Centre, UK
HadRM3H, HadRM3: RCM developed by Met Office Hadley Centre, UK
HIRHAM4: RCM developed by Danish Meteorological Institute, Denmark
REMO: RCM developed by Max-Planck Institute for Meteorology, Germany
RCA3: RCM developed by Swedish Meteorological and Hydrological Institute, Sweden

Table 4 Summary of existing European guidelines on climate change adjustment factors on design floods and design rainfall.

Country	**Region**	**Variable**	**Guideline**	**Reference**
Belgium	Flanders	Design floods	30% increase	Boukhris and Willems (2008)
Belgium	National	Design rainfall	30% increase	Willems (2011)
Denmark	National	Design rainfall	20%, 30% and 40% increase for return periods 2, 10 and 100 years	Arnbjerg-Nielsen (2008)
Germany	Bavaria	Design flood with 100-year return period	15% increase	Hennegriff et al. (2006)
Germany	Baden-Württemberg	Design floods	Increase between 0% to 75% depending on location and return period	Hennegriff et al. (2006)
Norway	National	Design floods	0%, 20% and 40% increase based on region, prevailing flood season and catchment size	Lawrence and Hisdal (2011)
Sweden	National	Design rainfall	Increase between 5% and 30% depending on location	SWWA (2011)
United Kingdom	National	Design floods	20% increase for 2085	Defra (2006)
United Kingdom	National	Design rainfall	10%, 20% and 30% increase for 2055, 2085 and 2115	Defra (2006)

