A Review of Applied Methods in Europe for Flood Frequency Analysis in a Changing Environment

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Flood frequency estimation methods and environmental change

A REVIEW OF APPLIED METHODS IN EUROPE FOR FLOOD-FREQUENCY ANALYSIS IN A CHANGING ENVIRONMENT

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Preface

This report has been prepared as part of the COST Action ES0901 "European procedures for flood frequency estimation (FloodFreq)". The main objective of the FloodFreq COST Action is to undertake a Pan-European comparison and evaluation of methods for flood frequency estimation under the various climatologic and geographic conditions found in Europe, and different levels of data availability.

The report has been prepared by Working Group 4 "Flood frequency estimation methods and environmental change". It provides a review of methods used and results of detection of trends in observations and climate projections of extreme precipitation and flood frequency in Europe.

More information about the COST Action ES0901 can be found at the FloodFreq website http://www.cost-floodfreq.eu

Summary

The report presents a review of methods used in Europe for trend analysis, climate change projections and non-stationary analysis of extreme precipitation and flood frequency. In addition, main findings of the analyses are presented, including a comparison of trend analysis results and climate change projections. Existing guidelines in Europe on design flood and design rainfall estimation that incorporate climate change are reviewed. The report concludes with a discussion of research needs on non-stationary frequency analysis for considering the effects of climate change and inclusion in design guidelines.

Trend analyses are reported for 21 countries in Europe with results for extreme precipitation, extreme streamflow or both. A large number of national and regional trend studies have been carried out. Most studies are based on statistical methods applied to individual time series of extreme precipitation or extreme streamflow using the non-parametric Mann-Kendall trend test or regression analysis. Some studies have been reported that use field significance or regional consistency tests to analyse trends over larger areas. Some of the studies also include analysis of trend attribution. The studies reviewed indicate that there is some evidence of a general increase in extreme precipitation, whereas there are no clear indications of significant increasing trends at regional or national level of extreme streamflow. For some smaller regions increases in extreme streamflow are reported. Several studies from regions dominated by snowmelt-induced peak flows report decreases in extreme streamflow and earlier spring snowmelt peak flows.

Climate change projections have been reported for 14 countries in Europe with results for extreme precipitation, extreme streamflow or both. The review shows various approaches for producing climate projections of extreme precipitation and flood frequency based on alternative climate forcing scenarios, climate projections from available global and regional climate models, methods for statistical downscaling and bias correction, and alternative hydrological models. A large number of the reported studies are based on an ensemble modelling approach that use several climate forcing scenarios and climate model projections in order to address the uncertainty on the projections of extreme precipitation and flood frequency. Some studies also include alternative statistical downscaling and bias correction methods and hydrological modelling approaches. 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 with rainfall-dominated peak flows, 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.

The review of existing guidelines in Europe on design floods and design rainfalls shows that only few countries explicitly address climate change. These design guidelines are based on climate change adjustment factors to be applied to current design estimates and may depend on design return period and projection horizon. The review indicates a gap between the need for considering climate change impacts in design and actual published guidelines that incorporate climate change in extreme precipitation and flood frequency. Most of the studies reported are based on frequency analysis assuming stationary conditions in a certain time window (typically 30 years) representing current and future climate. There is a need for developing more consistent non-stationary frequency analysis methods that can account for the transient nature of a changing climate

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Table of contents

1 Introduction

1.1 COST Action ES0901 FloodFreq

The main objective of the COST Action ES0901 is to undertake a Pan-European comparison and evaluation of methods for flood frequency estimation under the various climatologic and geographic conditions found in Europe, and different levels of data availability. A scientific framework for assessing the ability of these methods to predict the impact of environmental change on future flood frequency characteristics (flood occurrence and magnitude) will be developed and tested. The findings of the Action will be disseminated as a set of guidelines for professionals involved in flood management in Europe.

The objective will be accomplished through a series of network activities involving experts working on related problems through-out Europe. Specifically, the Action will produce the following deliverables:

1. Make available access to high-quality pan-European standard datasets and test-beds (detailed datasets including rainfall and runoff).
2. Produce a review of state-of-the-art methods for flood frequency estimation (considering both European and non-European methods).
3. Develop a scientific framework for assessing and comparing the performance of different methods (including considerations of prediction uncertainty).
4. Provide European-wide assessment of methods using the compiled datasets.
5. Provide a scientific framework for assessing the influence of environmental change on the future flood frequency characteristics.
6. Provide guidelines on flood frequency estimation for European professionals involved in flood risk management.

The work is organised in four working groups:

WG1: Compile dataset and inventories of existing data and methods

WG2: Use of statistical methods for flood frequency estimation

WG3: Flood frequency analysis using rainfall-runoff methods

WG4: Flood frequency estimation methods and environmental change

1.2 WG4: Flood frequency estimation methods and environmental change

Standard statistical procedures for flood frequency analysis are based on the assumption of stationarity; that is, the extreme flood statistics do not change in time, and hence past observations can be considered as representative of future observations and thus used to estimate design flood events. In a changing environment the assumption of stationarity might not be applicable, and more advanced statistical methods are required that explicitly accounts for the non-stationarity of extreme flood characteristics.

The main driver for this working group is climate change and its effect on flood frequency. Results from global and regional climate modelling studies have indicated that most parts of Europe will experience more frequent and more severe floods in the future. The scientific challenge is to downscale the projections from the climate models to operational tools enabling policy makers to assess the impact of climate change on a local scale. Besides climate related changes in flood frequencies also direct anthropogenic changes in the hydrological regime (*e.g.* land use changes, urbanisation, and wetland draining) and river infrastructure developments need to be addressed.

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 Floods Directive requires that Member States address flood risk using a three-stage procedure: 1) preliminary flood risk mapping; 2) detailed flood hazard and flood risk mapping for areas identified during the preliminary mapping; and 3) development of flood risk management plans. 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. One of the motivations for this directive was that the Water Framework Directive (2000/60/EC) does not particularly focus on measures related to the reduction of flood risk or on changes in flood risk under a future climate.

The Floods Directive, however, implicitly assumes that information regarding likely climate change impacts on flood frequency is readily available from global and regional climate projections such as those described in the most recent IPCC report (IPCC, 2007). This is, however, generally not the case as these impacts represent a local response to a changing climate and often cannot be directly interpreted from, say, regional projections for changes in precipitation. In addition, floods represent hydrological extremes and therefore demand high quality, high resolution input data to relevant models and analyses. Thus, the Floods Directive indirectly poses a rather pressing need for methods and tools for modelling and analyses, which will lead to projections for likely changes in flood frequency under a future climate.

A key component of the FloodFreq COST Action is to develop a scientific framework for assessing the impacts of environmental change on flood frequency characteristics. The framework will be based on analysis of trends in historical data, combined with projections of future climate conditions from global and regional climate models, and analysis of historical developments of human induced changes in hydrological and hydraulic conditions. Process-based modelling can be used to analyse human induced changes and isolate climatological changes in flood frequency characteristics. Powerful statistical tools are required to detect changes or trends in extreme flood characteristics and to model time dependent statistical properties. In addition, a changing environment calls for a completely new paradigm for risk-based design guidelines and standards.

WG 4 has the following deliverables:

1. Review of existing methods for detecting trends and shifts in time series of extreme precipitation and floods, and non-stationary flood frequency analysis. A list of methods for use in Europe will be identified.
2. Guidelines for development of regional procedures for flood frequency analysis in a changing environment under the different climatic conditions in Europe.
3. New framework for risk-based design under environmental change by introduction of non-stationary design estimates.
4. Collection of open-source computer programs for non-stationary flood frequency analysis.

1.3 Report structure

This report presents the results of the first deliverable of WG4 on review of methods used and results of detection of trends and climate projections of extreme precipitation and floods, and non-stationary extreme value analysis. The first part of the report summarises the reviews that have been prepared by the FloodFreq member countries. Nineteen reports have been submitted; see overview of contributing countries and organisations in Table 1.1.

Table 1.1 List of countries and organisations that have contributed to this report.

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	GECOsistema 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

The summary section is divided in three parts where methods and results from the country reports are summarised and discussed. The three parts are:

- Trend detection and attribution of precipitation extremes and floods (Section 2)
- Projections of precipitation extremes and floods under future climate change (Section 3)
- Non-stationary flood frequency and risk analysis, including a review of current guidelines in Europe and identified research gaps (Section 4)

The 19 country reports are given in Appendix A.

In addition, in Appendix B reports from three non-European countries (Australia, India and the United States) are provided. These reports have been collected by the World Meteorological Organization (WMO) Commission for Hydrology as part of their 2008-2012 programme 'Water, Climate and Risk Management'. The WMO Commission for Hydrology liaised with the FloodFreq project in June 2011 where it was decided to gather information from some WMO countries along the same lines as the reports being prepared by the FloodFreq member countries. The first reports from three countries are included in Appendix B. The work is expected to continue into the WMO Commission for Hydrology programme for 2013-2016.

2 Trend detection and attribution

Detection of trends in hydro-meteorological time series and analysis of the main driving factors that can explain the trends is important for understanding the impact of environmental change. Below is presented methods applied for trend detection and attribution of extreme rainfall and floods, followed by a summary of the main results of trend analyses in Europe.

2.1 Methods

Several steps should be followed when performing a trend analysis. First, a preliminary analysis should be carried out to remove errors in data series (Section 2.1.1). The power of statistical trend tests is improved when longer time series data are used, but problems of measurement heterogeneity will affect the results, which especially may be a problem with old records. It is therefore important to work with data sets that have been quality controlled.

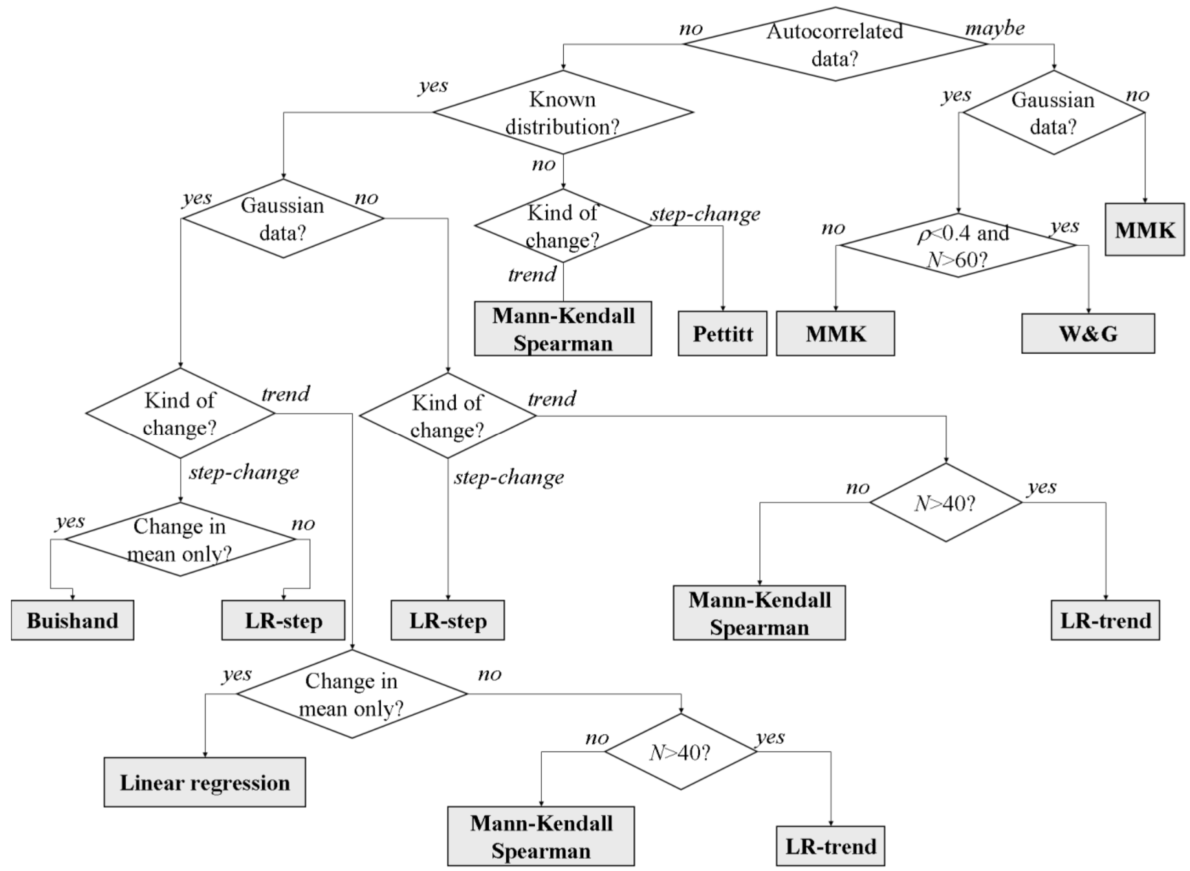

Figure 2.1 Flowchart for selection of a test for identifying trends and shifts in hydrological extreme value series (from Lang *et al.*, 2006). *N*: Sample size, □: autocorrelation coefficient, LR: Likelihood ratio test, MMK: modified Mann-Kendall test, Buishand: test based on Buishand (1982).

A first descriptive analysis of trends and shifts can be applied by comparison of statistics from different sub-periods (Section 2.1.2). More advanced approaches using statistical tests can be used to test the significance of trends and shifts in the time series (Section 2.1.3). A general framework for the selection of tests for trends and shifts has been developed by Renard (2006) (see Lang et al., 2006), taking into account a possible autocorrelation, the distribution type, the type of change, and the length of the data series, see Figure 2.1.

Finally, when trends and shifts have been detected and considered significant, one should make an analysis of possible driving factors that can explain the changes, such as land-use change, river works, and climate change (Section 2.1.4).

2.1.1 Preliminary analysis to remove errors in data series

Examination of spatial homogeneity of rainfall data by detecting local anomalies is a standard procedure performed by meteorological offices. Discharge data managers are also dealing with data control, especially in relation with the stability of the stage-discharge relationship, but such procedures cannot always ensure that the data series will be free of errors. It is therefore recommended to begin the trend detection analysis with a preliminary quality control of the data series.

The review reveals that some countries have implemented standard procedures for quality control of observed time series of precipitation and streamflow prior to trend analysis. In Greece, a methodology has been developed for automatic exploration and analysis of hydrological data, particularly focusing on the identification of changing relationships among hydrological variables. This method is applicable to many hydrological problems, such as identification of multiple stage-discharge relationships in a river section, data homogeneity analysis, analysis of temporal consistency of hydrological data, and detection of outliers (Tsakalias and Koutsoyiannis, 1999).

In Poland, measurement non-homogeneity, as a result of changes in measurement method or instrumentation, or time non-homogeneity, as a result of changes in the catchment conditions or river bed development over the observation period, is investigated using the Grubbs-Beck test (detection of outliers).

In Spain, the following procedure is applied:

- A graphical analysis is carried out at a local scale by plotting the cumulative annual maximum discharge (AMD) for each station. Shifts are detected by changes in the slope of the cumulative graph.
- The discordance measure of Hosking and Wallis (1997) is computed at a regional scale to identify stations that are grossly discordant with the group as a whole, taking advantage of the fact that trends and shifts in time series are reflected in the sample L-moments.
- Outliers are identified using the U.S. Water Resources Council method (USWRC, 1981). High outliers are removed from the AMD series and treated as historical data.

Homogeneity testing of the maximum discharge series from 70 hydrological stations in the Baltic States (Estonia, Lithuania, Latvia) analysed in Reihan *et al.*, (2007) was performed using double-mass plot, correlation analysis, and the standard normal homogeneity test (Alexandersson and Moberg, 1997).

In Denmark, precipitation data are compared based on monthly averages between stations, and extremes are verified against weather charts (Jørgensen *et al.*, 1998).

2.1.2 Descriptive analysis of trends and shifts

Reported methods applied for analysing trends and shifts 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. For example, intensity-duration-frequency (IDF) curves for Nicosia, Cypress, were estimated and compared for two different periods, 1931-1970 (Hadjiioannou, 1995) and 1971-2007 (Pashiardis, 2009).

Madsen *et al.* (2009) compared estimated regional IDF relationships for Denmark (Madsen *et al.*, 2002) for the periods 1979-1997 and 1979-2006.

A related method is to use a moving window approach in which the sampled extreme value distributions are analysed within each time window. This method was used for analysing extreme precipitation in Belgium where precipitation quantiles were computed based on the full series and for moving window sizes of 5, 10 and 15 years (Ntegeka and Willems, 2008). Quantiles derived from the sub-periods were compared with quantiles derived from the full series (for given return periods), and the ratio of these quantiles defined a “quantile anomaly”. The temporal (multi-decadal) variability of this anomaly was computed for a range of rainfall durations. In the analysis of precipitation extremes in Northeastern Italy, Brunetti *et al.* (2001) applied a 30-year moving window to estimate the trend in the frequency of extreme precipitation events. In the Czech Republic, changes were analysed using a yearly index of flood regime related to seasonality and its variation with time (Šercl, 2009).

2.1.3 Testing for trends and shifts

Different statistical tests have been applied for testing for trends and shifts in extreme precipitation or discharge time series. These tests can be grouped into:

1. at-site tests that are applied to a single time series
2. field significance tests that are applied to multiple time series to test their joint statistical significance, and
3. regional consistency tests that are used for testing the spatial coherency of trends within a region.

At-site tests

At-site tests are statistical tests applied to individual time series. The most widely used test is the Mann-Kendall test, which has been applied to nationwide trend analysis studies of extreme precipitation in Bulgaria (Bocheva *et al.*, 2009), the Czech Republic (Kyselý, 2009) and Denmark (Sadri *et al.*, 2009), and to flood discharge in Finland (Korhonen and Kuusisto, 2010), Germany (Petrow and Merz, 2009; Petrow *et al.*, 2009; Boormann *et al.*, 2011), Lithuania (Meilutyte-Barauskiene and Kovalenkovienė, 2007; Meilutyte-Barauskiene *et al.*, 2010), Slovenia (Jurko, 2009), and the UK (Hannaford and Marsh, 2008), and in two regional studies for the Baltic (Reihan *et al.*, 2007; Reihan *et al.*, 2012) and the Nordic (Wilson *et al.*, 2010) countries. 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 in Denmark (Gregersen *et al.*, 2010), Sweden (Bengtsson, 2011) and Greece (Nastos and Zerefos, 2008), and to flood discharge series in Germany (Bormann *et al.*, 2011), Poland (Strupczewski *et al.*, 2009), Slovenia (Jurko, 2009), and the UK (Robson *et al.*, 1998; Hannaford and Marsh, 2008). Strupczewski *et al.* (2009) applied linear regression analysis to both the mean and the variance of annual maximum flow series. In a study of extreme precipitation data in Thessaloniki, Greece Galiatsatou and Prinos (2007) applied polynomial regression of the estimated location and scale parameter of the Gumbel distribution.

Other applications of at-site trend tests that have been reported include Pettitt’s change point test and non-parametric sign test, which were applied to flood time series from Alpine basins in Switzerland by Castellarin and Pistocchi (2011); and normal scores regression and Spearman’s correlation tests, which were applied to UK annual maximum and peak-over threshold series by Robson *et al.* (1998).

In a French national study a number of different tests were compared, and a general framework for selection of tests was developed (Renard, 2006; Lang *et al.*, 2006), see Figure 2.1. Parametric tests based on the likelihood ratio between two alternative hypotheses (LR tests) appeared 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 the estimated Gumbel parameters (location and scale parameters).

Field significance tests

Field significance is assessed when a statistical test is repeated on several individual time series (*e.g.* from several locations in a given region) to test their joint significance and has been studied, for example, by Livezey and Chen (1983), Lettenmaier *et al.* (1994), Douglas *et al.* (2000), Yue and Wang (2002), Ventura *et al.* (2004), and Renard and Lang (2007). In a trend and change detection context, it aims at testing the H0-hypothesis: “data from all sites are stationary”. Several methods accounting for dependence between the series have been proposed to assess the distribution of the number of locally significant tests under the H0-hypothesis, including (1) an equivalent (or effective) number of stations (ENS) (Matalas and Langbein, 1962); (2) a bootstrap procedure (Douglas *et al.*, 2000); (3) a Gaussian copula methodology (Renard and Lang, 2007), and (4) the false discovery rate (FDR) (Benjamini and Hochberg, 1995; Ventura *et al.*, 2004).

In France, Renard *et al.* (2008) recommended the bootstrap procedure, as it is easier to apply and requires no parametric assumption about marginal and joint distributions of the data. On the other hand, 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. Thus, the choice between the bootstrap and the FDR procedure depends on the expected type of change. When no prior information about the regional change is available, a pragmatic approach would simply consist in applying both tests to the data. In the trend analyses of flood time series in Germany by 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). In the analysis of flood time series in the Nordic countries Wilson *et al.* (2010) used the bootstrap procedure described by Burn and Hag Elnur (2002) to determine the percentage of stations that are expected to show a trend due to the effect of cross-correlation between stations.

Regional consistency tests

Since climate change is likely to have an impact over large areas, river flows in nearby catchments located within the same homogenous climatic area are expected to be impacted by a similar change. Several methods have been developed to test for regional climate changes: (1) 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); (2) the regional average Mann-Kendall test proposed by Douglas *et al.* (2000) and Yue and Wang (2002); (3) a semi-parametric approach based on a normal score transformation and multivariate Gaussian distribution (Renard *et al.*, 2008). In terms of power, Renard *et al.* (2008) found no best method, but they recommended the semi-parametric approach as it forces the regional trend to be consistent. Sadri *et al.* (2009) applied the regional Mann-Kendall test to extreme precipitation data in Denmark.

2.1.4 Trend attribution

When trends or shifts have been detected, the next step in many studies is to analyse for the causes and attribute the changes to drivers such as climate change, land-use change, river developments, etc. Petrow and Merz (2009) analysed the spatial and seasonal patterns of changes in flood time series in Germany. They concluded that the spatial and seasonal coherence of the trends suggested that the observed changes in flood behaviour were climate-driven. In a follow-up study, Petrow *et al.* (2009) related the trends in flood time series to changes in circulation patterns and concluded that changes in the dynamics of atmospheric circulations have an influence on the changes in floods. Bormann *et al.* (2011) analysed time series of flood stages, flood discharges, flood frequency and in stage-discharge relationships for 78 stream gauges in Germany. They concluded that the comparison of results of different tests and different time series can suggest or exclude causal mechanisms driving observed trends. For example, while trends in peak discharge may suggest climatic and/or land-use change, changes in flood stages (in the absence of trends in discharge) may suggest in-stream river training.

In the study of Alpine catchments in Switzerland, Allamano *et al.* (2009ab) proposed and applied a simple conceptual model that relates temperature regimes to the frequency of floods. They showed that an increase in the frequency of floods may be explained in terms of temperature increases. The model of Allamano *et al.* (2009ab) was shown to be able to explain observed trends in annual maxima series in alpine basins in Switzerland (Castellarin and Pistocchi, 2011). In the analysis of spring floods in the Baltic countries trends towards earlier and decreasing spring floods were found, which could be related to increasing temperature (Meilutyte-Barauskiene and Kovalenkovienė, 2007; Reihan *et al.*, 2007; Reihan *et al.*, 2012). Renard *et al.* (2008) applied a procedure developed by Andreassian *et al.* (2003) to assess the relationship between rainfall and flow changes on four stations in the North-East of France.

Recently, Merz *et al.* (2012) argued that state-of-the-art trend analysis lack scientific rigour in trend attribution and most attribution studies are based on qualitative reasoning or even speculation. They advocate for a statistically consistent approach for hypothesis testing of trend attribution and discuss ways forward to address this.

2.2 Summary of country review reports

The reported studies on trend analysis of extreme precipitation and flood frequency are summarised in Table 2.1. The summary includes information about:

1. Study location: nationwide, regional, specific river basins or catchments
2. Variable considered, i.e. precipitation (of given durations) or discharge time series, including information, if available, on No. of stations and length of the time series included in the analysis
3. Trend detection method(s) applied
4. Summary of key findings
5. References

A summary of the general findings and comparison with projected climate change in extreme precipitation and flood frequency is given in Section 3.3.

Trend analyses have been reported for 21 countries in Europe with results for extreme precipitation, extreme streamflow or both, see overview in Figure 2.2.

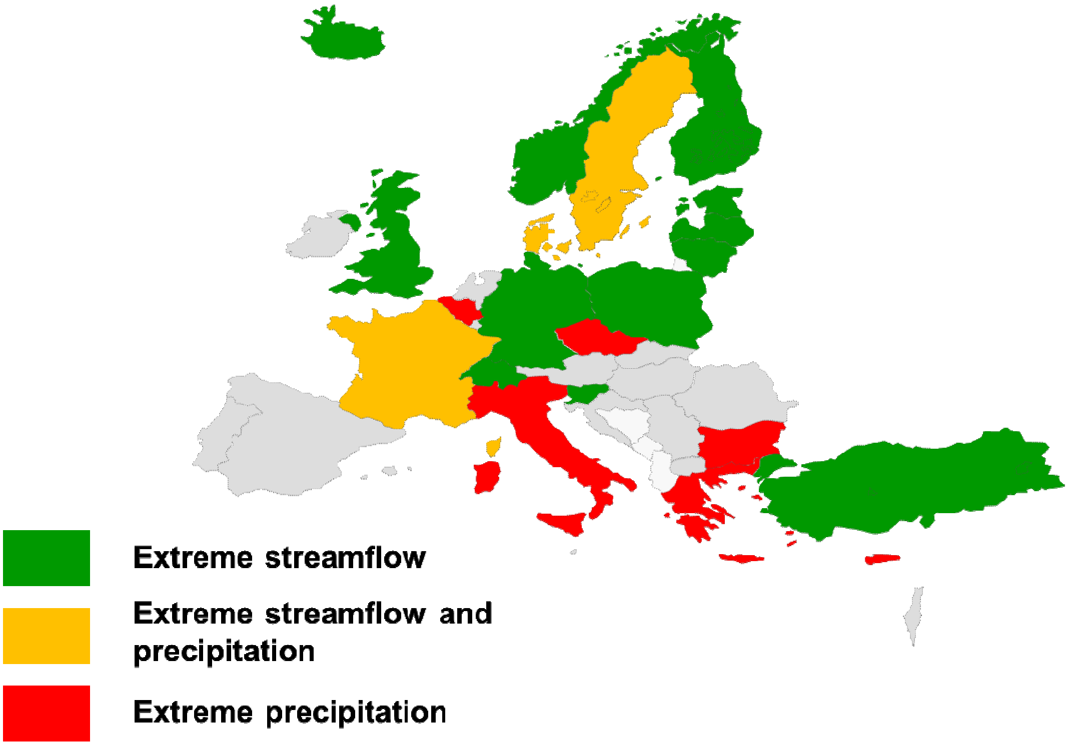

Figure 2.2 Overview of countries with reported trend studies on extreme streamflow, extreme precipitation or both.

Table 2.1 Summary of country review reports on trend detection of precipitation extremes and flood frequency.