Figures

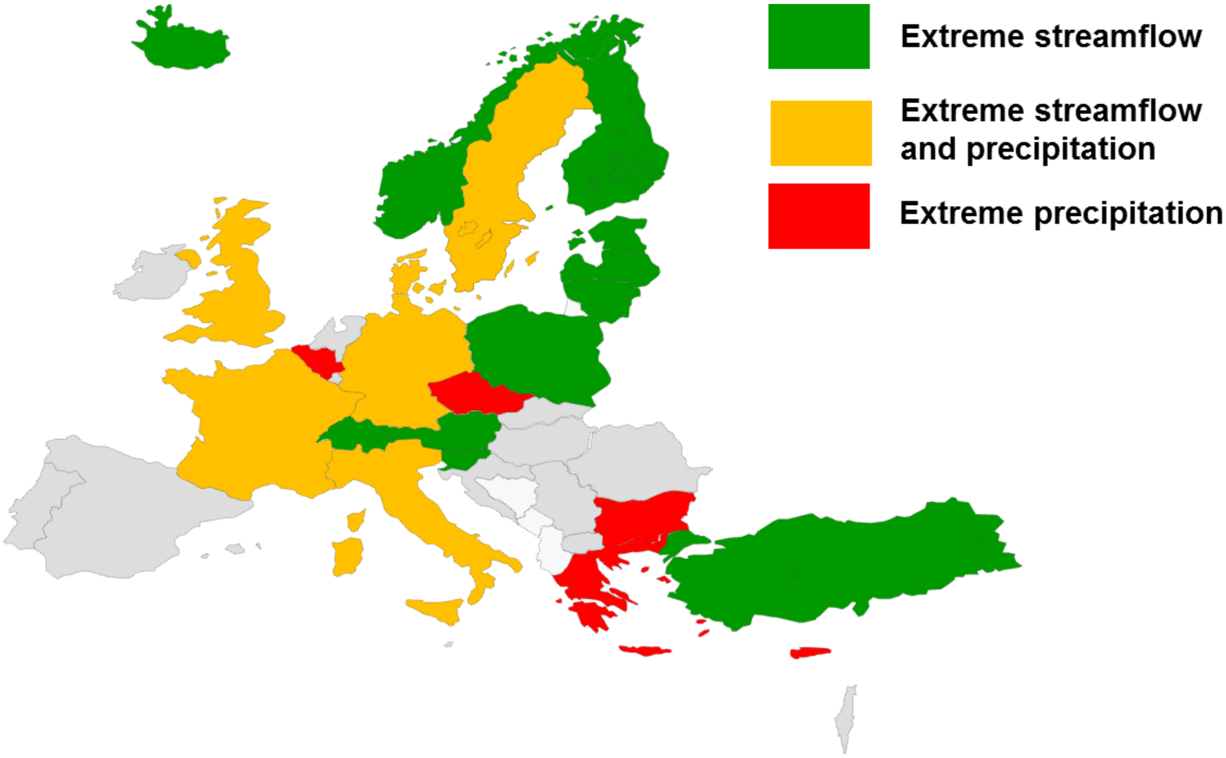

Figure 1 Countries with trend analysis studies reviewed of extreme precipitation, extreme streamflow or both.

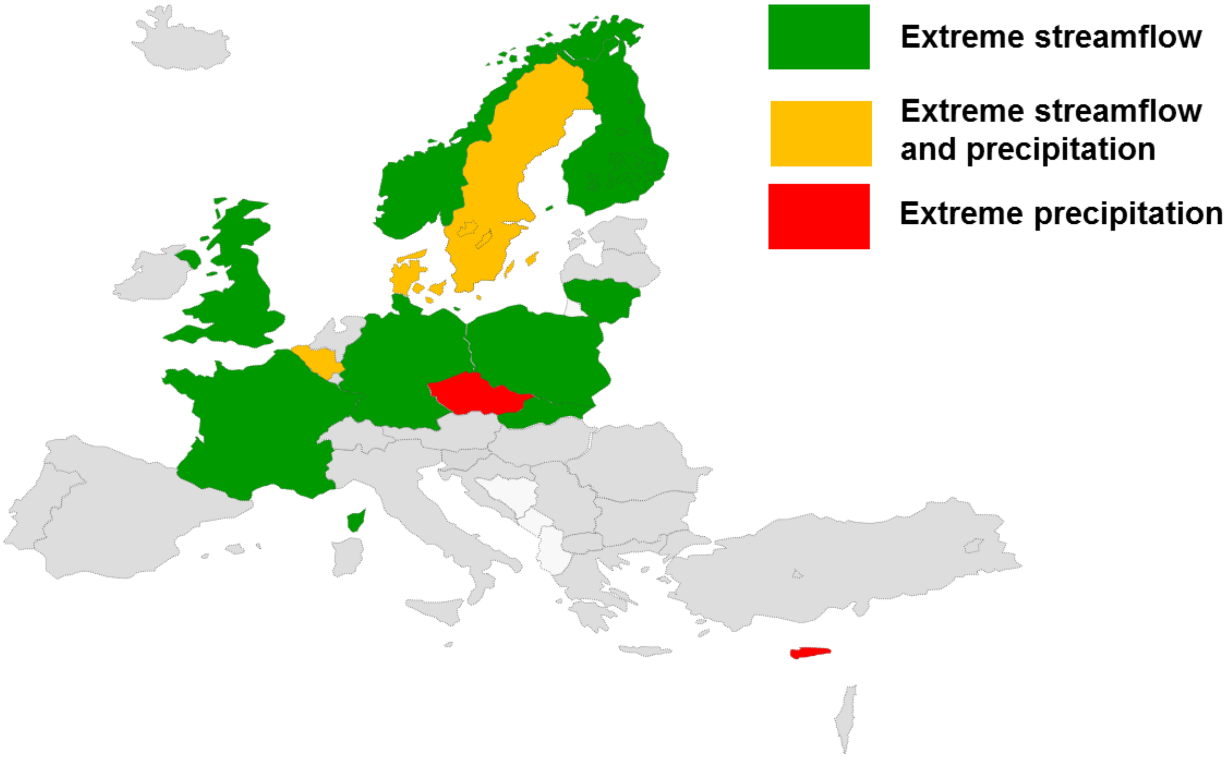

Figure 2 Countries with climate model projection studies reviewed of extreme precipitation, extreme streamflow or both.