Country/region	Data/variable	Methods	Key findings	Reference
Belgium Uccle, Brussels	Extreme precipitation with durations between 10 min and one month 107-year rainfall series	Trend detection and analysis of multi-decadal oscillations	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 1 min and 24 hours.	Arnbjerg-Nielsen (2006) Madsen *et al.* (2009) Sadri *et al.* (2009) Gregersen *et al.* (2010)
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 Nationwide study	195 stations Daily discharge	Field significance test Semi-parametric regional consistency procedure	No general change was found at the national scale. 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 (2006)
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	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)
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	7 stations Daily precipitation	Frequency analysis of extreme events using a 30-	Increase in the frequency of extreme events.	Brunetti *et al.* (2001)

Italy	(1920–1998)	year moving window		
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)
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)
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) Reihan *et al.* (2012)
Nordic countries (Norway, Sweden, Denmark, Finland, Iceland)	151 stations Extreme discharge data	Mann-Kendall test Field significance test (Renard *et al.*, 2008)	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	15 stations Extreme	Analysis of estimated IDF curves for different periods	Most precipitation series show no trend in extreme value statistics. At one location	Hernebring (2006)

Nationwide study	precipitation with durations between 5 min and 24 hours		(Malmö) an increase of 15-20% in the 1 and 2-year events for durations larger than 15 min was detected.	
Sweden Southern Sweden	200+ stations Daily precipitation	Linear regression analysis	No trends found in annual maximum series of daily precipitation	Bengtson (2011)
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)

3

3 Climate change projections

3.1 Methods

Assessment of climate change impacts on flood frequency due to projected changes in extreme precipitation requires a methodology comprising of a series of linked models and analyses (Figure 3.1). The basis for all methodologies is climate change projections from large-scale Global Climate Models (GCMs), which model coupled atmospheric-oceanic processes for historical and future periods. The GCM model runs are based on climate forcing scenarios representing various alternatives as to how society and technology will develop through the 21st century (and in some cases beyond) and the impacts this will have on greenhouse gas emissions and concentrations. Examples of climate forcing scenarios include the IPCC SRES scenarios (*e.g*. Nakićenović *et al.*, 2000) and the newer RCP (Representative Concentration Pathways) scenarios (Meinshausen *et al*., 2011).

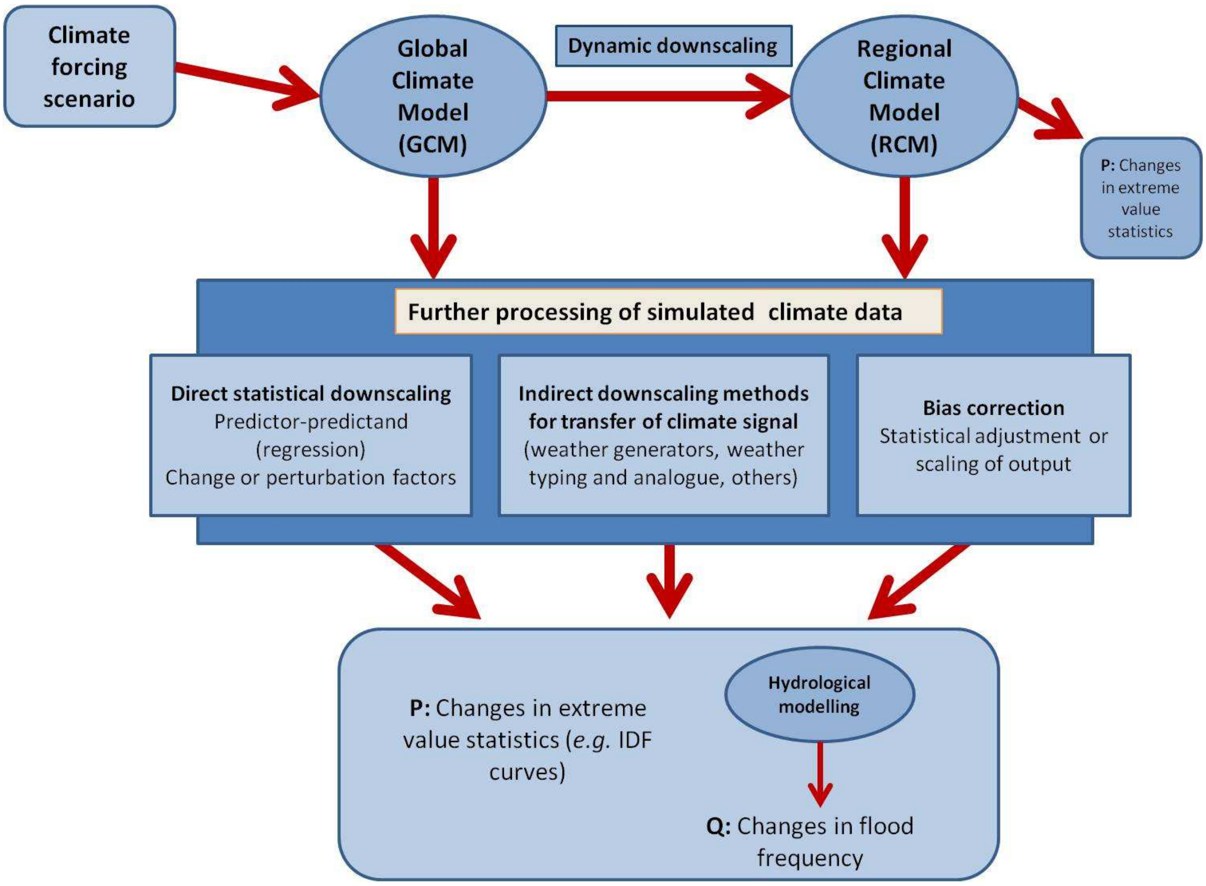

Figure 3.1 Relationships between various models and methodologies used to interpret likely changes in extreme precipitation and flood frequency under a future climate.

Output from GCMs, typically having grid cell sizes of 100 – 250 km, is generally too coarse for direct analyses of flood generating processes, and further processing is required before likely changes can be assessed. This further processing takes the form of a dynamical downscaling using a regional climate model (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 (Figure 3.1). There are, however, numerous alternative pathways between the GCM projections and a final analysis of likely changes in flood frequency, and most aspects of this process are currently under further development and refinement. Therefore, the diagram illustrated in Figure 3.1 should be taken as an attempt to sketch out a wide array of activity, rather than as a definitive distillation of a concrete set of methodologies.

A large proportion of the more recent analyses of likely changes in extremes are derived from RCM simulations. RCMs are run for regional domains using a finer grid cell resolution (*e.g*. 55; 25; 12.5 km) and input data from GCMs as boundary conditions. This process is referred to as dynamical downscaling. During the past 10 years, two large EU FP6 projects have produced RCM simulations using higher resolution grids for modelling domains that cover Europe. The PRUDENCE project (Christensen *et al*., 2007) focused on projections for the end of the 21st century, whereas the ENSEMBLES project (van der Linden and Mitchell, 2009) produced transient simulations from the mid-twentieth century to 2100 representing a wide range of GCM/RCM combinations. There have also been several other regional, national and international projects that have focused on generating dynamically downscaled RCM projections (*e.g*. EU FP6 CECILIA project, http://www.cecilia-eu.org/). CORDEX (COordinated Regional climate Downscaling Experiment, http://www.meteo.unican.es/en/projects/CORDEX) is a new programme that will produce regional climate change scenarios globally. Work on regional climate modelling is continuing with a focus on higher grid resolution and improved representation of small-scale processes, such as convective precipitation. However, there are currently limitations associated with computational issues and with process representation (*e.g*. Baker and Peter, 2008) such that the next step is not simply a matter of running the currently available climate models at higher spatial and temporal resolutions.

In some analyses of climate change impacts on precipitation extremes in Europe, likely regional changes under a future climate 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). However, it is often necessary to undertake further processing of GCM or RCM output prior to analysing changes in flood generating processes. This is particularly the case for analyses of catchment-scale impacts based on hydrological modelling requiring a daily (or higher temporal resolution) precipitation time series; however, it is also relevant for local-scale interpretation of likely changes in extreme precipitation. For the purposes of summarising approaches used for this further processing, it is useful to make a distinction between 1) direct statistical downscaling methods which use climate model output to derive adjustments that are applied directly to or are conditioned by observed time series; 2) more indirect methods which use changes in climate variables as interpreted from climate models to drive methods such as weather generators or climate analogue interpretations; and 3) methods for statistical bias correction of model output which adjust the output relative to observations for further direct use in modelling and analyses. The third category does not necessarily involve a change in spatial or temporal scale, and so, is distinguished here from downscaling methods in which bias correction is often already implicitly included. It should be noted that as methods continue to be developed, distinctions between the three groups of methods illustrated in Figure 3.1 become increasingly diffuse.

Direct statistical downscaling has been a popular method for working with GCM output due to the explicit need for refinement of spatial and temporal scales between the climate model and the information required for hydrological impact assessment. The classical approach for statistical downscaling is the use of a regression-based relationship between predictors from the GCM (such as sea level pressure, temperature, geopotential heights and others) and local scale climate variables (such as precipitation and temperature). The use of this method has been particularly facilitated by the SDSM software developed by Wilby *et al.* (2002), although refinements of this general approach have also now been developed (*e.g*. see review in Willems *et al.,* 2012). The statistical climate model WettReg used in Germany is also an example of direct statistical downscaling from GCM output to produce regional climate simulations (Enke et al., 2005).

The most widely-used approaches for statistical downscaling from both GCM and RCM model output have, however, been the 'delta change' or 'perturbation' methods (*e.g.* Reynard *et al.*, 2001) due to their simplicity. In the most basic application of this technique, estimates of monthly 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 ussually applied to the observed series). A considerable fraction of the studies which have considered climate change impacts on flood frequency (Table 3.1) 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*., 2012). The methodology has, however, been expanded to develop 'quantile-perturbation' factors for other statistics such as rainfall event intensities and frequencies (*e.g.* Boukhris and Willems, 2008; Olsson *et al*., 2009; Willems and Vrac, 2011) and inclsion of changes in precipitation variance (Sunyer *et al.*, 2012), and this development is of particular relevance for projecting changes in extreme precipitation and flood frequency. In addition, the application of change factors for the probability of wet *vs*. dry days, is a considerable improvement over change factors based on monthly changes in mean precipitation without such adjustment.

Indirect downscaling methods that have been applied to assess likely changes in extreme precipitation and flood frequency include, among others, the use of stochastic rainfall models or weather generators, the application of weather typing and resampling methods, and the use of climate analogues. When used for downscaling from climate models, stochastic rainfall models (*e.g*. Semenov *et al.,* 1998; Brissete *et al*., 2007; Burton *et al.,* 2008) are set up using probability distribution functions conditioned by outputs from the climate model, and these parameters are typically altered using 'change factors', such that the general methodology has much in common with direct downscaling. The difference, however, lies in the use of a rainfall simulator as an intermediate step for generating precipitation time series used for further analyses. The approach is particularly useful, for example, for studies of likely changes in subdaily precipitation intensities (*e.g*. Segond *et al.,* 2007) if suitable observed data are available for calibration of the rainfall simulator. Comparisons between different weather generators and with change factor methods indicate that certain weather generators are apparently more suitable for evaluating changes in extremes than simple change factor methods (Sunyer *et al*., 2012), although other studies have indicated that rainfall simulation methods may underestimate climate change impacts on extreme precipitation (Arnbjerg-Nielsen, 2012). Weather typing (and related resampling) is also used for downscaling precipitation (*e.g.* Enke *et al*., 2005; Boé *et al.,* 2006; Vrac *et al*., 2007) 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.* resampling of Orlowsky *et al*., 2008). A general limitation of many weather type approaches is that they do not allow for precipitation values which exceed those found in the observations. Alternatives, though, include relating future precipitation to both weather type and to temperature (*e.g.* Willems and Vrac, 2011) and the use of analogue data from other locations with observed precipitation series.

The first two sets of methodologies described above involve the use of quantities derived from climate model output to either directly adjust an observed series (*e.g.* change factor methods) or to generate data for further analyses. In addition to these methods, output time series from

RCMs are also used more directly for analyses, for example, of precipitation statistics or as input to hydrological models. For local scale analyses of precipitation and for catchment-scale hydrological modelling, it is generally necessary to bias correct the climate model output prior to further analyses. There are several methods for achieving this correction, such as a simple correction of the mean of the climate model output (*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 also bias corrections based on quantile-quantile plots (*e.g*. Déqué, 2007). The application of these techniques should also include a strategy for adjusting the number of rainy days, particularly if the precipitation data are to be used to analyse changes in flood frequency.

Analyses of changes in extreme precipitation are undertaken either directly on RCM output or on adjusted data. With respect to evaluating likely changes in flood hazard resulting from extreme precipitation (*e.g*. urban flooding), the focus is often on changes in short-term extreme precipitation statistics or on IDF (intensity-duration-frequency) relationships (*e.g*. see review of Willems *et al*., 2012). In some recent cases, projections have been further applied to assess their 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 used to simulate discharge time series. Many of the hydrological models applied in the climate change studies reported in Table 3.1 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), 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 likely climate change impacts on flooding (Ducharne *et al.*, 2010).

Figure 3.1 and the discussions in the preceding paragraphs show that there are numerous alternative approaches for assessing climate change impacts on 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, as well as alternative hydrological models can produce differing projections for the impact variable of interest. Consequently, a large proportion of climate change impact analyses now consider at least a number of climate projections to produce a distribution of outcomes, rather than relying on a single climate projection. This methodology is now commonly referred to as a type of 'ensemble' modelling approach and has been used in a large number of the studies described in Table 3.1. However, in addition to differences between climate models, several studies have indicated that alternative downscaling techniques (e.g. Beldring et al., 2008; Willems and Vrac, 2011; Sunyer et al., 2012) and hydrological modelling techniques (e.g Ducharne et al., 2010; Lawrence and Haddeland, 2011) can also produce discrepancies in outcomes which are of a similar magnitude to those resulting from differences between climate projections. Therefore, in some ensemble modelling analyses, a wider range of alternatives including multiple downscaling techniques or hydrological models have been applied (e.g. Ducharne et al., 2010).

3.2 Summary of country review reports

The reported studies on climate change projections of extreme precipitation and flood frequency are summarised in Table 3.1. The summary includes information about:

1. Study location: nationwide, regional, specific river basins or catchments
2. Climate change projections applied: GCMs, RCMs and analysed climate forcing scenarios
3. Bias correction and/or statistical downscaling method(s) applied
4. Hydrological modelling approach: type and name of hydrological model(s) applied and information on simulation approach
5. Variable considered, i.e. extreme precipitation (for given durations) or flood frequency
6. Summary of key findings, including projection horizon
7. References

A summary of the general findings and comparison with observed trends is given in Section 3.3.

Climate change projections have been reported for 14 countries in Europe with results for extreme precipitation, extreme streamflow or both, see overview in Figure 3.2.

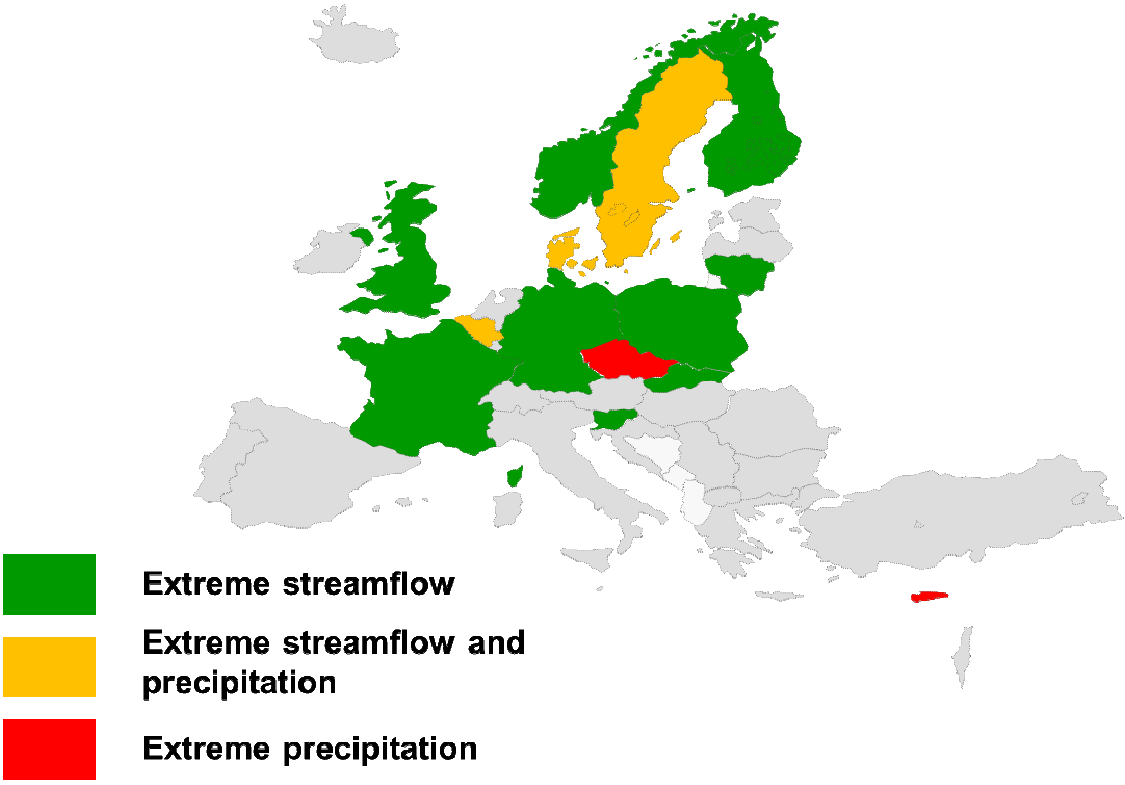

Figure 3.2 Overview of countries with reported studies on projection of extreme streamflow, extreme precipitation or both.

Table 3.1 Summary of country review reports 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 (A1B)	Change in RCM extreme value statistics		Extreme daily precipitation	Increase in 100-year event by about 23 % in 2100 (average of 12 RCMs)	Kysely *et al.* (2011)
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) Sunyer *et al.* (2012)
Denmark Southern Jutland	15 RCMs from ENSEMBLES (A1B)	Mean and variance correction (Sunyer *et al.*, 2012) Weighted ensemble	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	Madsen *et al.* (2011)

		average changes in mean and variance used for statistical downscaling			statistics.	
Denmark Nationwide study	HadAM3H/ HIRHAM4 RCM from PRUDENCE (A2)	Change in RCM extreme value statistics Stochastic rainfall generator Climate analogue		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)
Finland Nationwide study	15 GCMs and 5 RCMs from ENSEMBLES (A2, A1B, B1)	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 Bavaria and Baden-Württemberg	ECHAM4/REMO RCM (B2)	WettReg (Enke *et al.*, 2005) STAR (Orlowsky *et al.*, 2008)	Two distributed hydrological models (LARSIM and ASGi) Ensemble simulation approach	Flood frequency	15% increase in 100-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).	KLIWA (2011) 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 Nationwide study	13 RCMs from ENSEMBLES (A1B) 4 RCMs from PRUDENCE (A2, B2)	Delta change method Empirical adjustment method (Engen-Skaugen, 2007)	Lumped, conceptual rainfall-runoff model (HBV) Ensemble simulation approach Uncertainty in hydrological parameters	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 regions are generally	Lawrence and Hisdal (2011)

			included		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.	Kaczmarek (2003) Romanowicz *et al.* (2011)
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)
Slovenia Nationwide study	Details not given	Details not given	Lumped, conceptual rainfall-runoff model (HBV)	Flood frequency	In the Alpine and hilly catchments increase in flood peaks of about 30%. In karstic areas increases of about 10%.	Kobold (2009)
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	5–10% increase in short-duration extreme intensities in the period 2011–	Olsson *et al.* (2012)

				and 24 hours	2040 and a 10–20% increase in the period 2071–2100	
Sweden Nationwide study	16 RCMs	Distribution based scaling (Yang *et al.*, 2010)	Lumped, conceptual rainfall-runoff model (HBV) Ensemble simulation approach	Flood frequency	In the central part of the country, floods tend to decrease, mainly due to decreasing snowmelt floods in spring, while rain-fed floods in the south show the opposite tendency.	Bergström *et al.* (2012)
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 Nationwide study	HadRM3 RCM (A1B) Ensemble of three perturbed parameter simulations	No statistical downscaling of RCM	Lumped, conceptual (PDM) and distributed (G2G) rainfall-runoff models Ensemble simulation approach	Flood frequency	Upward trend in flood risk nationally	Kay and Jones (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

3.3 Comparison of trend analyses and climate projections

Brief details of the principal studies on trend analyses and climate projections of precipitation extremes and flood frequency are given in Table 2.1 and 3.1, respectively. Changes in and projections of extreme precipitation have only been reported by a subset of the countries participating in FloodFreq, whereas most countries have reported work on flood discharges in rivers. In addition, as reviewed in Section 2.1 on methods for trend detection and attribution and in Section 3.1 on methods for developing projections under a future climate, there are a range of analytical and modelling techniques that can be and have been applied in the reported studies. Time periods used for analyses or projections also vary between the studies, as do the actual quantities considered. These factors make it unadvisable to draw direct comparisons between individual sets of results. It is nevertheless feasible and useful to summarise the general findings, with a focus on comparisons between observed trends and projected impacts, and this is briefly pursued in the following paragraphs.

Countries reporting studies which consider trends or changes in observed extreme precipitation include Belgium, Bulgaria, Cypress, the Czech Republic, Denmark, France, Greece, Italy, and Sweden (Table 2.1). The results are summarised in Figure 3.3.

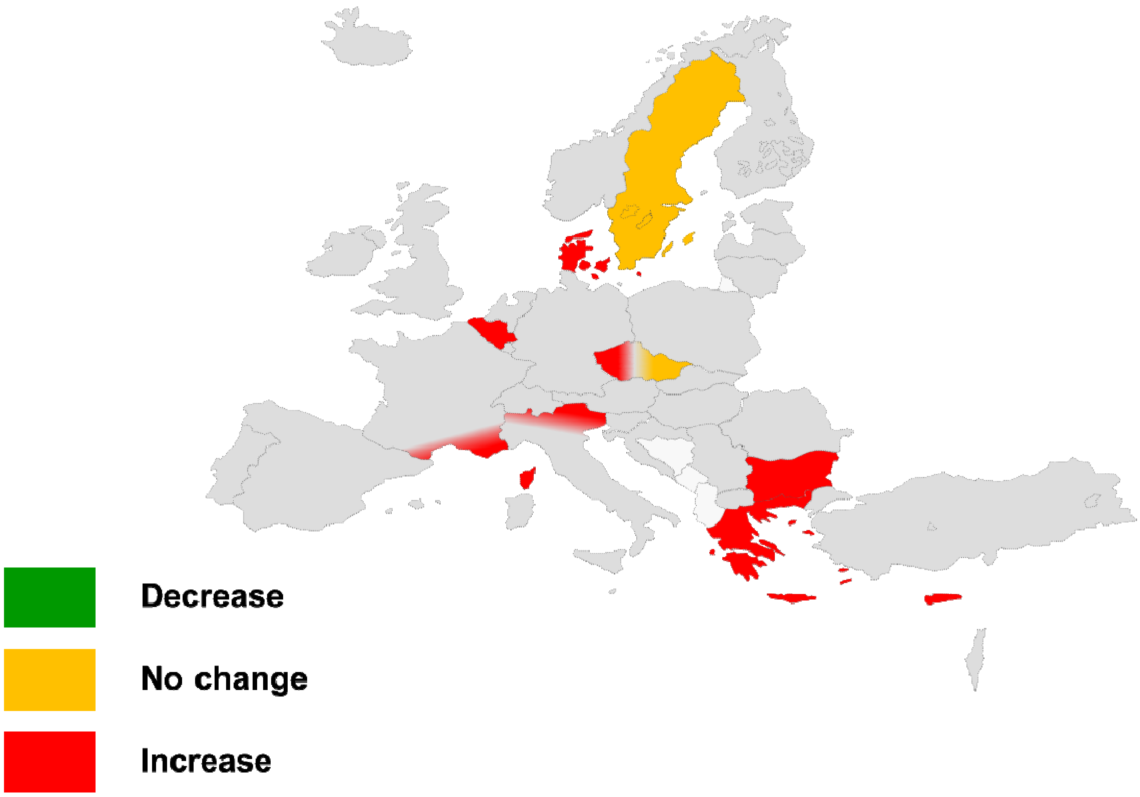

Figure 3.3 Summary of reported results of trend analysis of extreme precipitation.

Some studies report increases in extreme precipitation based on observed daily values (*e.g.* in Brussels, Belgium, Ntegeka and Willems, 2008; in the western part of the Czech Republic in the winter, Kyselý, 2009; in some regions in France, Pujol *et al.*, 2007; and in northeastern Italy, Brunetti *et al.*, 2001). Analyses in southern Sweden, however, 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. A few studies report changes in short-duration rainfall (from 5-10 min up to 24 hours), and these studies again generally report increases (*e.g.* in Brussels, Ntegeka and Willems, 2008; in regional extreme values for Denmark, Madsen *et al.*, 2009; and in Malmö, Sweden, Hernebring, 2006).

Studies reporting potential future changes in extreme precipitation due to climate change (Table 3.1) point more uniformly towards increases. The results are summarised in Figure 3.4.

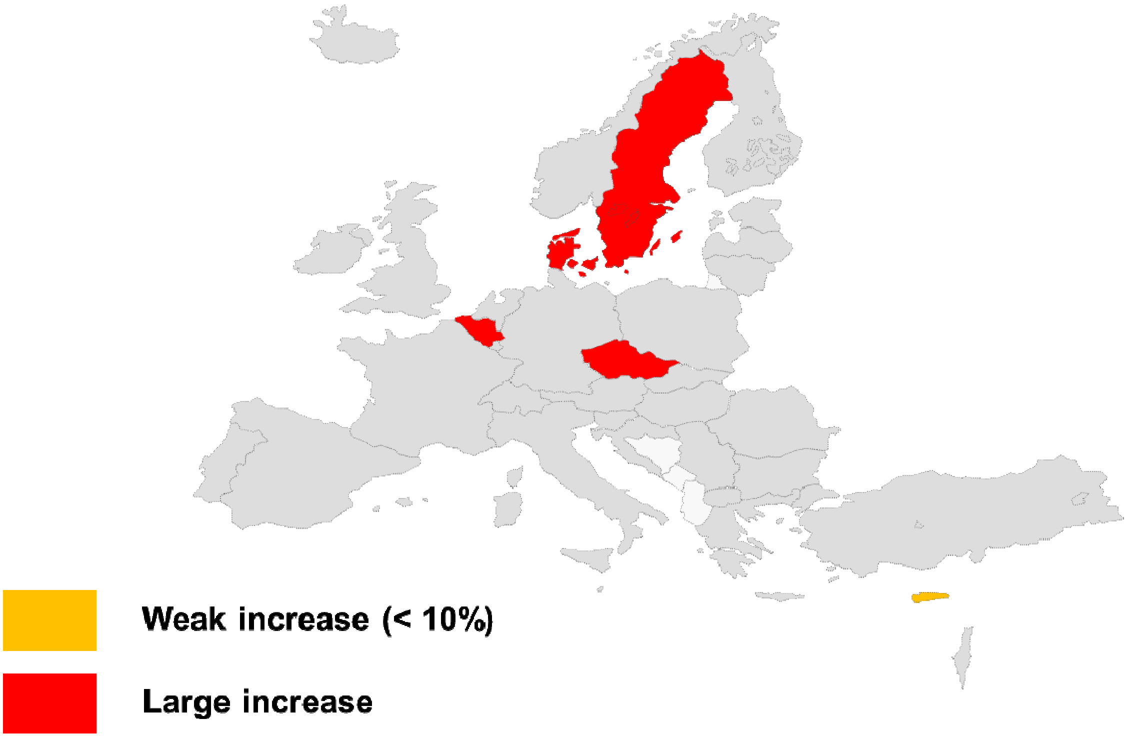

Figure 3.4 Summary of reported results of projections of extreme precipitation.

The projected changes reported include increases in 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). Also in Sweden increases in short-duration precipitation extremes are reported (20-60% in Kalmar, Olsson *et al.*, 2009; 10-20% in Stockholm, Olsson *et al.*, 2012). In summary, the studies reviewed here indicate that there is some evidence for increases in observed extreme precipitation at some locations in Europe. Projections for changes in extreme precipitation indicate that increases are also likely under a future climate.

A considerable number of national and regional studies of trends or changes in observed extreme streamflow have been undertaken across Europe (Table 2.1). The results are summarised in Figure 3.5.

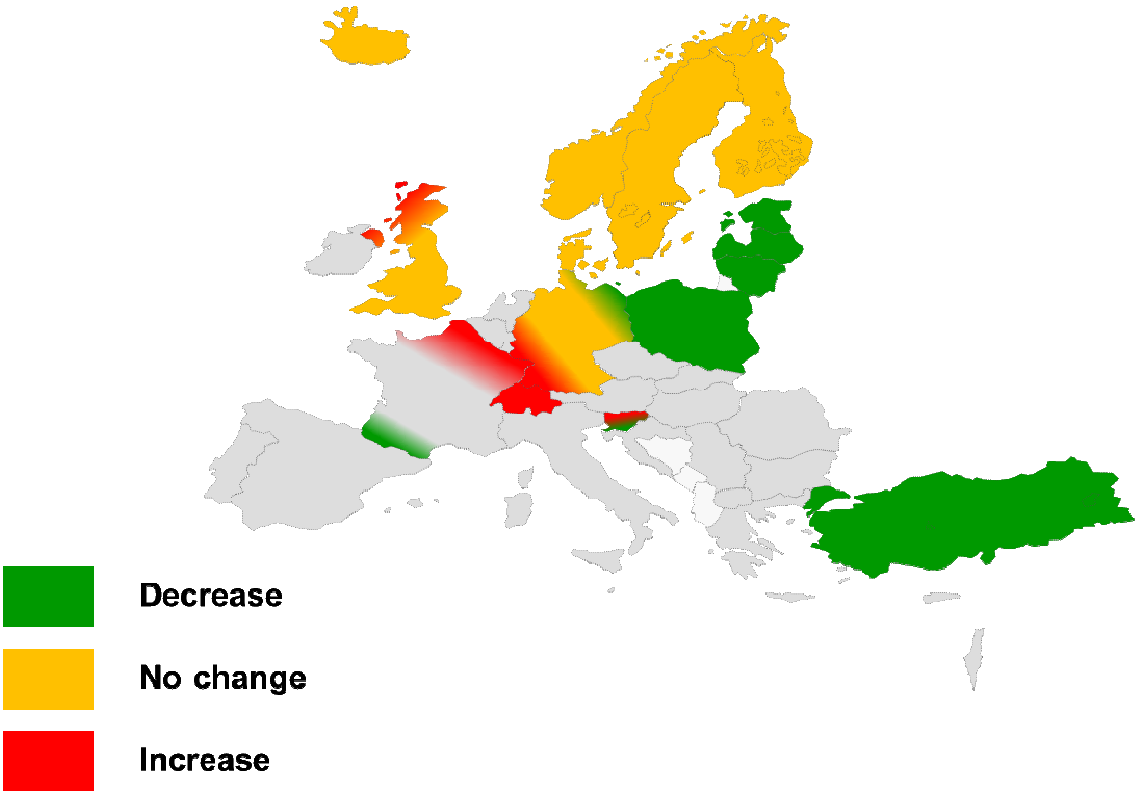

Figure 3.5 Summary of reported results of trend analysis of extreme streamflow.

Countries reporting nationwide studies include Finland, France, Germany, Lithuania, Poland, Slovenia, and the UK. In addition, regional studies covering several countries have been undertaken for the Baltic and the Nordic region. The general conclusion that can be drawn from these studies is that there are no clear national or larger-scale regions which uniformly exhibit statistically significant increases in flood discharges in recent years. In some cases, increases are apparent for smaller regions (*e.g.* increased flood peaks in northeast France and increasing runoff in the Alps, Renard, 2006; in the magnitude of annual peaks in alpine basins in Switzerland, Castellarin and Pistocchi, 2011; and in flood indices in upland, maritime-influenced catchments in northern and western UK, Hannaford and Marsh, 2008), although this can be influenced by the length of the time period considered in some of these studies. In many cases, individual stations in a country or a region may have both positive and negative trends (*e.g.* in mean annual flood and flood frequency for stations in Germany, Bormann *et al.*, 2011; in flood indices at stations in Slovenia, Jurko, 2009), or no evident trend (*e.g.* spring peak flows in Finland, Korhonen and Kuuisisto, 2010; and annual and seasonal maximum flows in the Nordic region, Wilson et. al., 2010). In Germany, there appears to be a spatial clustering of stations exhibiting significant positive *vs.* negative trends which may reflect differences in climate forcing (Petrow and Merz, 2009; Petrow *et al.*, 2009). Several studies, however, report decreases in peak discharges (e.g. in spring peak flows in the Baltic region, except western Latvia and Lithuania, Reihan *et al.*, 2007, 2012; in high flows in the Pyrenees, Renard, 2006; for stations located in mountainous areas in Slovenia, Jurko, 2009; and in annual peaks flow series for some stations in Poland, Strupczekski *et al*., 2009). 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, and more generally throughout the Nordic region, Wilson *et al.*, 2010; in the Alps, Renard, 2006; in Lithuania, Meilutytė-Barauskienė and Kovalenkovienė, 2007; and throughout the Baltic region, Reihan *et al.*, 2012).

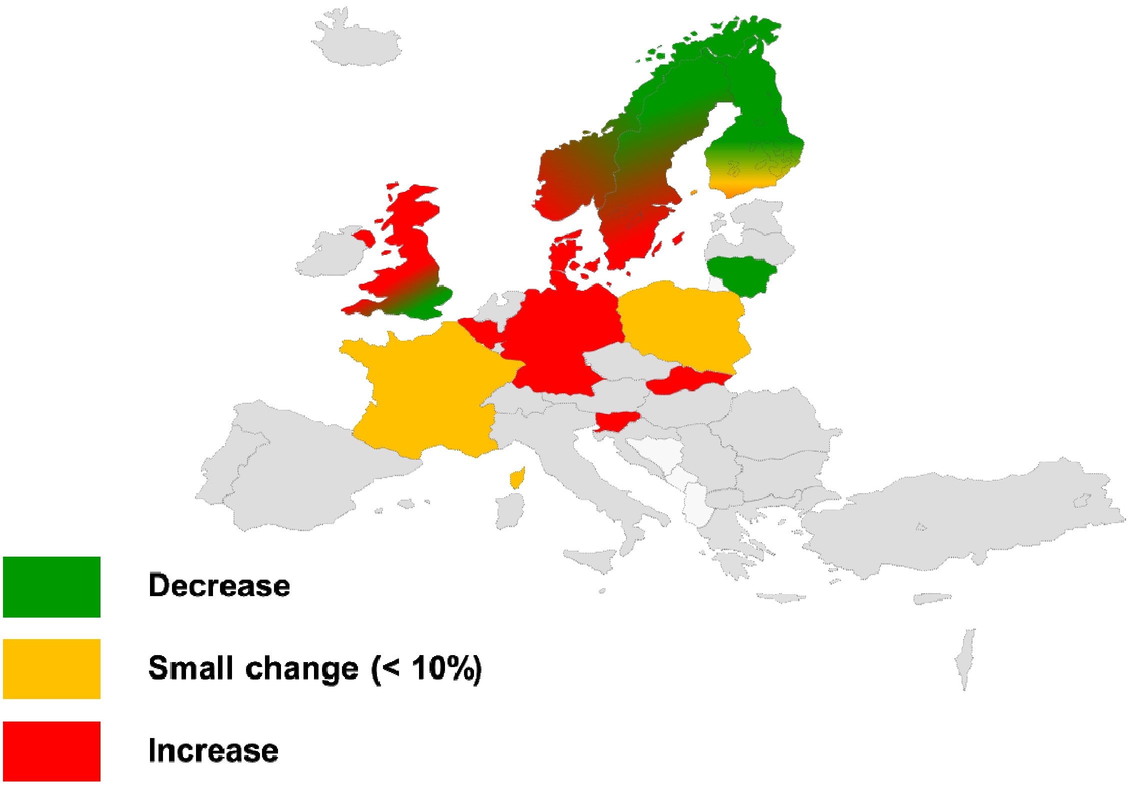

Figure 3.6 Summary of reported results of projections of extreme streamflow.

Hydrological projections for changes in peak flows and in flood frequency have been developed for catchments in several countries (Table 3.1) and are reported for Belgium (Flanders), Denmark, Finland, France, Germany, Lithuania, Norway, Poland, Slovakia, Slovenia, Sweden, and the UK. The results are summarised in Figure 3.6. Similar to the reported observed trends described above, both positive and negative changes in extreme discharge are projected. Increases in peak discharges and/or flood magnitudes are projected for sub-basins in the

Scheldt and Meuse in Flanders (Willems *et al.*, 2010), for catchments in Denmark (Sunyer *et al.*, 2010; Madsen *et al.*, 2011), 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 (Hlacova *et al.*, 2007), in alpine and hilly areas of Slovenia (Kobold, 2009), in coastal, southern areas in Sweden (Bergström *et al.*, 2012), and in many catchments within the UK (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 (Lawrence *et al.*, 2012) indicate a possible increase 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 (for some RCM/GCM realisations), and inland catchments in Norway (Lawrence and Hisdal, 2011) and in Sweden (Bergström *et al.*, 2012). In addition, Kay *et al.* (2006) also project decreases in flood magnitude for the catchments considered in south and east England.

There are several factors which determine the response of individual catchments to projected regional changes in temperature and precipitation, including the dominant flood generating mechanism and the size of the catchment. These factors contribute to the large differences across Europe in the reported projections. Of particular relevance in interpreting the regional pattern of projected increase *vs.* decrease in flood discharge is the role of snowmelt in flood generation. Despite expected increases in extreme precipitation throughout Europe, many areas dominated by peak flows during the spring and early summer snowmelt season are projected to have decreased flood magnitudes under a future climate, reflecting the decline in snow storage and the earlier peak flows. This latter factor is, indeed, consistent with the observed trend towards earlier snowmelt peaks and decreases in spring peak flows. On a more local scale, changes in the availability of groundwater storage may also play a role in possibly mitigating flood peaks in some areas (e.g. in karstic areas in Slovenia, Kobold, 2009; or in parts of the UK). Many areas of Europe are, however, likely to experience an increase in peak flood discharges according to the projections reported here. Although there are only a limited number of studies which report statistically significant increases in observed peak discharges, the regions and types of catchments in which increases are observed are also generally consistent with projected changes under a future climate.

4

4 Non-stationary flood frequency and risk analysis

4.1 Policy guidelines

Concerning the potential effects of environmental change on the frequency and magnitude of design floods, Norway, the UK, two river basin authorities in Belgium, and two federal states in Germany were identified as having developed guidelines for directly adjusting design flood estimates derived from models assuming stationarity. More details are provided below and in the individual country reports, while a summary of the results are provided in Table 4.1.

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 higher 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 allowances to be applied for design flood estimates. 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 (Hennegriff *et al.*, 2006).

In Norway, regional factors of 0%, 20% and 40% increase of design flood estimates derived assuming stationary conditions are recommended based on consideration of region, location (inland or coastal catchment), and prevailing flood season. For all catchments with a catchment area less than 100km^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, a number of procedures exist to adjust design flow estimates for the perceived influence of climate change and land-use. Considering the effect of climate change on design flood estimates a safety margin 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 impact factors (Prudhomme *et al.*, 2010), but these results have not yet found their way into official policy. The impact of urbanisation on flood frequency relationships was reported in Kjeldsen (2010) who developed a set of adjustment procedures allowing an adjustment of the estimates of the index flood and the two high-order L-moment ratios defining the flood growth curve according to the level of urbanisation in the catchment under consideration.

More specifically targeting urban drainage design, guidelines for adjusting design rainfall estimates were identified for Belgium, Denmark, Sweden and the UK. In Belgium, IDF-curves and design storms have been developed for high, mean, and low climate scenarios (after statistical downscaling). Rainfall intensities were found to 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 1.2, 1.3 and 1.4 (20%, 30% and 40%) when estimating design rainfall of 2, 10, and 100-year, respectively. While recognising that the effects might vary for different durations and geographical locations, these effects were considered secondary in relation to return periods, and thus, not considered.

The Swedish Water & Wastewater Association (SWWA, 2011) published guidelines for a regional climate factor, multiplying design rainfall totals with between 1.05 – 1.3 depending on the region.

For 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.

Table 4.1 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-Würrtemberg	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)

4.2 Research gaps

The review of the countries involved in the FloodFreq COST Action 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. For most countries flood frequency estimation is currently being undertaken using models based on a fundamental assumption of a stationary historical record, be it flood flows or rainfall.

However, in recognition that observed data represent the past, and that these same data might no longer provide all the required information needed concerning the future statistical behaviour of extreme precipitation and floods (i.e. non-stationarity), several countries across Europe have undertaken sensitivity studies of potential future changes to extreme precipitation and flood frequency relationships through the use of climate model projections (RCM and GCM). The most common method is to analyse precipitation and flood series derived for different time slices and compare the differences in design estimates. Typically, this is done by comparing design estimates obtained using data from a historical reference period (1961-1990) with estimates obtained for a simulated future climate scenario (say, 2071-2100).

More recently, the dynamic changes within the transient model simulations involving future climate scenarios have been reported by Kay and Jones (2012) and Lawrence *et al.* (2012), both applying a moving 30-year window across the simulated output. While these transient impact studies represent a more detailed investigation in the potential effects and the inherited uncertainties in impact modelling, they don't provide a full non-stationary frequency model.

The move beyond a sensitivity-type approach and towards a new non-stationary framework based on the use of non-stationary frequency models has been identified as an important aspiration within the European hydrological science community. 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 and estimate the model parameters using maximum likelihood methods (e.g. Strupczewski *et al.*, 2001a) or Bayesian methods (Renard *et al.*, 2006). For extreme rainfall, Hanel and Buishand (2011) used a non-stationary GEV model to estimate seasonal extremes in an ensemble of fourteen transient RCM rainfall series.

Other examples of this approach are available, but from outside Europe. For example, in a study examining changes in flood quantiles derived from annual maximum series of instantaneous streamflow in catchments from across continental US, Vogel *et al.* (2011) found that large increases were generally observed in regions with higher population densities. Stedinger and Griffis (2011) discussed procedures for introducing consideration of non-stationarity into the US design flood guidelines described in the Bulletin 17B (USWRC, 1981).

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Appendix A

Country Review Reports

Review of applied methods for flood-frequency analysis in a changing environment in Flanders, Belgium

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1. Description of methods

1.1 Detection of trends and shifts in time series of hydrological extremes (at-site and regional procedures)

Trend detection has been combined with the analysis of multi-decadal oscillations in rainfall and river flow series. Rainfall extremes were extracted from the series by means of independence criteria. Successive extreme events were considered independent when the inter-event time exceeds a given threshold and (for river flow series) when the lowest flow in between the two peak flows undercuts a given threshold. After calculation of empirical frequencies, quantiles (values of given frequency) were computed based on the full series and for block periods of 5, 10 and 15 years. Quantiles derived from the block periods were compared with quantiles derived from the full series (for given exceedance probabilities or empirical return periods). The mean ratio of these quantiles above a given probability was defined as “quantile anomaly”. The temporal (multi-)decadal variability of this anomaly was computed for a range of time scales and different stations in Belgium. Also the consistency of the findings with long daily rainfall records in neighbouring regions of northwestern Europe was checked.

1.2 Non-stationary flood frequency analysis (at-site and regional procedures)

The method used in 1.1 for analysis of multi-decadal oscillations involves non-stationary extreme value analysis. The analysis is done for block periods (moving windows) of various lengths (5, 10, 15 years). Quantiles obtained for each block period are compared with quantiles obtained from the full period of available data (see Ntegeka & Willems, 2008).

1.3 Rainfall-runoff modelling

For impact analysis on rivers and river hydrology, lumped conceptual as well as more detailed physically-based and spatially distributed models (and groundwater models) have been applied. Lumped conceptual models used are: NAM, PDM and a so-called “generalized” lumped conceptual model (VHM).They have been calibrated for almost all catchments in the Flanders area of Belgium. A step-wise calibration method is used, which involves a number of time series processing techniques, such as subflow filtering, separation of the time series in quick and slow flow events, and extraction of nearly independent high and low flows from the time series (Willems, 2009).

For impact analysis on urban drainage, a conceptual reservoir-type based approach is considered. This conceptual model is calibrated to a full hydrodynamic sewer system model (e.g. Willems, 2010).

1.4 Multivariate frequency analysis (e.g. storm surge, river flooding, urban flooding)

Research is on-going to study the correlations between storm surge heights (along the Belgian North Sea; Ullmann & Monbaliu, 2009; Ntegeka et al., 2011) and inland rainfall; idem for the changes in surge heights and rainfall intensities. River and urban flooding are still studied separately.

1.5 Uncertainty and risk analysis

In the method described in 1.1, significance testing has been done based on the calculation of confidence intervals on the quantile changes using a non-parametric bootstrapping method (see Ntegeka & Willems, 2008).

2. Data

2.1 Availability and use of streamflow/precipitation data and proxy data for change detection and frequency analysis

- Uccle rainfall series: 10-minutes rainfall intensities 1898-2005, not affected by instrumental changes or measurement inhomogeneity: owned by the Royal Meteorological Institute of Belgium.
- Meuse river discharges: daily discharges since 1910: owned by Rijkswaterstaat, The Netherlands.
- Storm surge heights along the Belgian coast at Ostend since 1925: owned by the Coastal Service of the Authorities of Flanders, Belgium.

These data series are not publicly available or for the FloodFreq project. Permission to use has to be obtained from the authorities that own the data on an individual basis.

2.2 Availability and use of data to assess changes in hydrological regime and river infrastructure development

For some river basins, research is ongoing to study the impact of urban drainage on the hydrological regime of the river basin and the downstream river flow. In some river basins (e.g. Grote Nete basin), urban surface runoff discharges are drained to wastewater treatment plants outside the basin, hence causing inter-basin water transfers. Next to the influence of urban drainage, river flows are for most rivers regulated / influenced by hydraulic regulation structures, weirs and sluices, flood control reservoirs, etc. Details on these “public works” are available for most rivers. For some rivers (e.g. Dender) the impact of recent works (past decades) on the river flows (incl. flow extremes and flood risks) has been studied by means of hydrodynamic river models (implemented in MIKE11 or InfoWorks-RS).

These data or models are not publicly available or for the FloodFreq project. Permission to use has to be obtained from the authorities that own the data, on an individual basis.

2.3 Availability and use of climate change projections from general circulation models and regional climate models, including statistical downscaling

Climate change projections were based on a set of about 30 simulations derived from about 10 RCMs (obtained from the EU projects PRUDENCE, ENSEMBLES and ESSENCE) (see Baguis et al., 2010; Ntegeka et al., 2009). The experiments were run for the IPCC regional future greenhouse gas emission scenarios. Since the RCMs were nested in a limited number of GCMs and that more runs were based on IPCC emission scenarios A2 and B2 than on other scenarios, scaling factors were required to make the scenarios more exhaustive (thus better taking into account the emissions uncertainty) by including changes from extra scenarios (notably the A1B and B1). These were derived from more than 20 GCM simulations considered for the 4th Assessment Report of IPCC. An “ensemble approach” thus is applied, considering as many climate model runs as available (Figure 3).

Statistical downscaling was based on quantile perturbations (Ntegeka et al., 2009), and by advancing the standard weather typing based statistical downscaling method including temperature rise effects (Willems & Vrac, 2010).

The IPCC, PRUDENCE, ENSEMBLES and ESSENCE RCM & GCM results are publicly available. Also the processed climate scenarios and related Excel perturbation tool can be made available for the FloodFreq project.

3. Applications

3.1 Purpose and areas of application (design of hydraulic structures, dams, urban hydrology, flood-hazard mapping, etc.).

- Schematic overview of the overall methodology: Figure 2.
- Flood-hazard maps for river flooding: for high, medium and low climate scenarios. The method combines time series perturbations of rainfall and ETo series (in a correlated way), impact simulations on sub-catchment rainfall-runoff flows by means of lumped conceptual models, statistical analysis of the runoff series and computation of composite hydrographs, simulation of these synthetic hydrographs in full hydrodynamic river models and quasi-2D floodplain models and GIS-based inundation and flood risk mapping (Willems et al., 2002; Figures 6 and 7)
- Urban flooding: changes in IDF-curves for precipitation and related changes in design storms (composite storms), and required storage capacities in urban drainage systems (Willems & Vrac, 2010; Figure 8)

3.2 Merits and drawbacks of different methods

- Merits:
  - o Ensemble approach is applied for climate model based changes (given that the uncertainties in the climate model impact simulations are extremely high).
  - o Instead of simulating the hydrological impact results for each climate model run (more than 30 in total in our case), tailored (high, mean, low) climate scenarios have been developed, which aim to represent a “pessimistic”, mild and “optimistic” climate scenario (Figures 3 and 5). A “perturbation tool” has been developed that can perturb rainfall, temperature, ETo and wind speed series, for these high, mean and low climate scenarios (Figure 4). The tool in the mean time became the standard in Belgium for climate change impact studies; it is being used by a large number of impact modellers (Ministry of Public Works, Environment Agency, Institute for Nature and Forest Research, several consulting and engineering firms).
- Drawbacks:
  - o High computational burden to simulate/apply all the models and modelling steps (hydrological models, river full hydrodynamic models, floodplain models, statistical analysis, GIS)
  - o Use of lumped conceptual models might not provide accurate results on changes in the groundwater component. The use of more detailed and spatially distributed hydrological models, however, does not allow long time series to be simulated in the model (because of the long computational times of these models), which is required to enable statistical extreme value analysis of results.

3.3 Recommendations for users

- Use of the climate scenarios and related perturbation tool in support of their sustainable water management and planning.
- New guidelines for the design of sewer systems have been set up: these include the bias corrected IDF-curves and design storms for current climate conditions; they also describe the new IDF statistics for high, mean, low climate scenarios (after statistical downscaling).
- The two main river authorities (Flanders Hydraulics, Flemish Environment Agency) have established guidelines for flood hazard mapping under current climate conditions and for high, mean, low climate scenarios.

4. Case studies

Examples of practical applications:

- Trend detection and analysis of multi-decadal oscillations in rainfall and river flow series (see method in section 1.1): The past 100 years showed for Belgium and neighbouring regions higher rainfall and river flow quantiles for the 1910s-1920s, the 1960s, and more recently during both winter and summer of the past 15 years (Figure 1). The increase in rainfall quantiles was due to both an increase in the number of extreme rainfall events and an increase in the intensity of the extreme events. The increases were found statistically significant at the 5% confidence level, and were found to be partly explained by persistence in atmospheric circulation patterns over the North Atlantic during periods of 10 to 15 years. Moreover, it is shown that the recent upward trend in these extremes is partly related to a positive phase of this oscillation, which coincided with the climate change influence (see Ntegeka & Willems, 2008; example in Figure 1). Consistency of these findings with long daily rainfall records in neighbouring regions of northwestern Europe was also found (not yet published; abstract Willems & Yiou, 2010).
- Flood hazard mapping for current climate and for high, mean, low climate scenarios (2071-2100) along most main rivers and 67 subbasins in the Flanders' areas of the Scheldt and Meuse basins (Boukhris & Willems, 2008; Boukhris et al., 2008; Figures 6 and 7). It is found that the peak flows may increase or decrease, depending on the climate scenario considered. In the high climate scenario, the peak flows (for return periods higher than 1 year) increase with about 30% by 2100. The low flows and groundwater levels decrease in all climate scenarios. The changes in low flows range from -20% to -70% (depending on the climate scenario and the catchment). The results indicated that Belgium has to take the increasing risk of future water scarcity serious. Already at present water suppliers over-pump groundwater resources; at some locations in the country, the groundwater levels are more than 100 m lower than the natural conditions (without groundwater based water supply). There is no awareness about this among the general public. The public is also not aware about the risk of future droughts.
- Changes in rainfall IDF curves for high, mean, low climate scenarios (after statistical downscaling) for Uccle, Brussels, in the range from 10-minutes to 15 days; corresponding changes in the design storms (so-called composite storms) used for the design of sewer systems in Flanders; changes in the storage capacity needed for sewer systems, storage tanks and infiltration ponds (Willems & Vrac, 2010; Willems, 2011; Figure 8). Rainfall intensities were found to increase with about 30% by 2100 in the high climate scenario (and between 0% and 30% for other scenarios). For the high climate scenario, 20% - 40% additional storage capacity would be required along the sewer systems in order to limit the frequency of floods and overflows to the current levels.
- IDF-curves for current climate conditions, which were obtained in previous studies based on rainfall series for 1967-1993. This period was considered too short for obtaining long-term statistics on rainfall extremes is a reliable way. Bias correction was applied to account for the multi-decadal oscillations (only internal report available so far, in Dutch). This bias correction equals an increase of the rainfall intensities with 7.5% (on average for the short durations between 10 minutes and 1 day) and was due to the oscillation low period of the 1970s and 1980s.
- The implications of the changes in flood and drought risks continued to be investigated in support of the MIRA-2009 and NARA-2009 Environmental Outlook reporting for the Flemish Environment Agency and the Flemish Institute for Nature and Forest

Research. The ecological impacts and the implications to society, water managers and policy makers were assessed (Brouwers et al., 2009). Potential severe impacts were predicted on river and sewer flood frequencies, sewer overflow frequencies, water scarcity frequencies (see also previous points), but also on water quality, vegetation, bird migration, and other animals.

- The impacts of the changes in river flood frequencies on wetland vegetation were studied (Willems et al., 2010). The impact analysis faced several problems due to important interfacing gaps between the disciplines hydrology and ecology.
- Comparison between the impact of climate scenarios and trends in urbanization projected till 2050 (Poelmans et al., 2010). The % paves areas increased from 7.2% in 1976 to 18.3% in 2000, and further increase is projected till 41.5% in 2050. These changes in future urbanization trends were found to be important, but less strong that the changes due to climate change. The increase in peak flows till 2050 ranges from 6% to 16% depending on the urbanization scenario, while they would increase up to 30% under the high climate scenario.

5. Plans for future development

- Analysis of more RCM simulations and new IPCC scenarios
- Apply ensemble method not only on climate model results, but also on statistical downscaling methods/assumptions.
- Taking into account the bi-directional interactions between urban drainage and river systems, including water transfers between basins (because of drainage of urban surface water to wastewater treatment plants outside the basin). This involves the study of the combined effect of climate changes on urban drainage and river catchment runoff.

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Open source software:

CCI-HYDR Perturbation Tool: tool for perturbing rainfall, temperature, ETo and wind speed series, following the high, mean and low climate scenarios developed for Belgium (ensemble approach on available climate model results). Can be downloaded from http://www.kuleuven.be/hydr/CCI-HYDR.htm

Selected figures:

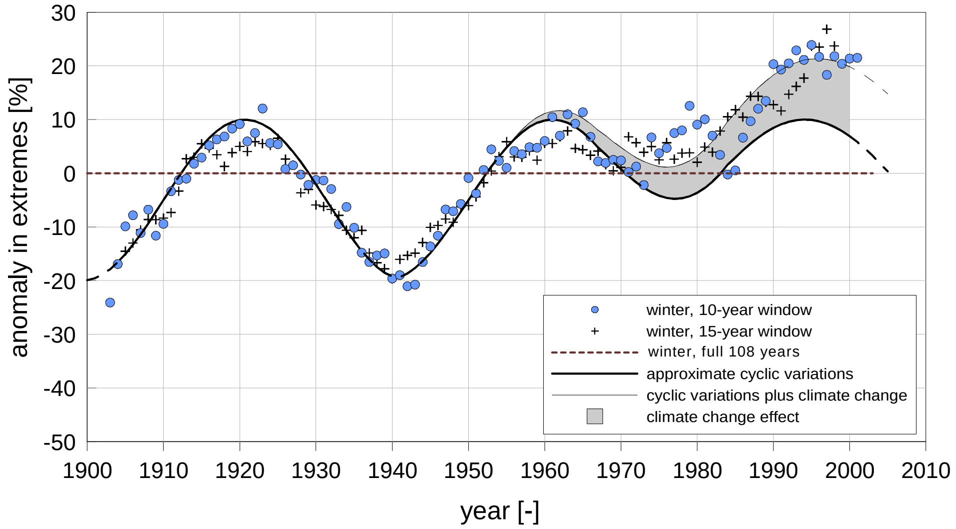


Figure 1. *Anomaly in quantiles of 10 minutes rainfall extremes (of return period longer than 1 year) at Uccle, Brussels, in the winter season, for moving windows of 10 and 15 years in comparison with the full period 1898-2005 (adapted from Ntegeka & Willems, 2008)*

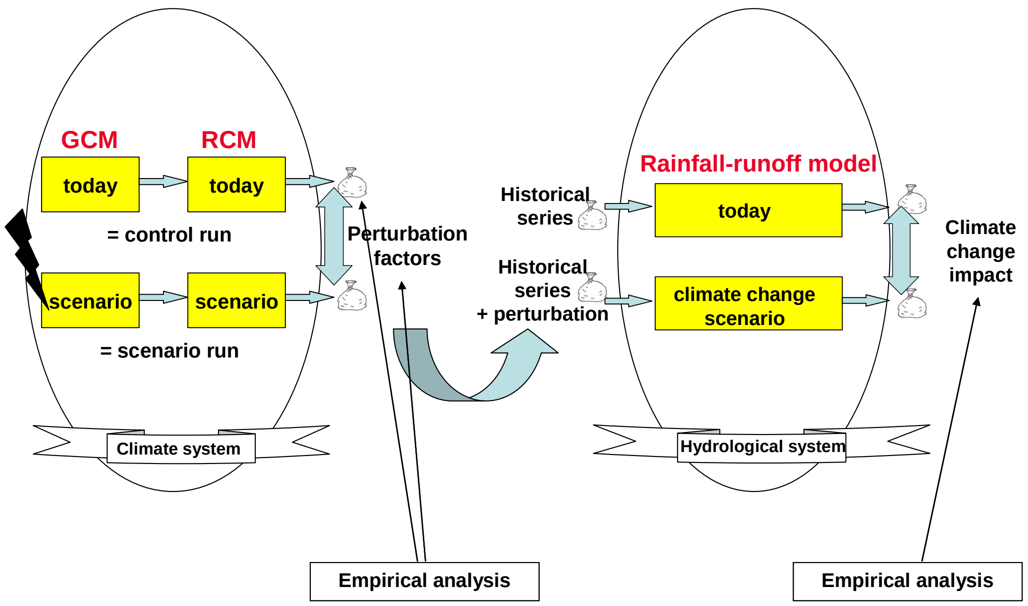
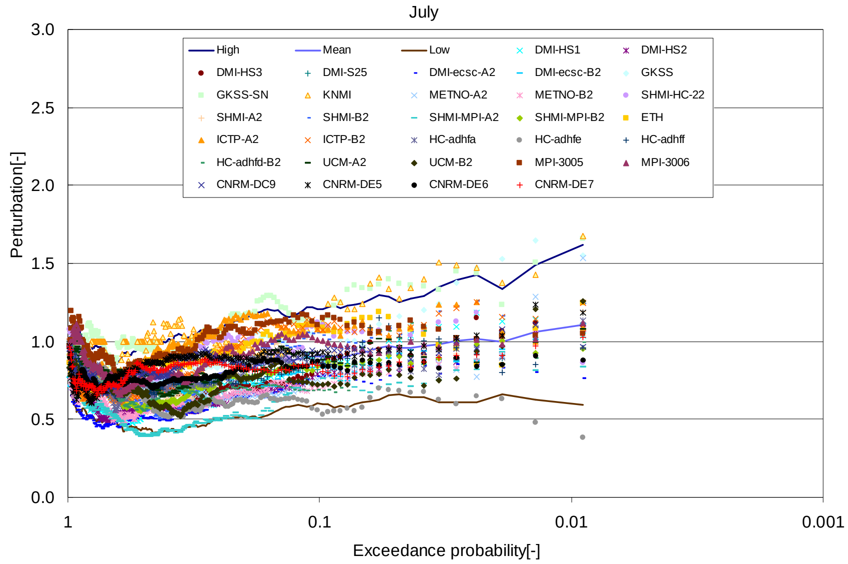


Figure 2. *Schematic overview of the method applied for climate change impact analysis.*



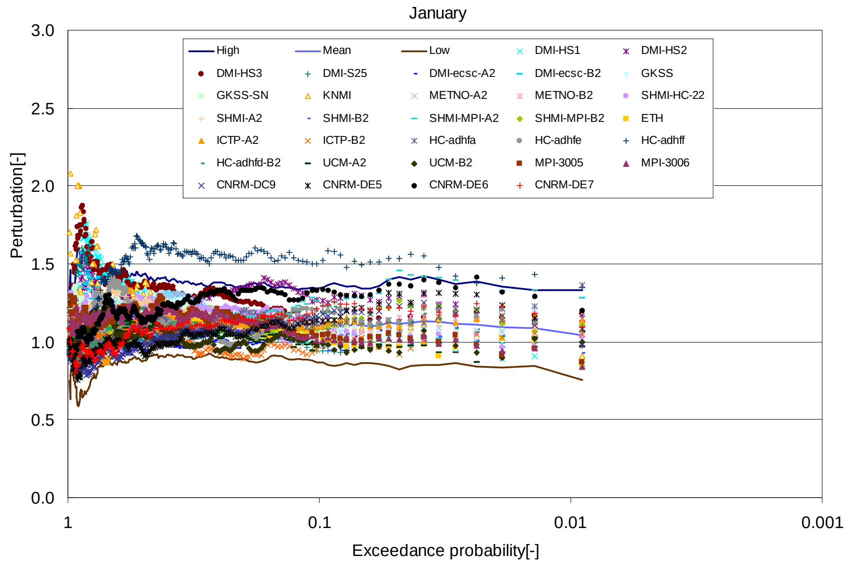


Figure 3*.* *Typical wet day rainfall quantile-perturbation projections for Uccle, Belgium, in summer (July) and winter (January). The high, mean and low scenarios are based on the normal distribution (95% confidence limits) and represent the range of the perturbations.*

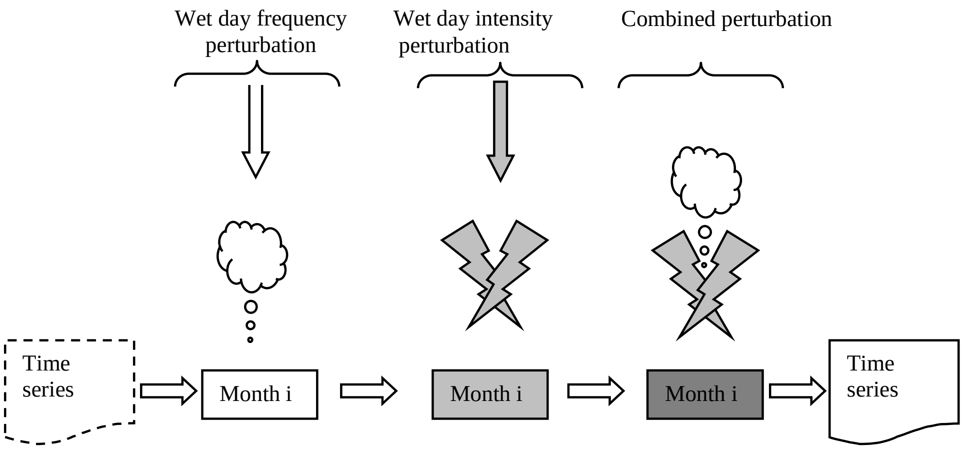


Figure 4. *Rainfall time series perturbation.*

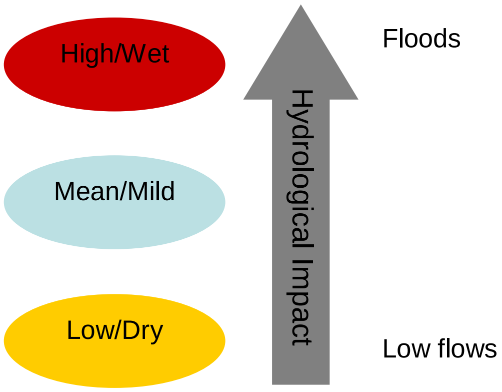


Figure 5. *The three climate scenarios for Belgium: high/wet, mean/mild and low/dry, representing pessimistic, mild and optimistic scenarios for flood and low flow studies, based on an ensemble of about 30 RCM runs and more than 20 GCM runs.*

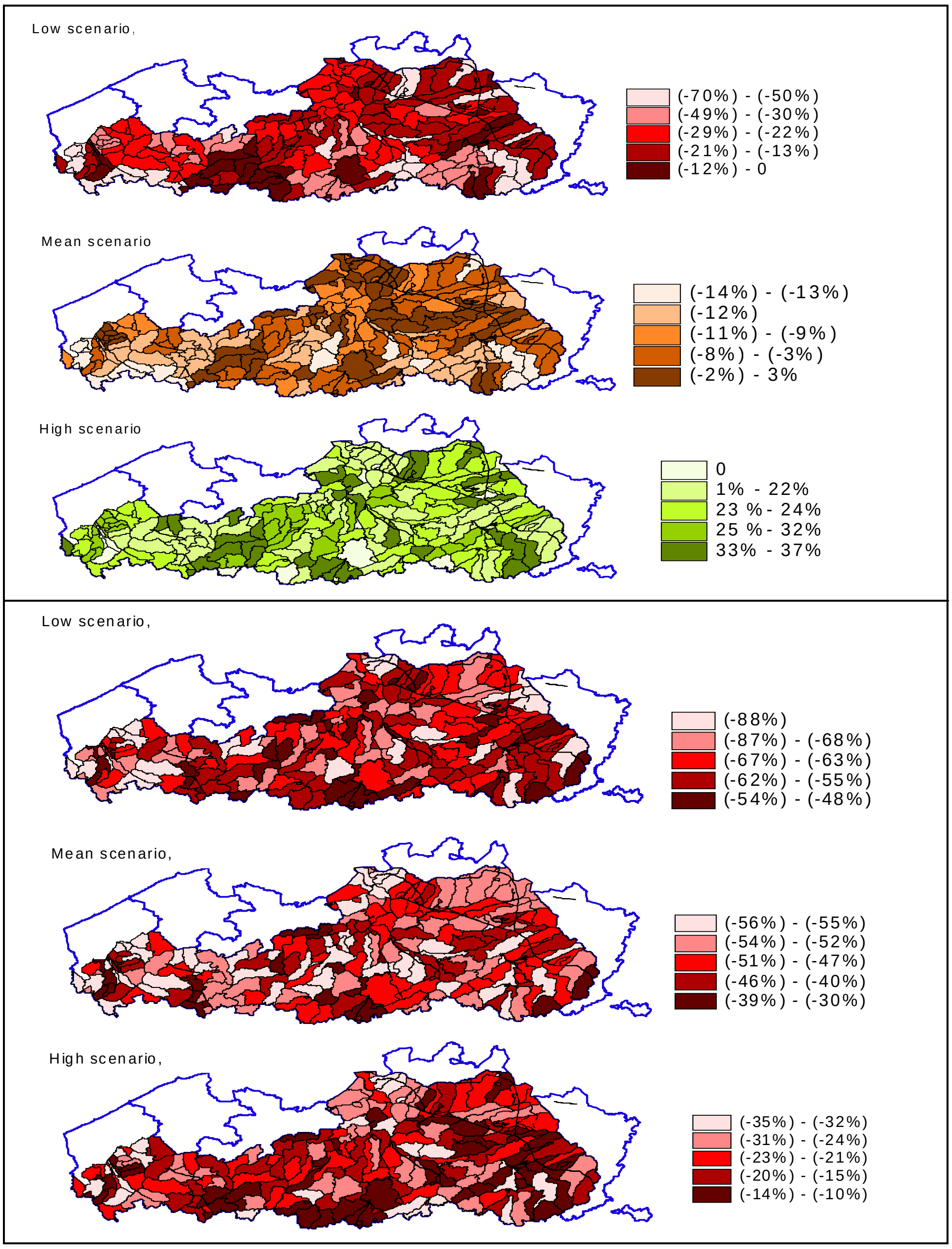


Figure 6*.* *Percentage of variation (for the future climate 2071-2100 compared to the control period 1961-1990) of hourly runoff peaks (top panel) and low flows (down panel) for the low, mean and high climate scenarios and based on NAM lumped conceptual rainfall-runoff models.*

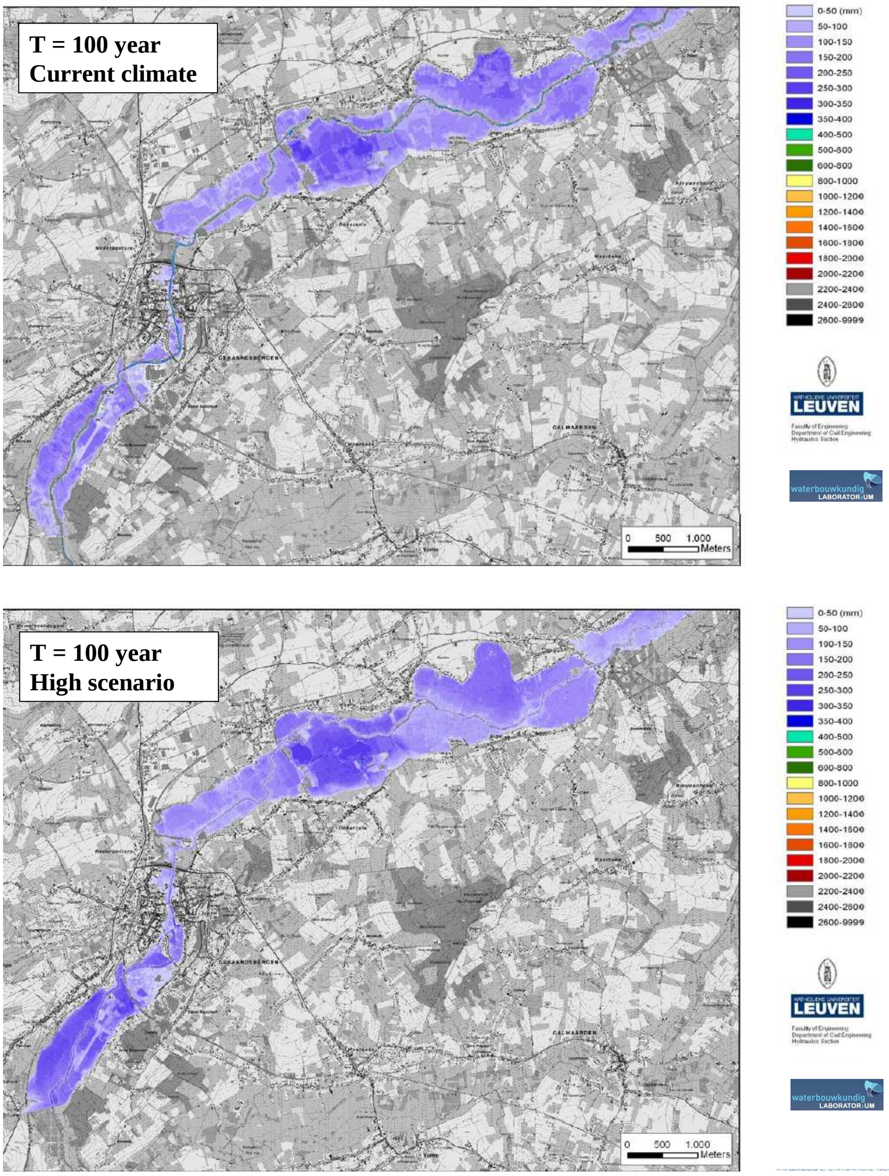


Figure 7. *Flood maps for the region around Geraardsbergen along the Dender river, Belgium, and a return period of 100 years, for the current climate and the high climate change scenario.*

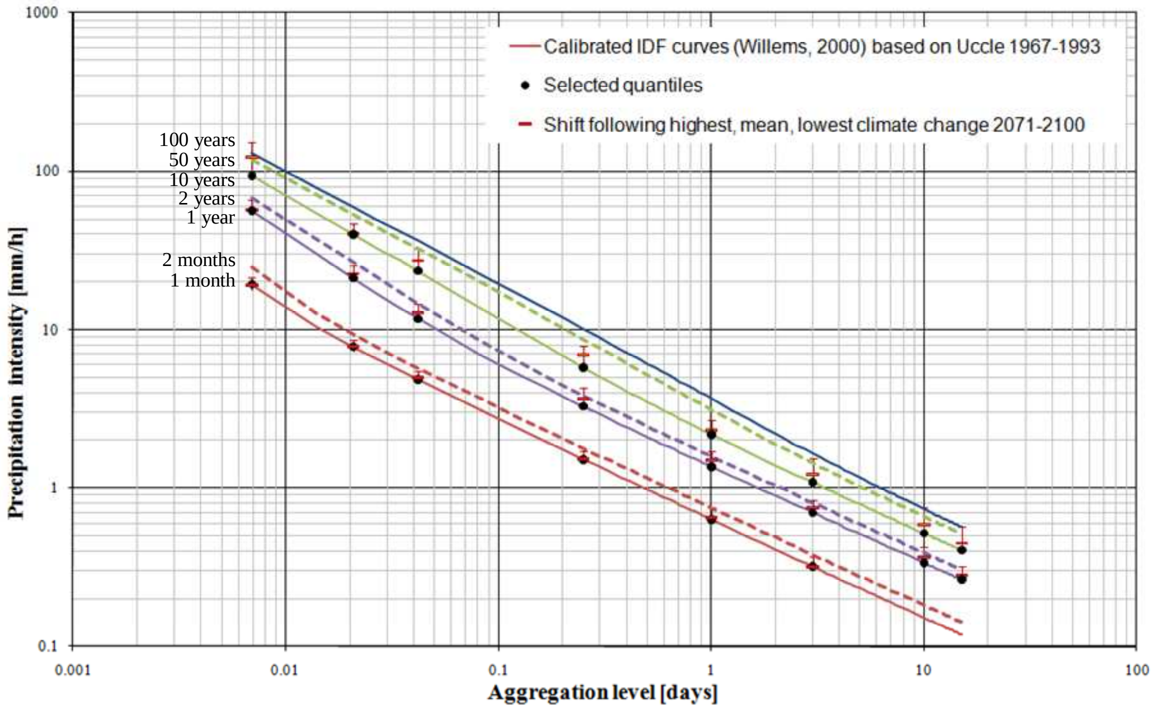


Figure 8. *Change in IDF-relationships for Uccle, Belgium, based on mean, highest and lowest change based on 17 ECHAM5 A1B runs and a quantile perturbation downscaling method (Willems and Vrac, 2010)*

Review of applied methods for flood-frequency analysis in a changing environment in Bulgaria

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1. Description of methods

1.1 Detection of trends and shifts in time series of hydrological extremes (at-site and regional procedures)

Trend analyses of extreme rainfall in Bulgaria are reported in Bocheva et al. (2009) and Bocheva et al. (2010).

1.2 Non-stationary flood frequency analysis (at-site and regional procedures)

Neither at-site nor regional non-stationary flood frequency analyses have been carried out in Bulgaria. We are planning to model hydrological extremes conditional on atmospheric variables using conventional extreme value analysis such as the standard point Poisson process technique. The quantile regression methodology would be adapted to identify time varying trends in some of the upper daily hydrological extremes to account for seasonal variation ensuring enough observed excesses in each season.

1.3 Rainfall-runoff modelling

Rainfall-runoff modelling is widely used in Bulgaria to assess maximum water discharge with different return periods for sites without conventional measurements and for stations with short time series (Gerasimov, 1988). The methodology is based on regional relationships. Regional empirical relationships for long-term maximum 24-hour rainfall as a function of elevation are derived for each region. The daily maximum rain depths with different probability of exceedance for each region are calculated using the relative quantiles. Maximum discharge with given return periods (1000, 100, 20, 10 years) is calculated using empirical formulas and regional rainfall reduction curves. This method is used for engineering hydrological studies and for river correction, building hydrotechnical constructions, etc. Regional flood frequency analysis is performed by means of a spatial interpolation technique based on the at-site annual maximum water discharges.

The NAM model (MIKE 11 software) have been used to provide discharges from rainfalls or snow melting for the Maritza and Tundja rivers (Roelevink et al., 2010). Different hydrological scenarios that might occur every 20, 100 and 1000 years were developed. The annual maximum discharges were fitted by the maximum likelihood estimation method to various distributions such as the Exponentail, Rayleigh, Lognormal, Gamma, Weibull, Gumbel, Generalized extreme value. Details can be found in technical reports prepared in The European Union's PHARE programme for Bulgaria "Technical Assistance for Flood Forecasting and Early Warning System for Maritza and Tundja rivers". This project was part of the European PHARE project "Capacity Improvement for Flood Forecasting in the Bulgarian-Turkey Cross Border Cooperation Region".

1.4 Multivariate frequency analysis (e.g. storm surge, river flooding, urban flooding)

Multivariate frequency analysis has not been carried out in Bulgaria.

1.5 Uncertainty and risk analysis

Uncertainty and risk analysis is not applied as standard procedure in hydrological practice in Bulgaria.

2. Data

2.1 Availability and use of streamflow/precipitation data and proxy data for change detection and frequency analysis

River discharge data (data base of the National Institute of Meteorology and Hydrology) are available for about 177 hydrometric stations.
Daily precipitation data (data base of the National Institute of Meteorology and Hydrology) are available for about 364 (36 synoptic, 88 climate and 240 gauge) stations for different periods, the majority starting from 1950.
An agreement for data use is needed.

2.2 Availability and use of data to assess changes in hydrological regime and river infrastructure development

It is difficult to accesses for all rivers.

2.3 Availability and use of climate change projections from general circulation models and regional climate models, including statistical downscaling

High resolution Regional Climate Model scenario simulations were performed by the ALADIN model for the present day climate simulation, so called control (1961-2000) as well as for two time slices of climate change scenario, i.e. mid-century run (2021-2050) and end-of-century (2071-2100). Daily precipitation data for the period 1961-1990 from about 60 weather stations across Bulgaria were used. Simulated 10 km ALADIN outputs (such as daily precipitation amounts, sea level pressure, daily min and max temperature, etc.) for the future climate conditions in Bulgaria were generated for 50 weather stations across Bulgaria within the framework of the EU funded CECILIA, project, see Spridonov (2007) and Farda et al. (2010).

3. Applications

3.1 Purpose and areas of application (design of hydraulic structures, dams, urban hydrology, flood-hazard mapping, etc.).

Flood frequency analyses are used in Bulgaria for design of hydraulic structures, dams and delineation of flood hazard maps. We are planning to assess the impact of climate change on flood fequency in Bulgaria, the scenarios will be driven by the ALADIN model, Farda et al. (2010).

3.2 Merits and drawbacks of different methods

The analyses are based on the annual hydrological extremes in most of the studies using various distributions as well as the peak over threshold method for few studies under the assumption of stationary of the extremes, which is obviously inconsistent.

3.3 Recommendations for users

4. Case studies

The project “Floods in the Maritza river basin: risk analysis and evaluation, mobilization of information sources for floods impact decrease” was part of the European PHARE project "Capacity Improvement for Flood Forecasting in the Bulgarian-Turkey Cross Border Cooperation Region". Within this project an operational information system for flood analysis, flood mapping and flood forecasting was developed, which would help mitigate in the future the flood consequences along the Maritza and Tundja rivers, and would provide real-time information to authorities from Bulgaria and Turkey in charge of alerting the population and of managing the operations during flood events.

5. Plans for future development

We are planning to apply the conventional non-stationary extreme value analysis of Coles (2001) and Reiss and Thomas (2001) to daily precipitation totals and river discharges using the point process technique to estimate the unknown parameters of the extreme value distributions, conditional on the atmospheric variables. As a consequence, physically-based models for the risk of extreme precipitation and floods will be assessed across the territory of Bulgaria.

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Review of applied methods for flood-frequency analysis in a changing environment in Cyprus

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1. Description of methods

The island of Cyprus with an area of 9.251 km^2 experiences severe water shortage problems. In order to address this problem Cyprus adopted the slogan “Not a drop of water to be wasted to the sea” and a series of dams has been constructed in recent years. Today almost all (seasonal) rivers are dammed (figure 1) and Cyprus has the largest number of dams per area in Europe.

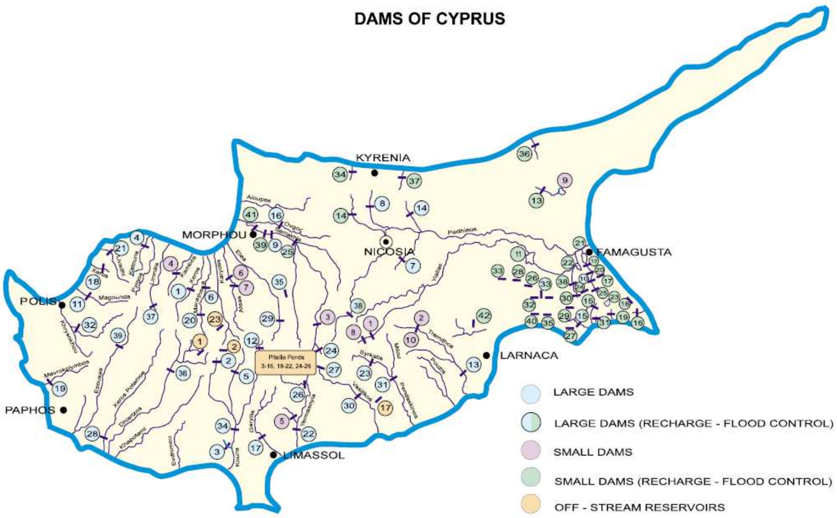

Figure 1. The Dams of Cyprus

Due the small size of the island, the lack of rivers with all year flow and the damming of the major seasonal rivers the most widely used method for flood flow prediction is the storm analysis. In particular, the methods used for flood frequency analysis for different applications are:

- Reservoir/ dam design (of significant rivers): Extreme Value Analysis of gauged rivers and storm analysis
- River crossings (bridges and culverts): Mainly storm analysis (extreme value analysis of stream gauges, if available data)
- Storm Water Drainage systems: Storm Analysis

1.1 Detection of trends and shifts in time series of hydrological extremes (at-site and regional procedures)

Rainfall data is the main source of hydrological data which may be analysed in order to detect trends and shifts in time series. Figure 2 presents the total mean annual precipitation over the period 1901 to 2009 (WDD, 2011) for the whole of Cyprus. The average precipitation of 541 mm in the period 1901 to 1970 dropped to 463 in the period 1971 to 2009.

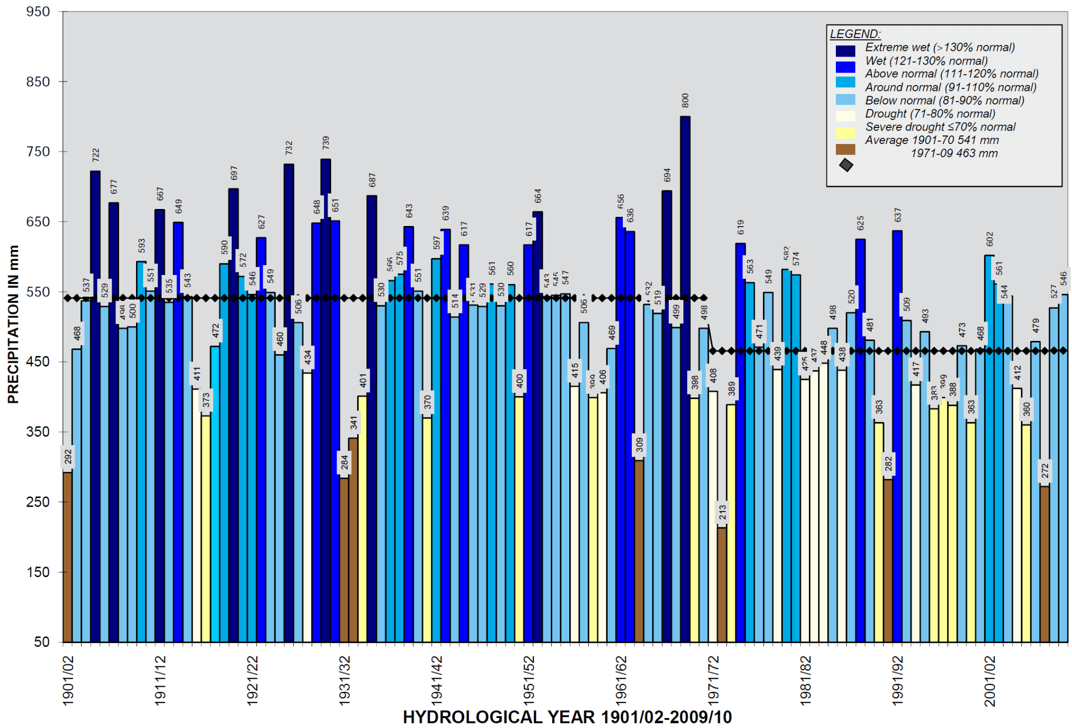

Figure 2. Annual precipitation 1901 to 2008

The most comprehensive study of rainfall extremes was published recently (Pashiardis, 2009) presenting rainfall intensity – duration – frequency (IDF) distribution/ curves for Cyprus. The equations describing these curves are in the format:

$$i(d,T)=\frac{\lambda\psi+\frac{\lambda}{k}\left[\left(-\ln\left(1-\frac{1}{T}\right)\right)^{-k}-1\right]}{(d+\theta)^{\eta}}$$

where

i : the rainfall intensity (mm/hour)

T : the return period (in years)

d : rainfall duration (hour)

κ, λ, ψ, η, θ are constants for the different locations.

Figure 3 presents the comparison of the IDF curves for Nicosia as derived from data covering the periods 1931-1970 (Hadjiioannou, 1995) and 1971-2007 (Pashiardis 2009). It is evident from these curves that the events of the recent years are more extreme than the equivalent over the initial years.

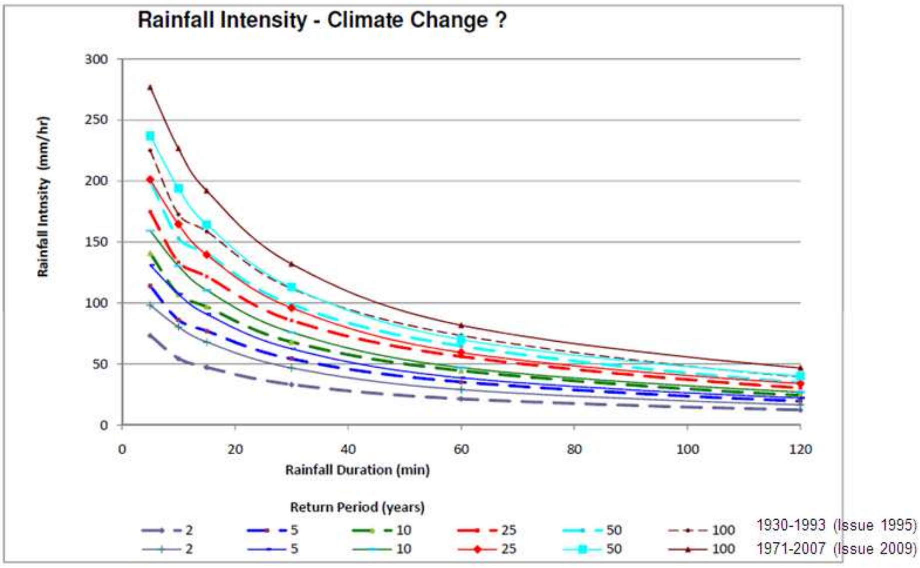

Figure 3. Rainfall Intensity-Duration-Frequency curves for Nicosia

Precipitation data for Cyprus lead to the conclusion that the mean annual rainfall is decreasing whilst the rainfall intensity of extreme events is increasing.

The decrease in annual rainfall causes reduction in vegetation and together with urbanisation they cause increase of run-off which coupled with the increase of rainfall intensity causes flood frequency increase.

1.2 Non-stationary flood frequency analysis (at-site and regional procedures)

At present the flood frequency analysis is carried out based on stationary rainfall data. Although there is evidence from the data analysis of rainfall data that there is an increase in flood frequency, this has not yet been quantified for application in engineering studies or flood management and flood risk.

1.3 Rainfall-runoff modelling

As referred above rainfall-runoff modelling does not yet take into consideration the observed trend of extreme rainfall intensity increase. This trend is normally discussed in engineering studies and additional measures are lately recommended/ taken to reduce the run-off in order to compensate for the rainfall increase. Such measures include SUDS (Sustainable Urban Drainage Systems), water harvesting (storing water locally for re-use), ground water infiltration, etc.

1.4 Multivariate frequency analysis (e.g. storm surge, river flooding, urban flooding)

Coastal flooding / storm surge is independent from fluvial and pluvial flood since Cyprus has no estuaries. Urban flooding is caused mainly from flash floods. The combination of the various causes of flooding has not been considered yet. No data has been published for sea level variation and storm surge levels. Data collected and analysed by the Oceanography Centre of the University of Cyprus is to be published shortly.

1.5 Uncertainty and risk analysis

The uncertainties and risks arising from various reasons are addressed in the design of dams, bridges and drainage systems using established engineering tools. The added uncertainty in rainfall and flows due to climate change is addressed in general but has not been quantified yet.

2. Data

2.1 Availability and use of streamflow/ precipitation data and proxy data for change detection and frequency analysis

Precipitation data is available and it has been analysed for change detection and frequency analysis. However, no such analysis has been published on streamflow data.

2.2 Availability and use of data to assess changes in hydrological regime and river infrastructure development

Precipitation data is available on a daily basis as well as streamflow at various stations. The Water Development Department gathers the data for streamflow. This data is available to the general public (for a fee). River development is strictly regulated and any infrastructure is well documented.

2.3 Availability and use of climate change projections from general circulation models and regional climate models, including statistical downscaling

Hadjinicolaou *et al* (2010) published a paper about the mid-21st century climate and weather extremes in Cyprus as projected by six regional climate models. The results of this study suggest a decrease of precipitation of 2-8% and the number of consecutive dry days will increase significantly.

3. Applications

3.1 Purpose and areas of application

Flood frequency analysis is used in the design of dams, the design of (dry) river crossings (bridges and culverts) and urban storm water drainage systems. Climate change is addressed by increasing the level of uncertainty in future precipitation values.

3.2 Merits and drawbacks of different methods

At present no methods are used to quantify the change in precipitation due to climate change.

3.3 Recommendations for users

Users of dams, bridges, drainage systems, such as government departments, public utilities and local authorities need to be informed about the uncertainties of flood flow intensity and frequency due to climate change and they must implement measures to address the increased risk of flooding/ damage. Such measures include the implementation of SUDS (Sustainable Urban Drainage Systems), installation of flood resilience systems (flood warning, flood barrier deployment, etc).

4. Case studies

The Drainage Board of Limassol is implementing SUDS as part of its policy to reduce the risk of flooding due to the changing environment (climatic, urbanisation etc).

5. Plans for future development

Data is constantly being collected and analysed. One of the aims of the analysis is to quantify the trend of increase of rainfall intensity due to climate change.

Cyprus is also participating in the FP7 programme SMARTeST which considers the application of flood resilience systems in reducing the consequences of flooding (living with the floods). An ongoing Nationally research programme, SATFLOOD, employs remote sensing techniques and GIS for flood risk assessment in catchment areas.

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Review of applied methods for flood-frequency analysis in a changing environment in the Czech Republic

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1. Description of methods

1.1 Detection of trends and shifts in time series of hydrological extremes (at-site and regional procedures)

Flood frequency estimation in the Czech Republic is carried out mainly by Czech Hydrometeorological Institute (CHMI). CHMI is national hydrological and meteorological service responsible for observation and data storage. For purposes of hydrological extremes analysis mainly series of maximum annual discharges are continually evaluated at CHMI. Values of discharges for different return periods are then revised based on statistical analysis of maximum annual discharges data. To be able to identify possible trends the long term average values (both simple and moving) and variation coefficient are assessed for maximum annual discharge values. However, these statistics are very sensitive to the length of measurement period and occurrence of very extreme events (Šercl 2009). New Index of Flood Regime (IFR) has been therefore defined in recent years at CHMI. This index describes character of measured streams from the point of view of seasonality. It is defined as:

$$IFR = \frac{\sum_{i=1}^{N} \frac{Q_{max,i}}{Q_{max,a}}}{N}$$

where

IFR is index of flood regime,

N is number of observation years,

*Q*max*, i* is maximum discharge in ith year,

Qmax, a is average maximum discharge for the observation period.

Value of maximum discharge is considered negative in case of occurrence in winter period (November to April in Czech Republic). Values of IFR move in interval [-1;1]. Value of -1 corresponds to pure winter maximum discharge regime, while value of 1 corresponds to pure summer maximum discharge regime. This index is helpful for identification of main principles of flood forming in given catchments which can help to choose suitable tool for rainfall-runoff analysis. Changes in hydrologic regime of streams can be detected using calculation of the index for different periods and its variation in time. Standard probabilistic methods are applied on sets of maximum annual discharges for flood frequency analysis in gauged catchments.

1.2 Non-stationary flood frequency analysis (at-site and regional procedures)

Several approaches to non-stationary flood and rainfall frequency analysis have been implemented in the Czech Republic. Kyselý et al. (2010) applied the region-of-influence method as a pooling scheme when estimating distributions of extreme rainfall events that consists in incorporating data from a region when fitting an extreme value distribution in any single gridbox. By region is meant a set of grid boxes of ENSEMBLE project scenarios.

Hanel et. al. (2009) introduced an index flood model with time-varying parameters as a tool to summarize changes of extreme precipitation in transient RCM simulations. This model allows the generalized extreme value (GEV) location parameter to vary over the region, while the dispersion coefficient (the ratio of the GEV scale and location parameters) and the GEV shape parameter are assumed to be constant over the region. The implementation of the method is in progress for area of the Czech Republic (Hanel and Buishand, 2011).

1.3 Rainfall-runoff modeling

There are two main fields of use of rainfall-runoff modeling in the Czech Republic. First one is represented by physically based models. These models are usually used for research purposes to analyse runoff process in more detail. In this case, also more parts of hydrologic process are usually considered. Typical disadvantage of such models are their demands on data and calibration. This is the reason why more conceptual or empirical models are usually used for practical purposes. These models can be represented by products of the Hydrologic Engineering Centre (HEC-1, HEC-HMS) which are mostly used in semi-distributed manner.

CHMI uses rainfall-runoff modeling to estimate possible change in flood frequency within the project on climate change impact evaluation, see for example: http://www.isvav.cz/projectDetail.do?rowId=SP%2F1A6%2F108%2F07). Based on various climate change scenarios (temperature, precipitation) a 1000 year long time series was stochastically generated and processed with the AquaLog modeling system (SAC-SMA, SNOW17 implemented). Temporal and spatial distribution was done using random selection of historical analogues.

SCS-CN method for calculation of direct runoff volume in combination with unit hydrograph method is often used for flood-frequency analysis in small ungauged catchments.

Methodology for estimation of 100-years specific maximum runoffs in ungauged catchments with area of 5 – 100 km^2 was developed at CHMI. This methodology introduces 100 year flood extremity index IE_{100} and assumes that it depends on effective rainfall and considers physical-geographical characteristics of catchments (Šercl 2009).

The BILAN model, which was developed for simulation of water cycle components in staff of T.G. Masaryk Water Research Institute in Prague (TGM WRI), has already been applied in great number of research projects and practical applications. It is a lumped physically-based model which simulates water balance components in a catchment (Kašpárek 2004), i.e. evapotranspiration, accumulation of water in snow, flow through the unsaturated zone, groundwater flow and streamflow. The version of BILAN using daily time step is used for assessment of changes in floods (Hanel et al. in prep.).

Flood-frequency version of the TOPMODEL is used for the estimation of floods with long return period (e.g. Blažková and Beven 2009). The study on assessment of changes in floods under climate change is in progress (see section. 5).

1.4 Multivariate frequency analysis (e.g. storm surge, river flooding, urban flooding)

Most of hydrologic analyses and studies carried out in the Czech Republic focuses on small ungauged catchments up to 100 km^2 (Šercl 2009). For these purposes mainly methods and models described above are being used. Rainfall-runoff modeling is often used for analysis on influence of different characteristics on resulting runoff. These characteristics are for example precipitation total and distribution of causal precipitation, different moisture conditions, land use changes etc.

For catchments above 100 km^2, regional precipitations with longer duration are more important. In case of water bodies with winter flood regime also snow melt must be considered. Gauging stations are usually operating on such streams so the discharge data can be available and analysis can be carried out using directly discharge data in combination with other variables. Results of such analyses can be further used in combination with hydraulic calculation as a basis for urbanisation planning and such issues.

1.5 Uncertainty and risk analysis

Any specific methods related to address changes in extremes have not been used yet in the Czech Republic. Frequency discharge data derived and provided by CHMI are of course including errors which are corresponding to the method used for its derivation. CHMI classifies provided data into 4 classes of accuracy. First one represents the most reliable data derived from good long term time series of discharges while the fourth one represents data for ungauged catchments and discharge characteristics derived from precipitation data. The discharges in the first class of accuracy can have an error to 15 % while in the fourth class the error can be up to 60 % for return period of 100 years.

From the point of view of reliability, estimates associated with long return periods derived from short time series can be problematic. Problems can also be related to the derivation of estimates from longer series without extreme events. Most of the maximum annual discharge data, for example, consist of data from 20th century which was relatively flood poor. This was the reason why the frequency data was often underestimated. Therefore the data had to be revised and corrected after flood events which occurred in last 15 years.

2. Data

2.1 Availability and use of streamflow/precipitation data and proxy data for change detection and frequency analysis

Data for flood frequency analysis (climate observations, streamflow in daily and hourly step etc.) are generally available at CHMI. For users outside the CHMI such data are available on request (generally only scientific non-commercial purposes and for a fee). Current real-time data on discharges at gauging stations as well as some meteorological parameters are published for free via web services. For example, discharges are available with 1 hour time step for up to 7 days back in each measured gauge station. TGM WRI has a framework agreement about reciprocal data providing with CHMI.

2.2 Availability and use of data to assess changes in hydrological regime and river infrastructure development

In order to identify changes in hydrological regime of the streams it is necessary to make statistical analysis of the hydrological and meteorological variables. Measuring of these parameters operates CHMI, but it doesn't provide the data for further use. It is possible to get some statistical parameters of the observed data (e.g. maximum annual discharges series), but these data must be paid for. It makes the large amount of data that is required for research practically unavailable, especially for non-commercial scientific institutions.

Possible approach to hydrological regime changes estimation is through mathematical modeling. Concerning the character of the used methods (see section 1.1), which are sensitive mainly to amount and time distribution of the precipitation, it is necessary to use design rainfall scenarios, if we want to analyse possible climate change impacts. These scenarios may be created only by high-qualified meteorological institution, and thus not generally available.

2.3 Availability and use of climate change projections from general circulation models and regional climate models, including statistical downscaling

Outputs of regional climate models (RCMs) from EU projects PRUDENCE and ENSEMBLES are widely used in the Czech Republic. For example, the changes in quantiles of 1-day precipitation extremes were assessed for the RCMs resulting from PRUDENCE (Kyselý et al 2009) and ENSEMBLES (Kyselý et al. 2010) projects. Bias correction and delta method are used for adjustment of data from RCMs before they are used in the subsequent hydrological modeling (e.g. Hanel and Vizina 2010).

3. Applications

3.1 Purpose and areas of application

Flood Frequency estimation is required for design of hydraulic structures, dams, urban hydrology, flood-hazard mapping, etc. In the Czech Republic, hydrological data are necessary for designing, building and operation of dams and waterworks on the streams, for the river canalizing and bridges and culverts design. They are also used for flood-hazard mapping and flood-control design, water-supply and for water-quality and environment problems solution.

The purpose of method introduced by Hanel et al. 2009 (described in section 1.2.) is to develop tool to summarize changes of extreme precipitations in transient RCM simulations.

3.2 Merits and drawbacks of different methods

The SCS-CN method (described in section 1.1) can consider retention capacities of the catchment and is considered a relatively good model which gives reasonable results in comparison with measured data. A weakness of this method is insufficient consideration of physical-geographical properties. The unit hydrograph method is then used after calculating for runoff routing. Its advantage is mainly in consideration of rainfall distribution in time, which is one of the most important factors affecting flood discharge distribution. Disadvantage is in complicated calculation of unit hydrograph parameters, which are mostly estimated using empiric equations. On the other hand, this method works very well when using measured data for calculation of unit hydrograph parameters.

Merits of method introduced by Hanel et al. (2009) are: looking at the parameters of the GEV distribution gives a better insight into the differences in distribution than looking at a single quantile only. The standard errors of the estimated common parameters are significantly reduced when compared to the estimates based on the data of an individual grid box.

3.3 Recommendations for users

The usability of methods presented in section 1.1 should ideally be verified against measured rainfall-runoff event or using data obtained from the official provider of such data (CHMI); e.g. using flood wave for given return period in a profile close to analysed location. There are some empirically calculated parameters involved in calculation procedures, which can be incorrectly determined. This can be corrected and calibrated by comparison with measured data. In case of unit hydrograph method, it is essential to consider sensitivity of the method on design rainfall and to calculate its distribution carefully, e.g. to take in account precipitation regime in given area (convection or frontal precipitations).

The most important national guideline concerning the impact of environmental change floods is the Plan of Main River Basins of the Czech Republic (Government of the Czech Republic, 2007). The Plan does not concern specifically climate change but it react to recent catastrophic floods and often flash floods in mountain areas by defining specific measures which have to be implemented in the recently flooded region and regions mostly endangered by floods.

The impact of changes in land use on floods is reflected widely in Building Act No.183/2006 Coll. and following regulation and guidelines.

4. Case studies

Significant increase of 20 - 30% in extreme precipitation in winter in the western part of the country was reported by Kyselý (2009). He used Mann-Kendall test on data from 175 stations with daily rainfall (1961-2005).

Evaluation of rainfall-runoff processes has been one of main research activities at the Department of Irrigation, Drainage and Landscape Engineering for long period. Runoff processes in eight small catchments in Central Bohemia Region were analysed in cooperation with regional authority for purposes of flood protection. The main aim of the study was to assess the changes in floods. The procedure of analysis was based on the data for the outlet of the catchment purchased from CHMI. This data was used for calculation of design discharges in given profiles within catchment using HEC-1 model. Hydraulic structures were then assessed using these discharges and new parameters were estimated. Also possibilities of affecting runoff from the catchments were analysed and retention basins were designed (Vrána et al. 2007).

The non-stationary index flood model for precipitation extremes in transient regional climate model simulations introduced by Hanel et al. (2009) was applied for the area of the Czech Republic (Hanel and Buishand, 2011). They analysed the 1-day to 30-day seasonal precipitation extremes over the Czech Republic in an ensemble of 14 RCM simulations. The study area was divided into four homogeneous regions in which a non-stationary GEV model was applied. The simulated precipitation extremes were compared to those of gridded observations for the period 1961–1990. The ensemble mean relative changes of the quantiles of precipitation extremes between the periods 1961–1990 and 2070–2099 were averaged over the study area. These changes are positive for all return periods (between 2 and

50 years), durations and seasons and vary from 0% to 30%.

The recent catastrophic floods in the Czech Republic have intensified the research on impact of land use change on floods. Langahammer (2010) presented the results of analysis of relationships between stream regulations and the geomorphic effects of floods for the case of the Blanice river and recommended a field survey based on hydromorphological mapping as an efficient tool for identifying potentially critical segments of streams.

5. Plans for future development

Main task for further research activities connected to flood protection and hydrologic extremes is to prepare methodology for quantification of predicted climate change influence on hydrologic regime of catchments. The use of mathematic models for calculation of hydrologic systems is considered as the best option for this purpose. If possible effects of climate change are evaluated as important it will be necessary also to prepare methodology for adaptation to changed hydrologic regime.

The research of influence of climate change on floods with long return period (10 000 years) using the outputs of RCMs from ENSEMBLE project is in progress. The outputs of research are important for safety assessment of dams.

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Review of applied methods for flood-frequency analysis in a changing environment in Denmark

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1. Description of methods

1.1 Detection of trends and shifts in time series of hydrological extremes (at-site and regional procedures)

Trend analyses have been made on rainfall data from a country-wide network of high-resolution tipping-bucket rain gauges (see Section 2.1). The data have been used to establish design guidelines for urban drainage systems in Denmark. Based on data up to 1997 a regional intensity-duration-frequency (IDF) model was developed (Madsen et al., 2002) for estimation of extreme rainfalls with durations ranging between 1 minute and 48 hours.

The regional IDF model was updated in 2006. The results from this analysis are reported in Madsen et al. (2009). Increases in extreme rainfall intensities are generally seen except for durations of 24 and 48 hours. For the durations and return periods typical for most urban drainage designs (i.e. durations between 30 min and 3 hours and return periods of about 10 years) the increase in rainfall intensity is in the order of 10%.

The apparent trends in the rainfall data were subsequently analysed using the Mann-Kendall trend test (Sadri et al., 2009). The results of the regional Mann-Kendall test were consistent with the results reported in Madsen et al. (2009), i.e. more significant increasing trends for durations between 10 min and 3 hours.

In an on-going study, Gregersen et al. (2010) applied parametric regression models to quantify the trends. The trend in the annual number of extreme events was studied by means of both ordinary linear regression and Poisson regression. Preliminary results show a general increase in the number of extreme events of about 2% per year for rainfall durations between 1 minute and 24 hours.

No national analysis has been carried out with respect to floods, but a Nordic study using Danish streamflow records shows no clear pattern of changes in extremes (Wilson et al, 2010).

1.2 Non-stationary flood frequency analysis (at-site and regional procedures)

The regional IDF model mentioned in Section 1.1 is currently being further developed to include non-stationarities with the aim of obtaining a more suitable description of the regional trends observed in precipitation.

1.3 Rainfall-runoff modelling

For urban applications, modelling typically combines a simple conceptual rainfall-runoff model with a hydraulic model of the sewer system, i.e. MOUSE and MIKE Urban. To take future climate changes into account, guidelines exist on the use of a climate factor for multiplication of design rainfalls (see Section 3.3.).

Hydrological modelling at the catchment scale is typically based on the Danish Water Resources model, which is a MIKE SHE model covering Denmark. Climate change impact assessment studies have so far mainly considered changes in the water balance components (van Roosmalen et al., 2010) and less emphasis has been put on the impact of changes in climate extremes.

1.4 Multivariate frequency analysis (e.g. storm surge, river flooding, urban flooding)

A few studies in Denmark have considered joint probabilities of different sources causing flooding. A procedure based on copulas was adopted for assessing the risk of flooding in a catchment in the southern part of Denmark subject to flooding from heavy precipitation in the upstream parts of the catchment and storm surges at the downstream part (Sunyer et al., 2009). The copula method has recently been applied for similar studies in an urban context for the city of Copenhagen, including assessment of the impact of climate change on flood risk (Pedersen et al., 2012).

1.5 Uncertainty and risk analysis

For design of urban drainage systems recommendations have been given to account for different types of uncertainties by introducing a safety factor in the design (Harremoës et al., 2005). Scenario uncertainty to account for future climate change and other non-stationary effects (e.g. urbanisation) is addressed within this framework. However, no standardised procedure is presently implemented in Denmark for quantifying uncertainties related to environmental changes. Development of methods for quantification of uncertainties related to climate change projections is being addressed in on-going research projects. Preliminary results on uncertainties related to different climate models and downscaling procedures are reported in Sunyer et al. (2011).

A risk analysis framework is currently being developed in order to quantify climate change impacts and adaptation options in an urban setting. Preliminary results can be found in Zhou and Arnbjerg-Nielsen (2011).

2. Data

2.1 Availability and use of streamflow/precipitation data and proxy data for change detection and frequency analysis

A comprehensive data set of high-resolution rainfall from a network of tipping-bucket rain gauges is available. Since the rain gauge system was established in 1979, about 110 rain gauges have been connected to the network. The raw data consist of one-minute intensities for rain events that are constructed based on a 0.2 mm resolution of the tipping bucket gauges. A large proportion of the raw rainfall data are freely available for download (http://svk28.env.dtu.dk/). Long daily records of precipitation as well as short series of regionally distributed 15-minute precipitation data are available from the Danish Meteorological Institute.

Daily records of streamflow can be obtained from the University of Aarhus. The longest records date back to 1917. A data set of the longest records has been extracted that consists of about 40 stations with record lengths ranging between 31 and 93 years and an average of about 65 years.

2.2 Availability and use of data to assess changes in hydrological regime and river infrastructure development

See Section 2.1

2.3 Availability and use of climate change projections from general circulation models and regional climate models, including statistical downscaling

The studies on climate change in Denmark have primarily used regional climate model data from the data archives made available from the two EU projects PRUDENCE (http://prudence.dmi.dk/) and ENSEMBLES (http://ensemblesrt3.dmi.dk/).

Research is presently being carried out to investigate different statistical procedures to downscale regional climate model data for different applications. The considered downscaling procedures range from simple delta change methods to more advanced stochastic weather generators (Sunyer et al., 2011).

3. Applications

3.1 Purpose and areas of application (design of hydraulic structures, dams, urban hydrology, flood-hazard mapping, etc.).

Frequency analysis methods are most widely used in the design and analysis of urban drainage systems. The interaction between rainfall over urban areas, moisture conditions in upstream rural catchments, and, in coastal areas, sea water levels has gained increasing interest for more accurate assessment of flood risk in the light of climate change and current observed increases in both pluvial floods and floods caused by storm surges.

3.2 Merits and drawbacks of different methods

A number of on-going research projects within different application areas address the problem of environmental change, impact assessment and adaptation that will highlight merits and drawbacks of different methods.

3.3 Recommendations for users

For the design and analysis of urban drainage systems, guidelines exist for use of a climate factor to multiply design rainfalls (Arnbjerg-Nielsen, 2008; Arnbjerg-Nielsen, 2011). The climate factor depends on the considered return period and planning horizon. For a 100-year planning horizon the recommended climate factor is, respectively, 1.2, 1.3 and 1.4 for return periods of 2, 10 and 100 years. Systematic differences in the climate factor have been observed depending on the duration of the precipitation, but this has not been incorporated into the design practice.

4. Case studies

As part of the Danish Climate Research Centre (CRES, http://cres-centre.net/) and the RiskChange project (http://riskchange.dhigroup.com/) different case studies have been established that will form the basis for analysing how key uncertainties and risks can be addressed in a cost-effective manner in decision making on climate change adaptation in urban and peri-urban settings. Case studies will also be part of the EU-financed project PREPARED where Danish partners contribute.

In a recent study, the impact of climate change on the flood risk and dike safety in the Vidaa River system, a cross-border catchment located in the southern part of Jutland, Denmark and northern Germany, has been analysed (Madsen et al., 2011). Changes in flood risk in this area are due to both changes in extreme precipitation and changes in storm surges. Climate model data from the ENSEMBLES data archive were used to assess the changes in extreme precipitation and resulting catchment runoff. Changes in storm surges were assessed by hydrodynamic model simulations forced by a regional climate model projection.

5. Plans for future development

A number of research issues related to frequency and risk analysis under climate change are presently being addressed:

- Development of statistical methods for downscaling projected climate extremes from climate models.
- Development of statistical multivariate frequency analysis methods for addressing joint probabilities of extreme events.
- Development of procedures for quantifying uncertainties in projected climate extremes.
- Development of non-stationary regional extreme value models.
- Development of guidelines and recommendations for risk analysis and risk management under climate change.

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Review of applied methods for flood-frequency analysis in a changing environment in Finland

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1. Description of methods

1.1 Detection of trends and shifts in time series of hydrological extremes

Korhonen and Kuusisto (2010) used the Mann-Kendall test to detect trends in observed discharges in Finland up to 2004. Annual and seasonal mean discharges and water levels, maximum and minimum flow and timing of spring peaks were analysed on 25 sites with long records including both unregulated and regulated rivers and lake outlets. The level of 5% was used for critical significance. Trend magnitude was calculated using a non-parametric linear Sen's slope estimator (Sen, 1968). If the data were found to be autocorrelated, the pre-whitening procedure presented by Wang and Swail (2001) was applied to remove autocorrelation from the time series. Finally, the trend significance was tested for the pre-whitened dataset (Korhonen and Kuusisto, 2010)

No statistically significant changes in mean annual flow were found in general, but there were clear trends in seasonal stream flow series. Winter and spring mean monthly discharges had increased in most of the observation sites. The timing of spring peak had become earlier in more than one third of the sites, even though the magnitudes of spring high flow had not changed. Minimum flows have increased at about half of the unregulated sites. However maximum flows did not generally show significant changes over the periods included in the study. The detected trends can be mainly attributed to observed increase in temperature, but on regulated rivers and lake outlets the changes in regulation have often enhanced the trends.

1.2 Non-stationary flood frequency analysis (at-site and regional procedures)

At present flood frequency analysis in Finland is performed under the assumption of stationarity, and non-stationary flood frequency analysis has not yet been carried out. Rainfall-runoff modelling using climate scenarios has been carried out by the Finnish Environment Institute (SYKE) to estimate potential impacts of climate change on discharges and floods. There are plans to perform non-stationary flood frequency analysis as part of future climate change projects.

1.3 Rainfall-runoff modelling

The Watershed Simulation and Forecasting System (WSFS) is a conceptual hydrological model covering all of Finland (www.environment.fi/waterforecast). This model is used both for i) operational hydrological flood forecasting and flood warnings, and ii) for climate change research. The main part of the WSFS is a conceptual rainfall-runoff model of the HBV-model type. The WSFS is semi-distributed as it divides the watersheds into small lumped sub-catchments (~20-250 km^2) each with their own parameters and water balance simulation for separate forested and open areas. The WSFS sub-models include a precipitation model for evaluating areal precipitation and its form, a snow model based on the temperature index approach, a rainfall-runoff component with three layer soil model, and lake and river routing (Vehviläinen et al., 2005).

The WSFS has been used to simulate climate change impacts on water resources and floods in Finland (Veijalainen et al., 2010a,b; Lotsari et al., 2010; Veijalainen and Vehviläinen, 2008; Vehviläinen and Huttunen, 1997). Most of the studies have used the delta change approach to modify the historical observation with the monthly changes from climate scenarios. Frequency analysis has been performed for the simulated hydrological variables in the present and future climate and these values have been compared.

1.4 Multivariate frequency analysis (e.g. storm surge, river flooding, urban flooding)

Multivariate frequency analysis has so far not been performed. Simple estimation of frazil ice risk and the changed in the risk due to climate change has been carried out in case study areas (Aaltonen et al., 2010).

1.5 Uncertainty and risk analysis

Climate change impact studies carried out with the WSFS hydrological model have used an ensemble of climate scenarios from several climate models and emission scenarios. This has provided some estimates of the uncertainty involved in climate change projections, although many other relevant uncertainties (model parameters and setup etc.) have not been studied.

2. Data

2.1 Availability and use of streamflow/precipitation data and proxy data for change detection and frequency analysis

Streamflow data are available from national database operated by Finnish Environment Institute (SYKE). The main part of the database is available for everyone after registration (www.ymparisto.fi/oiva), but at the moment this is only available in Finnish. The database contains daily data from 620 discharge observation points, from which 370 discharge stations are currently operational. Discharge observations for 30 years or more are available for approximately 200 stations. Precipitation data are measured and collected by the Finnish Meteorological Institute, but this data are currently not freely available.

2.2 Availability and use of data to assess changes in hydrological regime and river infrastructure development

National database includes information on infrastructure development, for example on dams and regulation. The dam safety section of the database includes information on dam structures such as location, contact information, permits, dam safety documents, hydrological design values and dam safety inspections. Another section of the database includes information of constructions and other measures which have taken place in the catchments such as construction of dams, levees, water power plants and artificial channels as well dredging and major restoration projects.

2.3 Availability and use of climate change projections from general circulation models and regional climate models, including statistical downscaling

Climate scenario data are available from several global climate models from the Finnish Meteorological Institute and several regional climate models from ENSEMBLES data archive. These projections are used together with hydrological model to produce estimates of changes in water resources. Traditionally, the delta change approach has been used to transfer the climate change signal to the hydrological model. The use of direct bias corrected RCM daily data as input of the hydrological model is under development.

3. Applications

3.1 Purpose and areas of application

Flood frequency analysis and estimates of climate change impact are used for design flood estimation for dams, flood-hazard and flood-risk mapping, planning of infrastructure and planning of adaptation measures i.e. changes in regulation practices for lakes.

3.2 Merits and drawbacks of different methods

The drawback of most of the methods used thus far in climate change studies is that they assume stationary data. Estimation of changes in floods is performed by comparing two time slices (control and future), each assumed to be stationary. There is a clear need for taking non-stationarity into account.

Two methods to transfer the climate signal to the hydrological model have been used: the delta change approach (e.g. Veijalainen et al., 2010a) and direct daily RCM data (Veijalainen et al., 2012). The delta change approach is easy to use, but since all monthly values are changed by the same factor, the changes in extremes could be incorrect. This may affect results especially where extreme precipitation is the main cause of floods. In Finland the largest floods are often generated by either snowmelt or in the lake area by prolonged periods of excess water from rain or snowmelt. The use of direct RCM data may offer a better way to include the projected changes in extremes, but due to the large biases in RCM data a bias correction is generally required (Veijalainen et al., 2012). The impact of bias correction on the results as well as impact of remaining biases has to be considered. The method is also more complicated to use than the delta change approach.

3.3 Recommendations for users

4. Case studies

Examples of practical applications:

In a recent study, changes in 100 year floods by 2010-39 and 2070-99 at 67 sites in Finland were estimated using the WSFS hydrological model and 20 climate scenarios to provide an overview of possible changes (Veijalainen et al., 2010a). The Gumbel distribution was used for frequency analysis of the simulated discharges for each time slice and the future 100 year floods were compared with floods from the control period 1971-2000. The changes in flood inundation areas were also estimated on four study sites. The results can be used for implementation of the EU flood directive as part of the flood-hazard mapping requirements. The results demonstrate that the impacts of climate change are not uniform within Finland due to regional differences in climatic conditions and watershed properties. In area dominated by snowmelt floods, the annual floods decreased or remained unchanged due to decreasing snow accumulation. On the other hand, increased precipitation resulted in growing floods in major central lakes and their outflow rivers. Important explanatory variables in the changes of floods are many watershed characteristics and meteorological properties (e.g. catchment area, lake percentage, latitude, average maximum snow water equivalent and percentage of snowmelt flood in control period), which in combination can explain most of the average changes in different sites and their explanatory power improves when applied separately to different hydrological regions. These variables could provide a basis for possible regionalization of the results within Finland. These first results are based on the delta change approach, but will be re-evaluated with other methods in the future.

The possibilities to adapt to climate change by changing the regulation practices and rules in Finland numerous regulated lakes have been evaluated (Veijalainen et al. 2010b). If changes to regulation permits are planned, an evaluation is carried out to determine how the new regulation permits will change the hydrological conditions.

5. Plans for future development

Future plans in Finland include development and testing of new methods in hydrological modelling of climate change impacts (for example use and bias correction of direct RCM data as input to the hydrological models), simulation of transient climate scenarios (for example 1951-2100) and use of non-stationary flood frequency analysis for both observed discharges and simulated discharges for transient climate scenarios. In an ongoing study bias corrections for direct RCM data are developed and this data will be used as input to the hydrological model to simulate transient climate scenarios for 1951-2099.

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Review of applied methods for flood-frequency analysis in a changing environment in France

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1. Description of methods

1.1 Detection of trends and step changes in time series of hydrological extremes (at-site and regional procedures)

At-site procedures

A French national project, funded by the National Research Programme on Hydrology (PNRH), on non-stationary flow series was set up in 2002 in order to study the variation of floods and droughts in France, based on a large set of discharge series. Three main objectives have been assigned to the PNRH project: 1/ to define a general framework for the selection of a limited number of tests for the detection of changes in hydrological series; 2/ to give an assessment about the stationarity of floods and droughts in France; 3/ to develop a statistical tool which enables incorporating non-stationarity into frequency analysis.

Monte Carlo simulations have been developed within the PNRH project in order to select adequate testing procedures for the detection of changes on extreme hydrological values. The main criteria were the preservation of the significance level, the power (ability to detect a small change), and the robustness on departure from initial assumptions (e.g. distribution, independence). Parametric tests based on the likelihood ratio between two alternative hypotheses (LR tests) appear to be the most powerful, especially for extreme data, provided that the distributional assumptions (e.g. Generalized Extreme Value (GEV) or Generalized Pareto distributions) are fulfilled by the data. Furthermore, a general framework for the selection of tests has been developed by Renard (2006) (Figure 1 and Table 1), taking into account a possible autocorrelation, the distribution type, the type of change and the length of the data series.

Regional procedures

Field significance is assessed when a statistical test is repeated on several distinct data series (e.g. from several locations in a given region) and has been studied, for example, by Livezey and Chen (1983), Lettenmaier *et al.* (1994), Douglas et al. (2000), Yue and Wang (2002), Ventura *et al.* (2004) and Renard and Lang (2007). In a change detection context, it aims at testing the hypothesis H0 *“data from all sites are stationary”*. Several methods accounting for dependence between the series have been proposed to assess the distribution of *N*, the number of locally significant tests under the hypothesis that all series are stationary, such as: 1/ an equivalent (or effective) number of stations (ENS) (Matalas and Langbein, 1962); 2/ a bootstrap procedure (Douglas *et al.,*2000); 3/ a Gaussian copula (Renard and Lang*,* 2007) and 4/ the false discovery rate (FDR) (Benjamini and Hochberg, 1995; Ventura *et al.,* 2004).

Renard *et al.* (2007**)** favoured the bootstrap procedure, as it is easier to apply and requires no parametric assumption about marginal and joint distributions of data. On the other hand, 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 change. In conclusion, the choice between the bootstrap and the FDR procedures depends on the expected type of change. When no prior information about the regional change is available, a pragmatic approach would simply consist in applying both tests to the data.

Regional Consistency. Climate is a global phenomenon and its change is likely to have an impact over an extended spatial area. Consequently, river flows in nearby catchments located within the same homogenous climatic area are expected to be impacted by a similar climate change. Several methods have been developed to account for regional climate changes: 1/ univariate analysis (e.g. Mann-Kendall test) by considering regional indices, i.e. variables defined over the entire region (e.g. the mean regional value of the date of occurrence of the annual maximum flood on all sites); 2/ the regional average Mann-Kendall test (RAMK), proposed by Douglas *et al.* (2000) and Yue and Wang (2002); 3/ a semi-parametric approach based on a normal score transformation and the multivariate Gaussian distribution, Renard *et al.* (2008). In terms of power, no method was found to perform better but the third test is favoured as it forces the regional trend to be consistent.

1.2 Non-stationary flood frequency analysis (at-site and regional procedures)

At-site procedures

Renard *et al.* (2006a) developed a Bayesian procedure to assess the flood distribution at a given site, considering several probabilistic models (stationary, step-change and linear trend models) and four extreme value distributions (exponential, generalized Pareto, Gumbel and GEV). Prior distributions are specified by using regional prior knowledge about quantiles. Posterior distributions are used to estimate parameters, quantify the probability of models and derive a realistic frequency analysis, which takes into account estimation, distribution and stationarity uncertainties.

Regional procedures

Renard *et al.* (2006b) developed a nonstationary regional model for describing annual maximum discharges of several gauging stations within a homogeneous region. A GEV distribution was used, GEV(α_i, β_i (1 + δt), ξ), where the position α_i and scale β_i parameters are local and the shape parameter ξ has a regional value. A prior estimate was taken for α_i and β_i parameters using the non-shared years of the regional data set, from a GEV distribution. An expert-based range of values of the ξ parameter was fixed by assuming a Gaussian distribution with zero mean and standard deviation 0.3. A Bayesian procedure was applied for six stations with 34 common years of record, and yielded the posterior distribution. The case study illustrates the benefit of a regional inference compared to at-site analyses, especially in terms of trend detection. This is particularly useful in the case of extreme value models, whose parameters are known to be particularly difficult to estimate.

1.3 Rainfall-runoff modelling

Cantet (2009) used a regional version of a rainfall simulation model, the Shypre model (Arnaud *et al.*, 2007). As the model uses only three climatic parameters (average number of daily events per year, average of the maximum daily rainfall, average duration of the events), it is possible to assess the effect of climate change by using the predicted values of the three parameters from a climatic model. Application of this approach to France provided an assessment of the rainfall distribution in 2050 and in 2100. Two regions are expected to have more intense rainfall events (Lorraine and east of Cevennes).

1.4 Multivariate frequency analysis (e.g. storm surge, river flooding, urban flooding)

Several researches coped with multivariate analysis, but in a stationary context. From our knowledge, the extension to a non-stationary context has not been addressed.

1.5 Uncertainty and risk analysis

Uncertainty quantification was central in the approaches presented in Section 1.2. In particular, Bayesian model averaging was used in an attempt to quantify the uncertainty related to the existence of a change (in addition to parameter estimation uncertainty). Instead of choosing one model (with a risk of error), each possible model is weighted by its relative probability: the final assessment takes into account uncertainty both due to sampling errors and model errors.

2. Data Availability and use of streamflow/precipitation data and proxy data for change detection and frequency analysis

Large set of data is available from Meteo-France. Official agreement should be signed between the user and Meteo-France (only for research activities, within an official project, data only available during the period of the project). For example, within the ExtraFlo project (https://extraflo.ce) devoted to the comparison of extreme rainfall and flood estimation methods, it was possible to get access to a set of 1900 daily rainfall series and 230 hourly rainfall series.

2.1 Availability and use of data to assess changes in hydrological regime and river infrastructure development

A special data set of discharge data is available from Cemagref (about 1000 stations, without influence, at least 40 years of record, good quality). An agreement is needed to use data within the FloodFreq action..

2.2 Availability and use of climate change projections from general circulation models and regional climate models, including statistical downscaling

Precipitation projections from General Circulation Models (GCMs) over France are at a too coarse spatial resolution to be used in flood frequency estimation. However, a number of dynamical downscaling experiments have been performed over the last few years, notably within the ENSEMBLES project (van der Linden and Mitchell, 2009). In this project, several Regional Climate Models (RCMs) have been driven by several GCMs under the A1B emission scenario. Available outputs through the project website (http://ensembles-eu.metoffice.com) for research projects are transient climate projections at 50 or 25km over Europe. Precipitation data are widely recognized as biased and should not be directly used for flood frequency assessment.

Several statistical downscaling methods have been used: delta change methods, quantile-quantile corrections, weather type analogy, etc. Experiments of statistical downscaling have been performed over the whole of France by Pagé and Terray (2010) based on the 3rd Coupled Model Intercomparison Project (CMIP3, http://cmip-pcmdi.llnl.gov/cmip3_overview.html) global projections and a method based on weather type developed by Boé *et al.* (2006). Available outputs (by agreement with CERFACS) are transient climate projections over a 8km grid over France, as well as streamflow projections computed with the SIM hydrometeorological suite (Habets *et al.*, 2008) forced with an older version of the downscaling method. Both climate and hydrological data are recognized to underestimate extreme events and should not be directly used for flood frequency assessment.

3. Applications

The different methods described above are not already able to provide a flood-frequency analysis in a changing environment for operational purposes. The main reason is that the magnitude of the detected changes are either not significant or too small compared to the uncertainties associated to extreme values. The climate model projections for 2050 or 2100 remain uncertain for extreme values, as France is located in an area where the effect of climate change is not coherent (contrarily to North and South Europe). Additional uncertainties are related to downscaling at fine temporal and spatial scales.

Therefore, the present strategy in France is to keep design values from standard methods based on the stationary assumption. No particular guidelines or recommended practices have been established in relation to the impact of environmental changes on floods. But an active research work is in process to develop new methods for a changing context. When the change will be significant, the methodology will be transferred to applied purposes.

4. Case studies

Following the general framework for trend detection (Figure 1 and Table 1), Figure 2 shows the detected changes on a set of 192 French hydrometric data series, with at least 40 years of record. No consistent trend emerged in the analysis of the flood magnitude (annual maximum (AM) or peak-over-threshold (POT) values), contrary to the significant increase in flood damages, which can be explained by the greater exposure to flooding. The number of flood events seems to decrease in a part of the data set, and therefore the duration between two successive events is increasing. Further investigations are necessary to explain such changes and to understand what is related to human influences (reservoir for drought compensation, pumped storage) and to climatic influences (dry periods).

The two regional procedures (Field significance and Regional Consistency) have been applied by Renard (2006) to France, using daily discharge data from 195 gauging stations. No generalized change was found at the national scale based on the field significance assessment of at-site results. Hydro-climatic regions were then defined, and the semi-parametric regional consistency procedure was applied. Most of the regions showed no consistent change, but three exceptions were found: in the North-East flood peaks were found to increase, in the Pyrenees high and low flows showed decreasing trends, and in the Alps, earlier snowmelt-related floods were detected, along with less severe drought and increasing runoff due to glacier melting. The trend affecting floods in the North-East was compared to changes in rainfall, using rainfall-runoff simulation. The results showed flood trends consistent with the observed rainfall.

Pujol *et al. (*2007) used a regional approach for trend detection in precipitation series of the French Mediterranean region. A sample of 92 daily precipitation series was selected in the French Mediterranean region over the period 1945–2004, to study the stationarity of extreme events. The series are used to define seven homogeneous climatic zones. For each one, regional series of daily peaks over threshold records are extracted from the raw data. The scale and occurrence parameters of the model are not constant, and linearly depend on time. This approach allows studying the stationarity of both the occurrence and the intensity of extreme events, at the regional scale. The only statistically significant results is an increase of the occurrence and intensity of extreme daily rains in the North of the Lozère 'department' (France) and the southern part of the Auvergne, as well as an increase of the intensity of extreme rainfalls in Languedoc-Roussillon.

Among about 20 research projects devoted to the simulated impact of climate change on water regime in French basins, a few addressed the flood regime like the GICC-RHONE project (Boone *et al.*, 2005) on Rhone basin, and the REXHYSS project (Ducharne *et al*., 2009) on Seine and Somme basins. The EXPLORE2070 project (http://www.developpement-durable.gouv.fr/Explore-2070-Eau-et-changement.html) is currently in process to get a national overview of the impact of climate change in France and propose a strategy of adaptation.

5. Plans for future development

A major improvement to the non-stationary model developed by Renard *et al.* (2006b) will be to introduce a hierarchical model to account for spatial variability in the catchment's response to climate change. This is the subject of a current research of X. Sun (PhD at Cemagref Lyon, 2010-2013).

Two future research studies will be based on coupling a stochastic rainfall generator in a climate change context and a rainfall-runoff model.

As the Shypre model has already two components (rainfall generator and rainfall-runoff model), the next step will be to use the regional version of the Shypre model with 2050 or 2010 predicted values of its three parameters and to transform rainfall simulated series into discharge series with the rainfall-runoff model.

The Schadex method (Paquet *et al.*, 2006) is a simulation approach which combines a weather-pattern-based probabilistic model and a conceptual rainfall-runoff model. P. Brigode (PhD at EDF Paris, 2010-2013) aims to adapt this method to a changing climate. Climate models will be used to assess the future relative weight of the weather patterns in France. Such values will be introduced within the Schadex model, with the assumption that the rainfall distribution of each weather pattern remains the same.

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Table 1 Applied trend tests for various hydrological variables.

Variable	Distribution	Autocorrelation ρ	Applied trend-test
Annual maximum	GEV	No	LR
POT	Generalized Pareto	No	LR
Annual number of floods	Poisson	No	LR
Inter-arrival duration	Exponential	No	LR
VCN30	GEV	Has to be checked	MMK if ρ significant, LR otherwise
QCN30	GEV	Has to be checked	MMK if ρ significant, LR otherwise
Volume deficit	unknown	Has to be checked	MMK if ρ significant, MK otherwise
Drought duration	unknown	Has to be checked	MMK if ρ significant, MK otherwise

Abbreviations: GEV: generalised extreme value; POT: peak over threshold; VCN30: annual minimum 30-day discharge; QCN30: annual minimum 30-days non- exceedance discharge; LR: likelihood ratio; MMK: Modified Mann-Kendall; MK: Mann-Kendall.

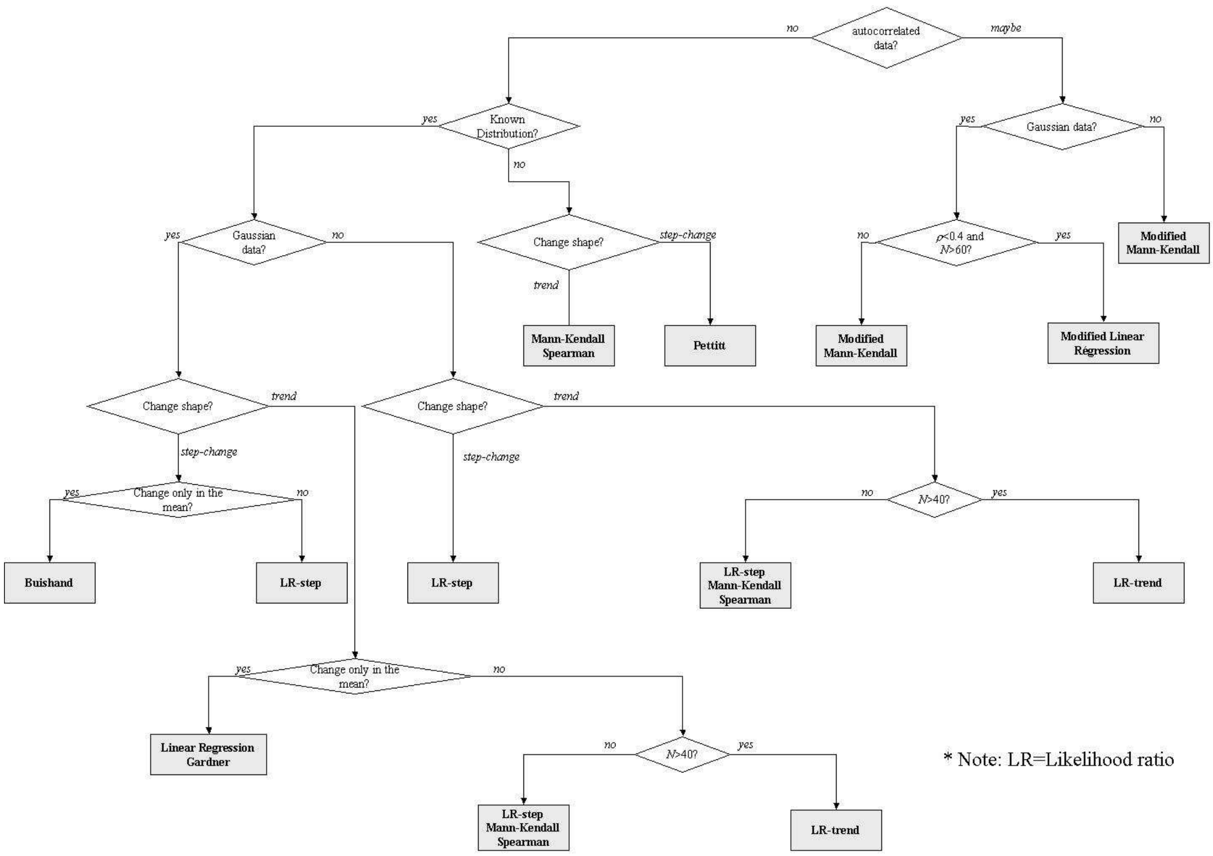

Figure 1. Selection of a test for identifying change within a sample of hydrological extreme values. From Lang *et al.* (2006).

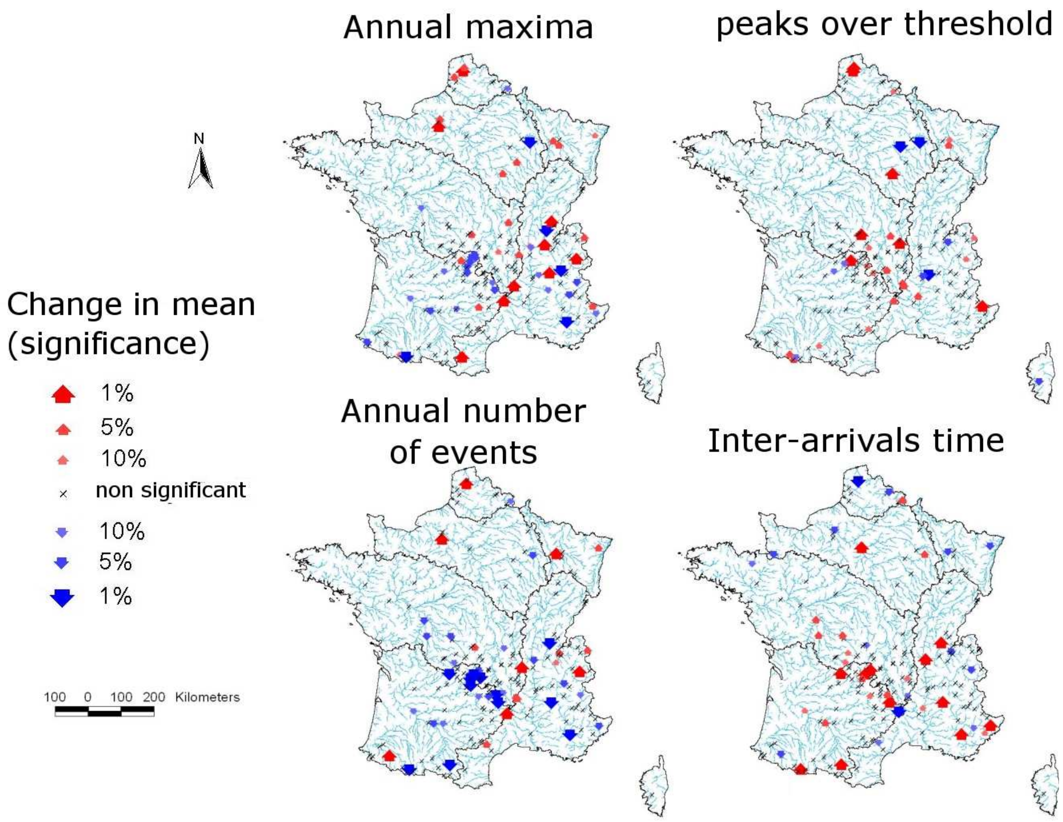

Figure 2. Detection of changes on French extremes for floods. From Lang *et al.* (2006).

Overview of methods used to consider the impact of environmental change (particularly climate change) on flood frequency in Germany

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Preamble

In Germany, there is no central authority which is responsible for flood risk assessment and management. Flood risk management is in the responsibility of the Bundesländer (federal states), hence, almost all studies are limited in geographical extent, and there are only a few attempts for Germany-wide analyses. On the other hand, climate change impact on floods is a major topic for authorities at the level of the federal states and on the national level, and comprehensive studies are under way. It would be a major effort to compile all the recently finalized and ongoing activities, hence, this report is restricted to:

- studies that take a Germany-wide approach,
- selected "local" studies that are seen as innovative from a methodological point of view,
- selected case studies that are seen as highly significant in terms of application.

1. Description of methods

1.1 Detection of trends and shifts in time series of hydrological extremes (at-site and regional procedures)

There is no Germany-wide procedure for dealing with trends and shifts in time series, and flood time series are not systematically screened for changes prior to flood frequency analysis. In some studies on climate change impacts, flood time series have been homogenized to take into account the effects of river training and implementation of retention basins and dams on the flood peaks.

Petrow and Merz (2009) investigated trends in flood time series for 1951-2002 for approx. 150 catchments, distributed through-out Germany. They applied the Mann-Kendall test, and estimated the trend slope via Sen's estimator. The time series were pre-whitened according to Yue et al. (2003), in order to consider the potential error that could be introduced into the trend significance estimation by auto-correlation. Field significance was evaluated by the bootstrapping method of Douglas et al. (2000), using a slightly refined approach which assesses field significance of upward and downward trends separately (Yue et al., 2003). They found that results varied according to the chosen flood indicator (annual maximum flood, peak over threshold, annual or seasonal peaks), and detected flood trends for a considerable fraction of basins. Marked differences emerged when looking at the spatial and seasonal patterns. Basins with significant trends were spatially clustered. The study concluded that the spatial and seasonal coherence of the trend results suggested that the observed changes in flood behavior were climate-driven.

In a follow-up study, Petrow et al. (2009) related the detected trends in flood time series to changes in circulation pattern time series. They pooled catchments according to flood seasonality into three regions. The temporal behavior of flood indicators of each region was compared to atmospheric indicators derived from circulation patterns. They found significantly increasing persistence of flood-prone circulation patterns during the winter season throughout Germany. The comparison of circulation pattern time series and flood time series led them to conclude that changes in the dynamics of atmospheric circulations influenced the flood hazard in 1951-2002.

Bormann et al. (2011) analyzed time series of different length for trends in flood stages, flood discharges, flood frequency and in stage-discharge relationships for 78 stream gauges in Germany. Three different approaches were applied to test for trends. Trends in flood frequency over time were investigated using the chi-squared test on two-way contingency tables of designated flood versus non-flood years (Pinter et al., 2006). Trends in maximum annual flood stages and discharges were determined by ordinary least-squares linear regression and by the Mann-Kendall test. Specific gauge analysis (Jemberie et al., 2008) was applied for detecting changes in the stage-discharge relationship over time for all gauging stations and all years for which both stage and discharge data were available. Comparing the results of different tests and different time series can suggest or exclude causal mechanisms driving observed trends. For example, while trends in peak discharge may suggest climatic and/or land-use change, changes in flood stages (in the absence of trends in discharge) may suggest in-stream river training (Bormann et al., 2011).

1.2 Non-stationary flood frequency analysis (at-site and regional procedures)

Flood frequency analysis in Germany is currently based on the stationarity assumption. One of the few exceptions is Petrow et al. (2008) who applied non-stationary flood frequency analysis at the Germany-wide scale. They analyzed flood time series of 145 catchments for 1951-2002 using a non-stationary GEV. The location parameter was allowed to vary linearly in time. GEV parameters were estimated via MLE. Further, the likelihood deviance test described in Coles (2001) was used to evaluate if the non-stationary model (GEV with 4 parameters) was a significant improvement over the stationary model (GEV with 3 parameters).

1.3 Rainfall-runoff modelling

There are a large number of rainfall-runoff models that are used for investigating past or future changes in flood behavior in Germany. In this chapter, we will focus on studies which aim at the Germany-wide scale.

Hattermann et al. (2011a) used the semi-distributed hydrological model SWIM (Krysanova et al., 1998) to simulate changes in flood magnitude across Germany for the period 1951-2006. SWIM integrates all relevant hydrological processes such as snow development, soil percolation, groundwater and river routing, and has been extensively validated for German conditions. Observed meteorological data were fed into SWIM, producing spatially-distributed river discharge time series for 3768 river reaches throughout Germany. In a second step, Hattermann et al. (2011a) applied the Mann-Kendall test to detect trends in the annual maximum river discharges derived from the generated discharge time series. The simulated changes in flood behavior were in agreement with observed trends in flood peaks. Further, the areas with increasing flood trends agreed with the areas in Germany where intense precipitation increased significantly during the same period. Hence, Hattermann et al. (2011a) suggested that this correspondence illustrated the climate change track in flood trends.

Hundecha and Merz (2011) implemented a model-based approach to attribute past changes in flood flows to meteorological drivers for 8 case study catchments in Germany. The hydrological model SWIM was employed together with a multi-site, multivariable weather generator. Ensembles of meteorological time series were generated using the weather generator and were used to drive the hydrological model. To assess the relative importance of the meteorological variables in explaining the detected flood trends, the variables were generated by accounting for the year to year variability of the distribution of one of the variables at a time while keeping the distributions of the others temporally stationary. The results showed the robustness of the approach in identifying the meteorological variable that was associated with the detected change in the extreme flow under situations where a comparison between trends in flow extreme and meteorological variables failed to reveal any association. This can be explained by the fact that the model-based approach is able to take into account the complex spatio-temporal relationship between precipitation and discharge extremes, whereas the traditional approach of comparing trends in the catchment average precipitation with trends in catchment outflow is more limited.

KLIWAS (Impacts of climate change on waterways and navigation - Searching for options of adaptation) is an ongoing activity of the German Federal Ministry of Transport, Building and

Urban Development. The aim of KLIWAS is, among others, to analyze the potential consequences of climate change for navigation on inland and coastal waterways (KLIWAS, 2011). Floods are not in the focus of KLIWAS, however, the activity is mentioned here, since it is a large-scale effort and parts of the model chain could also be used for flood analyses. The aim of KLIWAS is to implement a comprehensive multi-model chain (emission scenarios – global climate model – regional climate model – bias correction – hydrological model – impact model). KLIWAS strives to consider all available climate projections in order to identify the span of the potential future climatic evolution. In addition, for each step of the model chain several different models or approaches will be implemented. For example, it is planned to implement 9 different hydrological models for the Rhine catchment, 5 models for the Elbe catchment and 4 hydrological models for the Danube catchment (KLIWAS, 2011). In this way, KLIWAS attempts to give the best possible estimate of the span of possible future conditions in inland and coastal water bodies.

1.4 Multivariate frequency analysis (e.g. storm surge, river flooding, urban flooding)

To the author's knowledge, authorities and consultants in Germany use univariate flood frequency analysis. However, there are research projects which have developed or applied multivariate frequency analysis. One example is the study of Klein et al. (2010). Bivariate probability analyses of different flood variables using copulas were applied in the Unstrut river basin in Germany. This basin consists of two reservoirs located downstream of the main tributaries and flood polders. The spatial distribution of flood events within the river basin was analyzed by the joint probability of the inflow peaks at the two reservoirs. Furthermore, copulas were used for risk analysis of the individual flood detention structures, considering the joint probability of flood peak and volume.

1.5 Uncertainty and risk analysis

Concerning climate scenarios and climate change impact on flood frequency, several activities follow the ensemble approach in order to address the uncertainty. Currently, the most ambitious project in the direction in Germany is KLIWAS (KLIWAS, 2011, see Figure 1) as introduced above.

2. Data

2.1 Availability and use of streamflow/precipitation data and proxy data for change detection and frequency analysis

A significant fraction of the discharge data is distributed, mainly located with the authorities of the different federal states. Proxy data for change detection (e.g. changes in flow regulation, changes in monitoring sensors) are not coherently provided. BFG (Federal Institute for Hydrology, Koblenz) provides daily discharge time series for gauges on navigable rivers. In some cases daily time series of discharge are quite long, e.g. Dresden/Elbe since 1805.

Meteorological data are collected, documented and provided by the German Weather Service (DWD) on a Germany-wide scale. For example, there exists a homogenized precipitation data set with daily resolution of more than 2300 stations for 1951-today throughout Germany.

2.2 Availability and use of data to assess changes in hydrological regime and river infrastructure development

Data and information on in-stream changes and interventions in catchments are not coherently collected and provided. For some rivers and catchments the impact of in-stream changes or of changes in the catchment on floods has been estimated by hydrological/hydraulic models. However, many of these studies are not readily accessible. An example of an easily accessible study is the work of Lammersen et al. (2002) who report on the effect of the construction of a series of weirs along the upper Rhine on flood peaks at the lower Rhine.

2.3 Availability and use of climate change projections from general circulation models and regional climate models, including statistical downscaling

There exist different regional climate projections for Germany. Two of them were officially commissioned by the German Environmental Agency (Hattermann et al., 2011b). They are a standard of climate downscaling for Germany using climate change projection generated by the General Circulation Model ECHAM5 (Roeckner et al., 2003) for the IPCC scenarios A1B, A2 and B1. One set of regional projections was generated by the statistical regional climate model WettReg (Enke et al., 2005), and another set by the physically-based regional climate model REMO (Tomassini and Jacob, 2009). WettReg uses large-scale climate variables, namely temperature and circulation pattern, which are relatively well represented in global climate models and establishes statistical relationships between them and regional weather variables.

3. Applications

3.1 Purpose and areas of application (design of hydraulic structures, dams, urban hydrology, flood-hazard mapping, etc.).

A summary is provided of the approaches used by the federal states of Bavaria and Baden-Württemberg to cope with climate change in the process of flood design. These two states have introduced design allowances to account for the effects of climate change on flood frequency, based on the cooperation project KLIWA (Climate change and consequences for water management, KLIWA, 2011). The objective of KLIWA is to assess the possible effects of climate change on the water balance for the time horizon 2021-2050. The methodology of KLIWA is based on model chains. Three approaches were used for regional climate projections to obtain a bandwidth of possible developments: the regional climate model REMO, and the statistical methods WettReg (Enke et al., 2005) and STAR (Orlowsky et al., 2008). These models were driven by the global climate model ECHAM 4 and the IPCC emissions scenario B2. Finally, the regionals scenarios were used as input for the water balance models LARSIM and ASGi, available in the Federal States of Baden-Württemberg and Bavaria.

The scenario simulations showed that the flood runoffs will possibly increase in many catchments in Baden-Württemberg and Bavaria. Therefore, the authorities agreed that from today's point of view it is necessary to take into account the effects of climate change when designing new water management facilities in the form of a "climate factor". In Bavaria, a climate change factor of 15% has initially been specified as a blanket increase in the 100-year flood peak, i.e. the design discharge for the 100-year flood is multiplied by 1.15. Due to the uncertainties in the model chains, updating of the climate change factors is foreseen. In Baden-Württemberg, a similar procedure has been established, however, the climate factor varies between 1.0 and 1.75, depending on the region and the return period (KLIWA, 2011, Hennegriff et al., 2011).

4. Case studies - examples of practical applications

As an example, one of the more comprehensive case studies is given, namely the assessment of climate change impacts on water resources in the German State of Saxony-Anhalt by Hattermann et al. (2011b). This study assessed climate change impacts including possible adaptation measures as basis for a federal adaptation directive. An important aspect of the project was the two-way exchange of information and knowledge between scientists and decision makers in the water sector. This study implemented a climate change impact model chain, consisting of (1) the IPCC scenarios A1B, A2, B1, (2) the general circulation model ECHAM5, (3) the physically-based regional climate model REMO and the statistical regional climate model WettReg for downscaling of climate variables to the catchment scales, (4) the hydrological model SWIM. One realization of each scenario was generated by REMO, while WettReg generated 20 realizations of each scenario to reproduce also part of the climate variability. Flood frequency curves, using GEV, were constructed based on the time series discharge generated by the model chains for the periods 1961–1990, 2011–2040, 2041–2070 and 2071–2100. The study results suggested significant changes in flood frequency and in flood seasonality for future periods. However, the authors pointed to the high uncertainty associated with future changes in flood frequency and intensity.

5. Plans for future development

Since there are many research groups and authorities who are dealing with flood frequency and environmental change, and since this topic is high on the agenda of different sectors, it can be assumed that there are many plans for future development. There seems to be consensus that the uncertainty of future scenarios has to be taken into account. To this end, the ensemble approach is currently being extended (in terms of a larger number of scenarios and in terms of including – if possible – all steps of the model chain in an ensemble approach). A further direction is an increasing spatial resolution of regional climate models. For example, the study of CEDIM (www.cedim.de) uses two regional climate models with resolution of less than 10 km in order to provide scenarios which can be used for flood estimation for the next few decades in medium-size catchments. Further, the Helmholtz Association plans to compile the knowledge on climate change and its impacts for Germany in an assessment report.

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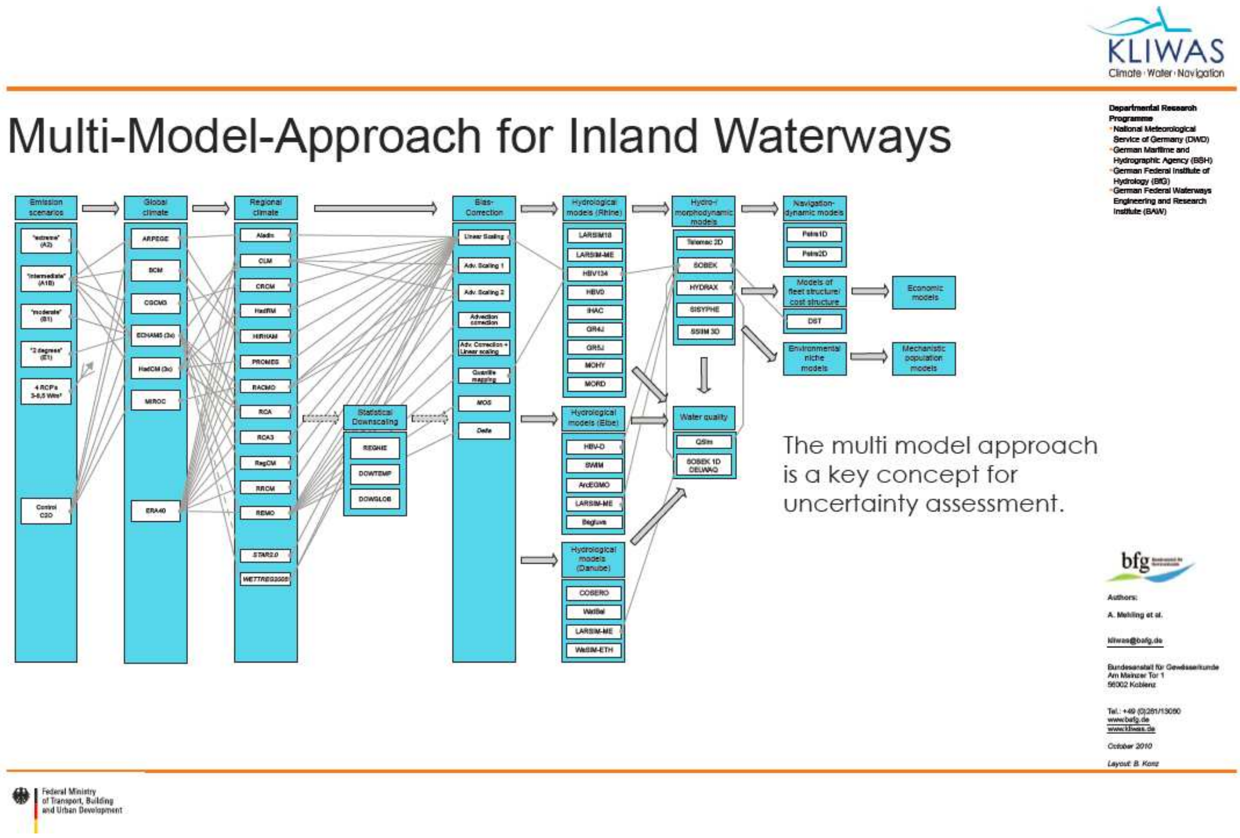

Figure 1. Multi-model approach applied in the KLIWAS project (KLIWAS, 2011)

Review of applied methods for flood-frequency analysis in a changing environment in Greece

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1. Description of methods

1.1 Detection of trends and shifts in time series of hydrological extremes (at-site and regional procedures)

In Greece, time series are not systematically investigated for trends prior to undertaking frequency analysis. High quality data are only available at meteorological stations of the Hellenic National Meteorological Service. However, as the Ministry of Environment, Energy and Climate Change has the responsibility of maintaining the hydrometric data, a systematic effort has been started to compile high quality hydrometric data in the Enhydris database (www.openmeteo.org and www.hydroscope.gr).. Trend methods are mainly used by the Greek Universities and Research Organizations. A methodology was developed for the automatic exploration and analysis of hydrological data, particularly focused on the identification of shifting relationships among hydrological variables, and is applicable to many hydrological problems, such as identification of multiple stage-discharge relationships in a river section, data homogeneity analysis, analysis of temporal consistency of hydrological data, detection of outliers, and determination of shifts and trends in hydrological time series (Tsakalias and Koutsoyiannis, 1999). Outliers and trend detection tests of rainfall extremes in Greece have been examined in a case study by Galatsiatou and Prinos (2007). In this study, daily rainfall from the city of Thessaloniki, Greece was analyzed using Extreme Value methodologies to a) detect possible outliers present in the series and b) investigate the existence of polynomial temporal trends of specified forms in the parameters of the Extreme Value model used. Four different methodologies were used to decide upon the inclusion of the largest observation (the possible outlier) in the data: a) the estimation of x_{ult}, b) the conditional probability of the event estimated through a Bayesian formula, c) a Gumbel plot and d) a q-q plot for an appropriately selected model for extreme events of the rainfall process. Then, simple polynomial temporal trends for the location and the scale parameters were incorporated in the point process model and a simple test, the deviance statistic D, was used to identify the significance of such trends (Galatsiatou and Prinos, 2007). Trend detection has been combined with the analysis of multi-decadal oscillations in rainfall and temperature series (e.g. Loukas et al., 2001; Anagnostopoulou et al., 2003; Tolika and Maheras, 2005; Feidas et al., 2007; Nastos and Zerefos, 2008) and in extreme climate indices (Kioutsioukis et al., 2010) in Greece. Observed shifts in these time series were often regarded as deterministic components (trends or jumps) and removed from the time series so that the residual could be processed using classical statistics. This would be an efficient approach if a deterministic model existed, which could explain these components and also predict their future behaviour. However, this is hardly the case, as most typically the trends or shifts are identified only *a posteriori* and expressed mathematically by equations lacking physical meaning (e.g. using linear regression) and thus applicable only to the relevant parts of the time series and not their future evolution. A more consistent alternative is to approach this behaviour in a stochastic manner. A stochastic basis for dealing with these shifts and trends is offered by simple scaling processes that are consistent with the assumption of hydroclimatic fluctuations on multiple time scales, a behaviour that is known as the Hurst phenomenon (Koutsoyiannis, 2003; Koutsoyiannis, and Montanari, 2007; Koutsoyiannis, 2011).

1.2 Non-stationary flood frequency analysis (at-site and regional procedures)

Standard procedures for flood frequency analysis in Greece are based on an assumption of stationarity (Koutsoyiannis et al., 1998; Loukas et al., 2001; Kioutsioukis et al., 2010). There are currently no systematic analytical procedures for accounting for the effect of environmental change on discharge timeseries. Koutsoyiannis (2004) demonstrated that the Gumbel distribution is quite unlikely to apply to hydrological extremes and that the extreme value distribution of type II (EV2) is a more consistent choice for annual maximum frequency analysis. In addition, he proposed a two parameter version of the EV2 distribution which simplifies the fitting and the general mathematical handling of the distribution (Koutsoyiannis, 2004). Furthermore, extreme rainfall has been examined for non-stationarities in selected rainfall stations in Greece using wavelet analysis to detect the main time intervals of these non-stationarities, as well as the main periodicities of the signals. Analysis of at-site extreme rainfall events, exceeding appropriate thresholds, is then carried out, using a non-homogeneous Poisson process and polynomial parametric models are fitted to the data, to detect the existence of long term trends. These models consider that the parameters of the extreme value models vary with time as well as with the values of the NAO index (Galatsiatou and Prinos, 2009).

1.3 Rainfall-runoff modelling

Rainfall- runoff modelling procedures can be found in several studies from Greece for selected catchments and for several applications (i.e. flash floods, runoff modelling). Integrated modelling procedures have been incorporated in recent studies for continuous streamflow modelling (Efstratiadis et al., 2008; Kourgialas et al., 2010; Nalbantis et al., 2011) and single-event modelling for flash floods and flood management (Angelidis et al., 2010; Koutroulis and Tsanis, 2010).

Research on climate change effects on streamflow within Greece is very limited due to the lack of hydrometric stations and the low quality of the data of the existing hydrometric stations. However, studies in selected Greek catchments can be found in the scientific literature (Panagoulia and Dimou, 1997a; 1997b; 1997c; Kalleris et al., 2001, Varanou et al., 2002; Koutsoyiannis et al., 2007). These studies use a Global Circulation Model and a statistical downscaling method to assess changes in temperature and precipitation or they use hypothetical scenarios of increase and/or decrease of precipitation and temperature. Furthermore, the majority of these studies use a simple downscaling method (the delta method) to assess climate change effects on precipitation and temperature series from a GCM. Then these changes are perturbed in the original series of precipitation and temperature and with the use of a reliable daily hydrological model changes in runoff components are estimated for future climate conditions. Only the work of Panagoulia and Dimou, (1997a) has focused on flood events and they showed that the combination of higher and more frequent flood events could lead to greater risks of inundation and possible damage to structures. Furthermore, the winter swelling of the streamflow could increase erosion of the river bed and banks and, hence, modify the river profile (Panagoulia and Dimou, 1997a). The University of Thessaly (UTH), Greece, has also investigated the effects of climate change on floods and subsequently on flood frequency. Both types of simulation (event-based and continuous) for flood frequency estimation have been analysed. For continuous simulation, the modification of the flood response due to future climate change is calculated for the Illecillewaet catchment of British Columbia, Canada (Loukas et al., 2002a,b; Loukas et al., 2004) and demonstrated for the Yermasoyia catchment of Cyprus. Single event modeling was performed in the study of Loukas (2002; 2006). This study evaluated the effect of the increased storm intensity due to climate change on the frequency and magnitude of floods in seven catchments of coastal British Columbia, Canada. The historical annual maximum daily rainfall was truncated according to the projections of the second generation Canadian GCM (CGCMa2) to produce the future rainfall data. The historical and future climate rainfall were used as input to an event-based rainfall-runoff Monte Carlo simulation procedure to generate the frequency of the annual maximum hourly and daily peak flow for the study catchments. These results were compared with the historical observed flood data. This methodology has subsequently been applied in a small ungauged catchment at Ksiropotamos river of Western Macedonia Greece for flood peak and volume estimation, and is going to be validated in selected gauged catchments in Greece by the authors. Flood frequency curves for ungauged catchments are very important and useful, especially for Greece where both rainfall and streamflow data are limited both in space and time. The procedure proposed by Loukas (2002) provides an alternative to the more traditional methods applied in Greece (Mimikou and Gordios, 1989) for ungauged catchments.

1.4 Multivariate frequency analysis (e.g. storm surge, river flooding, urban flooding)

Up to now storm surges, river and urban flooding are still studied separately. The responsible authorities for assessing risks and protecting the public from certain sources of flooding are not clearly defined within Greece. However, as the Ministry of Environment, Energy and Climate Change (MEECC) has the responsibility for the implementation of the EU Flood Directive in Greece, methods for multivariate flood frequency analysis will likely be considered in the near future.

1.5 Uncertainty and risk analysis

The uncertainty of floods is often considered as part of flood frequency studies. This is most frequently achieved by testing the sensitivity of floods to changes in model parameter values and/or input values (precipitation and temperature). Studies with climate change scenarios can be found in section 1.3. The quantification and the understanding of the uncertainties in several climatological parameters are of major interest in recent climate studies (Anagnostopoulou et al., 2008; Koutsoyiannis, 2006; Koutsoyiannis et al., 2007; Koutsoyiannis 2010). These studies demonstrate that the natural variability of the climate system is largely chaotic and thus “maybe unpredictable”. To this direction, Vasiliades et al. (2009) using a stochastic bias correction statistical downscaling method for monthly precipitation showed that future climate predictions (in monthly precipitation) should be handled with caution and their uncertainty should always be evaluated. Future rainfall predictions due to climate change should be handled with caution and always with their respective uncertainty bounds (Vasiliades et al., 2009). Recently, Koutsoyiannis (2011) proposed an interesting theory based on Hurst-Kolmogorov stochastic dynamics to estimate the uncertainty of the hydrometeorological variables. Hurst-Kolmogorov (HK) dynamics provides a useful key to perceive multi-scale change and model the implied uncertainty and risk. Furthermore, the HK approach can incorporate deterministic descriptions of future changes from GCMs, if available (Koutsoyiannis, 2011).

2. Data

2.1 Availability and use of streamflow/precipitation data and proxy data for change detection and frequency analysis

Streamflow and precipitation (interpolated from station data or grid points) data are very limited for Greek catchments. Especially flow measurements at fine time scales (10 minutes, hourly or daily) which are essential for flood assessment are only available for two experimental catchments in Athens, Greece and they cover small time periods. Hydrological information provided from these sites is a service of the Hydrological Observatory of Athens, operated by the National Technical University of Athens. It is an evolution from the hydrometeorological network METEONET and provides access to a single database, which will gradually incorporate further stations and hydrological measurements, including the ones of the Experimental Basin of Athens – Xbasin (Hydrological Observatory of Athens, http://hoa.ntua.gr/). Meteorological information apart from the Hellenic National Meteorological Service (http://www.hnms.gr/) can be found from other sources such as the meteorological network of National Observatory of Athens (www.meteo.gr) and the METAR network of meteorological stations (www.metar.gr). It should be noted that these databases have been installed recently and cover a period of maximum 5 years of daily and smaller time scale values.

2.2 Availability and use of data to assess changes in hydrological regime and river infrastructure development

Data on river infrastructure development are not documented and are thus more difficult to obtain. However, as the Greek Ministry of Environment, Energy and Climate Change has the responsibility for the implementation of the EU Flood Directive, an initiative has been started to share geospatial and hydrometeorological information (http://geodata.gov.gr/geodata/ and www.openmeteo.org, respectively) within the framework of the Infrastructure for Spatial Information in the European Community (INSPIRE) Directive, for operational and research purposes within Greece. Furthermore, from the cadastral project implementation in Greece, high quality orthophoto maps have been produced for the whole country for the period 2007-2009 (http://gis.ktimanet.gr/wms/ktbasemap/default.aspx). The spatial resolution accuracy of these maps is 20 cm for urban areas and 50 cm for the rural areas. Until now, these orthophoto maps are not available to the public but it could be used to extract information about the hydrological regime and river infrastructure.

2.3 Availability and use of climate change projections from general circulation models and regional climate models, including statistical downscaling

In Greece several studies have been performed to assess simulation results from Regional Climatic Models (RCMs), within the ENSEMBLE Project to estimate temperature and rainfall projections under future climate conditions (Zanis et al., 2009; Nastos et al., 2011). The RCMs simulations for the period 2001–2100 were made under the A2, A1B, and B2 emissions scenario, while the simulations for the period 1951–2000 were made under the 20C3M emission scenario, which represents a 20th century simulation using historical GHG concentrations. Changes in six climatic variables (i.e. rainfall, wind speed, temperature, etc.) for the future climate were estimated for the period 2070-2100 from the ensemble results of 13, 12 and 8 RCMs simulations, respectively.

Statistical downscaling have been performed at extreme climatic indices (Tolika et al., 2008), maximum and minimum temperature (Kostopoulou et al., 2007), seasonal (winter, spring) precipitation and raindays for selected Greek stations (Tolika et al., 2007) daily precipitation (Kioutsioukis et al., 2008) and monthly precipitation (Vasiliades et al., 2009). The authors have ongoing research into the potential impacts of climate change on various hydrological parameters (evaporation, discharge, snow water equivalent, soil moisture deficit, groundwater volume), based on UBC modelling for individual catchments and UTHBAL model. Two downscaling methods, the delta change method, and a stochastic bias correction statistical downscaling method have been used to downscale precipitation and temperature at catchment or raster level. However because of the lack of daily streamflow data these methods are applied at monthly timescale in Greece and in daily timescale at catchments in Cyprus and Canada to estimate runoff changes due to climate change.

3. Applications

3.1 Purpose and areas of application (design of hydraulic structures, dams, urban hydrology, flood-hazard mapping, etc.).

Flood frequency analyses are widely used in Greece for the design of hydraulic structures, dam safety assessments, flood risk mapping and urban flooding, but the implementation of procedures for incorporating potential climate change effects are likely to be considered in the near future.

3.2 Merits and drawbacks of different methods

Current operational engineering practices and national procedures do not consider possible environmental change effects.

3.3 Recommendations for users

It is important for water resources management and for design purposes to examine whether the flood frequency distribution is likely to change under a different future climate (Loukas et al., 2004). This includes use of multiple GCM's and RCM's to verify flood response due to climate change alteration, and use of advanced statistical and dynamical techniques to minimise downscaling uncertainty. The research group 'Atmospheric Chemistry and Climate Change Modelling' of the National Observatory of Athens (NOA) (http://www.meteo.noa.gr) has performed various simulation analysis of how climate will be in the future, according to the scenarios A2 and B2 of the IPCC Special Report of Emission Scenarios (SRES) based on RCMs. These simulations could be used in flood frequency studies to estimate extreme design rainfall under future conditions.

4. Case studies

Examples of practical applications

Recently, the Climate Change Impacts Study Committee of the Bank of Greece has completed a comprehensive study of the impact of climate change for Greece – in particular of the cost of climate change that would be borne by the Greek economy, the cost of implementing adaptation measures, as well as the cost of moving to a low-emissions economy, in the context of the global effort to mitigate climate change (http://www.bankofgreece.gr/Pages/en/klima/default.aspx). This study produced climate projections for Greece, in a detailed geographic breakdown up to the year 2100. Considering that the occurrence of extreme climate events in the future cannot be excluded, policies for mitigation and adaptation should be viewed as contingency measures against such an eventuality; as such, they are advisable irrespective of the results of the cost-benefit analysis. This study is a starting point for more comprehensive and detailed research that could provide the backbone for a national strategy for addressing climate change.

To this direction, the adaptation measures that are currently under implementation in Greece are part of a broader network of measures that applies to the specific areas of identified vulnerabilities. However, the Ministry of Environment, Energy and Climate Change has planned, in the context of the National Strategic Reference Framework for the period 2007-2013, the following projects to be implemented (www.ypeka.gr):

- Study of the vulnerability of the Greek coastal areas and proposals of appropriate adaptation policies and measures.
- Study of the impacts of climate change per geographical prefecture.
- Elaboration of a National Strategy for the Adaptation to Climate Change.

Especially for floods, the Ministry of Environment, Energy and Climate Change (MEECC) has been planned various preventive adaptation measures which are currently implemented, as part of a wider flood-preventive policy, in integrated water resources management plans that are compatible with the EU Water Framework Directive. Further information about MEECC actions can be obtained from the 5th National Communication to the United Nations framework convention on climate change (http://www.ypeka.gr/Default.aspx?tabid=472&language=el-GR).

5. Plans for future development

- *Use of RCM simulations and new IPCC scenarios*
- *Application of ensemble methods not only on climate models, but also on statistical downscaling methods and/or assumptions*
- *Estimation of hydrological model uncertainty*
- *Application of methods on Greek and Cyprian catchments*

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Review of applied methods for flood-frequency analysis in a changing environment in Italy

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1. Description of methods and data

Concerning climate change effects, a number of studies have been conducted with reference to the Italian situation. However, these take often the form of scientific investigations rather than systematic analyses in support of flood management. As such, they refer to specific case studies and do not yet allow a general understanding of trends or the definition of widely applicable, general methods. A short account of some relevant studies is provided hereafter.

In the Alps, trends in climate-induced hydrological change have been detected in some cases, especially in Switzerland where a wealth of long time series of discharges enables sound assessment. Among other works, Allamano et al. (2009ab) have proposed and applied a simple conceptual model relating temperature regimes to the frequency of floods in Alpine catchments. The authors show that an increase in frequency of floods may be explained in terms of temperature increases, hence larger shares of catchments above the freezing point during extreme precipitation events contributing to floods.

The model of Allamano et al. (2009 ab) has been shown to be not only capable of predicting future increases in flood frequencies following climate change, but also explaining observed trends across the XX century in more than a half of the annual maxima series available for Switzerland with more than 90 years of record (Castellarin and Pistocchi, 2011).

Based on this evidence and further investigation, Castellarin and Pistocchi (2011) proposed a simple method to compute design discharges under climate change on the basis of present design discharges and an assumed shift in return periods (e.g. from 100 years to 20 years) of a design flood of given intensity.

Analyses of extreme precipitation in Northeastern Italy indicate that similar shifts in frequency occur in rainfall (Brunetti et al., 2001). It might be argued that, although physical mechanisms yielding an increase in frequency of floods are substantially different, the practical approach proposed by Castellarin and Pistocchi (2011) could be used for handling flood risk management in catchments with both pluvial and nival regimes.

In Italy, qualitative flood records are relatively long (e.g. Tropeano and Turconi, 2004) but recorded annual maxima of discharges are sparse and fragmentary. One notable exception is given by the reconstructed 200-year long series of discharges in the Po river presented by Zanchettin et al. (2008) and the discharge series in Mazzarella and Rapetti (2004). In both cases, time series of discharges have been used to detect trends in flood frequency over time.

Besides analyses on long time series of discharges or precipitation, specific insights on the relationship between climate change and floods have been or are being produced in projects such as e.g. HYDRATE (http://www.hydrate.tesaf.unipd.it/) on flash flood forecasting, and THESEUS (http://www.theseusproject.eu; Zanuttigh, 2011) on coastal floods, and other similar investigations.

Another issue of utmost importance in Italy is the effect of soil sealing, consequent to urban development, on the formation of floods in small catchments, particularly in the Po plain. During the 1990's, a few severe rainfall events have highlighted the weakness of the natural and artificial drainage network in regions such as Emilia Romagna, originally designed and managed to serve agricultural catchments, that have been burdened with increasingly urban land uses over time. Several studies have been conducted in order to characterise and control the effect of soil sealing on drainage and floods. In particular, a method aimed at ensuring the hydraulic invariance of land cover change has been proposed (Pistocchi, 2001; Pistocchi and Zani, 2004). The method consists in calculating an equivalent storage volume that should operate the detention of excess runoff associated to soil sealing. The equivalent storage volume needs to be constructed in land use transformations, and is a net cost supported by land developers. In this way, “external” costs of increased flood risk due to soil sealing are “internalized” in the budget of land development, and designers are stimulated to maintain surfaces as pervious as possible to minimize the costs of the detention volumes. The “hydraulic invariance” methodology has been adopted in other Italian regions such as Veneto (where severe floods occurred in 2010 owing to relevant soil sealing) and is going to become a national standard in flood management plans. The documentation of the method and related legislation is currently in Italian (www.regione.emilia-romagna.it/baciniromagnoli/diret_idra.htm) and will be presented in an upcoming English publication.

3. Applications

3.1 Purpose and areas of application

Practical methods are required for the definition of design events and scenarios on which flood management plans should be based. At present, although the whole Italian territory is covered by analyses on flood frequencies and areas at risk of flooding have been identified during the 2000 on the grounds of pre-existing Italian legislation, little or no guidance is available for the inclusion of hydrological change considerations in flood management. Although flood and rainfall frequency analysis is useful to gain insights on the trends of these variables, it seems that no generally applicable method is available for the simulation of scenarios of climate-induced hydrological change. Changes due to land use are in comparison rather straightforward to predict, as different land use types are robustly parameterised in hydrological models.

3.2 Merits and drawbacks of different methods

While the “hydraulic invariance” methodology appears suitable for the control of land use related hydrological change, a similarly simple and widely applicable procedure should be built to account for climate change related hydrological change in flood management plans.

3.3 Recommendations for users

The method proposed by Castellarin and Pistocchi (2011) allows drawing scenarios for design events under an assumed impact of climate change. It uses information on the present frequency distribution of floods and the expected increase in flood frequency to calculate a modified flood frequency distribution for use under climate change conditions.

The method has been proposed for an Alpine context, where the effect of temperature on snow storage is rather obvious. It should be tested more extensively with reference to precipitation extremes in low-lying catchments such as those of the Po plain. Preliminary tests are under development at the Autorità dei Bacini Regionali Romagnoli.

Although simple and practical, the method requires critical assumptions on the increase in frequency of floods. For a sound assumption, an investigation of the expected frequency increase may be obtained from analysis of extreme rainfall/discharge time series but also from regional climate models that, although currently not fully able to quantify extreme convective events, may provide insights on trends in extreme weather conditions.

4. Case studies

The “hydraulic invariance” methodology is operational in the Emilia Romagna regional catchments within the “Hydrogeological risk management plan” (“Piano stralcio per il rischio idrogeologico”) in force since 2001. This plan will be harmonized in the broader context of flood management plans following the EU Floods Directive.

5. Plans for future development

Both the “hydraulic invariance” methodology and the definition of design events under climate change conditions following the proposal of Castellarin and Pistocchi (2011) may be proposed as a general methodology for flood management plans in Italy. These ideas are currently discussed in the working groups involving Regione Emilia Romagna, namely in the Po hydrographic district and the Northern Apennines.

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Review of applied methods for flood-frequency analysis in a changing environment in Lithuania

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1. Description of methods

1.1 Detection of trends and shifts in time series of hydrological extremes (at-site and regional procedures)

Long-term observational series permit to estimate both the frequency and variation of spring floods. Lithuania has long time series of hydrological data for the last 80 years. Spring flood parameters (flood duration, runoff peak, height of maximum discharge and its timing) for Lithuania and all Baltic countries were assessed for four periods (1922–2008, 1941–2008, 1961–2008 and 1991–2008). We used 32 hydrological data series of spring flood parameters from the Lithuanian rivers. The Mann-Kendall test and the nonparametric Sen's method for the magnitude of the trend were used to detect trends in time series for the selected periods. The index flood method was used to estimate the maximum discharge in ungauged catchments. The results showed that maximum discharges and heights of spring floods decreased over a longer time. Spring flood peaks took place on earlier dates. Only some significant trends of maximum discharges and their timing were found in the last time period (1991-2008). All these changes could be caused by the increasing ambient temperature and precipitation in the last decades (Meilutyte-Barauskiene and Kovalenkovienė, 2007; Reihan et al., 2007; Reihan et al., 2012; Gailiusis et al., 2011).

1.2 Non-stationary flood frequency analysis (at-site and regional procedures)

Non-stationary flood frequency analysis has not yet been carried out in Lithuania, but we have plans to use non-stationary flood frequency analysis for both observed discharges and simulated discharges for different climate scenarios.

1.3 Rainfall-runoff modelling

Climate change impact on hydrological processes in the Nemunas river basin which is the largest river basin in Lithuania (75% of Lithuanian territory) has been estimated through combination of results from A1B, A2 and B1 emission scenarios and global climate models (ECHAM5 and HadCM3). Temperature and precipitation simulations were transferred to meteorological station sites using the delta change approach. These climate scenarios were used as input data for the HBV hydrological model. Projections of climate change impacts on hydrological processes were calculated with HBV for the period 2011-2100. Projected changes in Nemunas river runoff are linked to changes of temperature and precipitation (Kriauciuniene et al., 2008). Modelling of the Nemunas river floods was done by the snowmelt-runoff model (SRM) (Simaityte-Volskiene et al., 2004).

1.4 Multivariate frequency analysis (e.g. storm surge, river flooding, urban flooding)

Multivariate frequency analysis has not been performed. Research is on-going to perform mapping of flood areas in Lithuania.

1.5 Uncertainty and risk analysis

Estimation of uncertainty in catchment-scale modelling of climate change impact was performed considering uncertainties of hydrological model parameters, emission scenario and global climate model. The GLUE (Generalized Likelihood Uncertainty Estimation) method was applied for analysis of runoff modelling in the Merkys river catchment (Kriauciuniene et al., 2009).

2. Data

2.1 Availability and use of streamflow/precipitation data and proxy data for change detection and frequency analysis

Daily river discharge and water levels are available from about 150 water measurement stations (WMS). Data sets are of different length (from 2 to 200 observation years).

Time series are short for many stations. Therefore, for detailed analysis of flood frequency the longest time series of daily discharges from 32 WMS were used. There are long-term data series of air temperature and precipitation from 17 meteorological stations (MS) in Lithuania. The owner of all meteorological and hydrological data in Lithuania is the Lithuanian Hydrometeorological Service (LHMS) under the Ministry of Environment. Researchers from Lithuanian Energy Institute can publish the results from analysis of hydrological data. However, we do not have the right to deliver the hydrological data for the third parties. An agreement with LHMS is needed for data use.

LHMS is responsible for data quality. LHMS is implementing the projects “Modernization of Lithuanian meteorological observation network” and “Optimization and development of hydrological monitoring network”, partialy supported by European regional development funds. Since 1992, Lithuania has been member of the World Meteorological Organization. LHMS participates in the creation of the world's river discharge database with the Global Runoff Data Centre and participates in *CEE–WMO/GWP Associated Programme on Flood Management.*

2.2 Availability and use of data to assess changes in hydrological regime and river infrastructure development

All long-term daily time series of river discharge, temperature and precipitation (as data of reference period) can be used for projection of river runoff in the context of climate change.

National database includes information on infrastructure development. The study of evaluation of the influence of hydrotechnical structures on the Lithuanian rivers’ runoff is done (Gailiusis and Kriauciuniene, 2009).

2.3 Availability and use of climate change projections from general circulation models and regional climate models, including statistical downscaling

Climate scenario data is available from ENSEMBLES data archive. These projections are used together with hydrological models to produce estimations of changes in water resources. Traditionally, the delta change approach has been used to transfer the climate change signal to the hydrological model. Climate change impacts on hydrological processes in the Nemunas river basin has been estimated through combination of results from A1B, A2 and B1 emission scenarios and global climate models ECHAM5 and HadCM3 for the period 2011-2100 (Kriauciuniene et al., 2008).

3. Applications

3.1 Purpose and areas of application

Flood frequency analysis is used for design flood estimation for dams, flood-hazard and flood-risk mapping, planning of water infrastructure and planning, and evaluation of climate change impacts on flood frequency.

3.2 Merits and drawbacks of different methods

Estimation of changes in floods in the future is performed by comparing time series from two periods (reference and future). The delta change approach is a popular method for transferring the climate signal to the hydrological model. All monthly values of temperature and precipitation are changed by the same factor using data of the reference period. The drawback of this approach is that the changes in extremes may be incorrect.

3.3 Recommendations for users

There are some Lithuanian environmental regulatory documents related to flood frequency analysis: “Standard rules for maintenance and use of water reservoirs”, “Design, construction and operation of small hydropower plants”. Applying new flood-frequency analysis methods for Lithuanian rivers could be useful for supplement of Technical Requirements for Construction Activities (design and reconstruction of hydrotechnical constructions) and development of rules for preparing reports of Environmental Impact Assessment in Lithuania.

4. Case studies

Some examples are described below.

1. Assessment of spring flood parameters (flood volume, spring flood peak and spring flood timing during 3 periods: 1922-2003, 1941-2003 and 1961-2003) was done using Mann-Kendall test in the three hydrological regions of Lithuania: Western, Central and Southeastern Lithuania. Daily discharges from 32 water measurement stations (WMS) have been used for this research (Meilutyte-Barauskiene and Kovalenkovienė, 2007).
2. Spatial distribution of trends in spring floods for all Baltic countries (Lithuania, Latvia, and Estonia). Trends in spring flood maximum discharge were calculated for the periods 1922-2003, 1941-2003 and 1961-2003. The Mann-Kendall test was used for this research. The decrease in spring flood magnitude and earlier start of river flooding is evidently due to increasing air temperature in the winter period. The increase in air temperature causes a decrease of the water equivalent of snow and the number of days with snow (Reihan et al., 2007).
3. Climate change impact on hydrological processes in the Nemunas river basin has been estimated through combination of results from A1B, A2 and B1 emission scenarios and global climate models (ECHAM5 and HadCM3). Temperature and precipitation simulations were transferred to meteorological station sites using the delta change approach. These climate scenarios were used as input data for HBV hydrological model. Projections of climate change impacts on hydrological processes were calculated with HBV for the period 2011-2100. Projected changes in the Nemunas river runoff are linked to changes of temperature and precipitation. In the winter season, the runoff will increase and in the spring season it will decrease according to all of the emission scenarios in the XXI century (Kriauciuniene et al., 2008).
4. Constructed water reservoirs on the rivers are usually classified as heavily modified water bodies. There are currently 83 hydroelectric power stations (HPS) and more than 1000 water reservoirs in Lithuania. The investigations of the changes of hydrological regime in rivers due to construction of water reservoirs were performed by Gailiusis and Kriauciunienė (2009). The differences of the hydrological regime in tailwaters were analyzed when the water reservoirs are installed with and without HPS. The duration of runoff regulation in the water reservoir with HPS is one of the most important factors in determining the maximum flow change. According to empirical data, the calculated theoretical discharge curves have shown decreasing spring flood maximum discharge and increasing minimum floods after construction of the water reservoir.

5. Plans for future development

1. Analysis of more RCM simulations and new IPCC scenarios.
2. Application of different downscaling methods for modeling of water resources changes and changes in runoff extremes.
3. Use of non-stationary flood frequency analysis for both observed discharges and simulated discharges for different climate scenarios.

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Overview of methods used to consider the impact of environmental change (particularly climate change) on flood frequency in Norway

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1. Description of methods

1.1 Detection of trends and shifts in time series of hydrological extremes (at-site and regional procedures)

Time series are not systematically investigated for trends prior to undertaking frequency analysis. However, trends in various hydrological quantities have been investigated at 151 stations in the Nordic region (Wilson, *et al*., 2010), including changes in the timing of magnitude of spring and autumn peak flows. The results indicate weak and strong trends towards an earlier spring flood at many stations in the region, although trends with respect to the magnitude of peak flows are weaker and more variable, with some stations indicating weak positive trends and some weak negative trends. Shifts in time series are investigated prior to flood frequency analysis and adjustments are made in relation to watercourse regulation. A regulated series is naturalised by maintaining continuity of the water balance, through either adding or subtracting changes in the reservoir water level and diversions in and out of the catchment.

1.2 Non-stationary flood frequency analysis (at-site and regional procedures)

Standard procedures for flood frequency analysis in Norway (NVE, 2011) are based on an assumption of stationarity. There are currently no systematic analytical procedures for accounting for the effect of environmental change. In dam safety assessments the effect of environmental change is partly taken into account through a requirement that assessments are repeated every 15 years.

The Norwegian Water and Energy Directorate (NVE) are investigating allowances that should be made to flood frequency estimates to account for the effects of climate change. One approach being considered involves specifying allowances to make to flows/final water levels on a catchment or sub-catchment basis, where regional climate projections provide an expected increase in the 200-year flood of greater than 20% over the next 20-100 years (NVE, 2010). In many inland regions in Norway, however, a decrease in the flood magnitude is actually expected as a result of climate change, due to the projected decrease in winter snow storage. Therefore, much of the current emphasis is on delineating regions and catchment characteristics (for example, catchment size) which are most likely associated with increased flooding in the future (*e.g*. Lawrence and Hisdal, 2011).

1.3 Rainfall-runoff modelling

Projected changes in the 200-year flood referred to in 1.2 above are based on hydrological (HBV) modelling with locally adjusted climate scenario input data (Lawrence, 2010; Lawrence and Engen-Skaugen, 2010), mostly derived from the EU FP6 ENSEMBLES project. Climate scenario data have been adjusted to 1 x 1 km gridded data for Norway using two techniques: an ‘empirical adjustment’ method developed by the Norwegian Meteorological Institute (Engen-Skaugen, 2007) and the delta change method. The adjusted input data have been used with calibrated/validated HBV models for 115 catchments distributed throughout Norway to produce daily discharge time series. The percentage change in the 200-year flood has been estimated based on the fitting of GEV and Gumbel extreme value functions to the annual maximum of 30-year modelled daily discharge series.

1.4 Multivariate frequency analysis (e.g. storm surge, river flooding, urban flooding)

The responsible authorities for assessing risks and protecting the public from certain sources of flooding (for example, inundation resulting from extreme precipitation in urban areas) are not clearly defined within Norway. However, as NVE has responsibility for the implementation of the EU Flood Directive in Norway, methods for multivariate flood frequency analysis will likely be considered in the near future. NVE is also now considering mapping the projected sea level in 2100 with the 200-year return period alongside fluvial flood risks (NVE, 2010).

1.5 Uncertainty and risk analysis

The uncertainty of final water levels and/or flows is often considered as part of dam safety assessments and flood risk mapping studies. This is most frequently achieved by testing the sensitivity of resultant water levels/flows to changes in model parameter values. The uncertainty in projections for changes in the mean annual flood (Lawrence and Haddeland, 2011) and in the 200-year flood (Lawrence and Hisdal, 2011) have been assessed using an ensemble methodology which involves the use of several climate scenarios, HBV hydrological model parameter sets, and fits for the extreme value function. Uncertainty in the hydrological projections for 115 catchments is assessed as the difference between the 10th and 90th percentiles of the cumulative distribution of all the projections for an individual catchment (see, for example, Lawrence and Engen-Skaugen, 2010).

There are also standard tools available within the NVE's HYDRA-II datasystem which allow the user to estimate and plot uncertainty bounds on fitted extreme value functions using either resampling or maximum likelihood analyses. These tools can be applied to either historical or scenario data stored in NVE's national database (see section 2. below for further details).

2. Data

2.1 Availability and use of streamflow/precipitation data and proxy data for change detection and frequency analysis

Streamflow data and precipitation data (from individual precipitation stations or as a 1 x 1 km grid) are readily available for Norwegian catchments. Streamflow data is stored in NVEs HYDRA-II datasystem can be obtained by contacting NVE, and precipitation data for stations can be downloaded directly from http://eklima.met.no. Unfortunately, proxy data for the detection of environmental change is lacking. In some cases, comments may have been added to a flow record in HYDRA-II to describe a change that has taken place, but this most frequently concerns changes in regulation, monitoring procedures or the discharge rating curve.

2.2 Availability and use of data to assess changes in hydrological regime and river infrastructure development

Daily hydrological data, and for some catchments also data with a finer resolution (Findata*), are readily available to assess changes in the hydrological regime. Data on river infrastructure development are not documented and are thus more difficult to obtain.

*Findata is high resolution data whereby changes in the gradient of a hydrograph limb are recorded, rather than observations at set intervals.

2.3 Availability and use of climate change projections from general circulation models and regional climate models, including statistical downscaling

NVE has ongoing research into the potential impacts of climate change on various hydrological parameters (evaporation, discharge, snow water equivalent, soil moisture deficit, groundwater volume), based on HBV modelling for individual catchments and on a gridded version of HBV, as applied to the whole of Norway. Projections based on three ENSEMBLES scenarios are available (ECHAM5/DMI-HIRHAM5, HadCM3Qref/Met.no-HIRHAM and BCM/SMHI-RCA3). Two downscaling methods, the delta change method, and an empirical adjustment method (Engen-Skaugen, 2007) have been used to transfer GCM/RCM model outputs to a 1 by 1 km grid. Table 1 details the periods for which downscaled climate projections have been stored on NVE's HYDRA-II data system, which is, in principle, available to registered external users. At the moment, the climate projections are stored as 'work series', restricted to internal use only. There are additional downscaled scenarios available which have been downscaled from the ENSEMBLES project scenarios which are not stored on NVE's central database, but which could be made available to COST partners for use in collaborative research with NVE.

Table 1. Projection periods for downscaled GCM/RCM scenarios stored in HYDRA-II

GCM/RCM	**Statistical downscaling method**	
	Empirical adjustment method	**Delta Change**
ECHAM5/DMI-HIRHAM5	1951-2099	2021-2050
HadCM3Qref/Met.no-HIRHAM	1951-2050	2021-2050
BCM/SMHI-RCA3	1961-2095	2021-2050

3. Applications

3.1 Purpose and areas of application (design of hydraulic structures, dams, urban hydrology, flood-hazard mapping, etc.).

Flood frequency analyses are widely used in Norway for dam safety assessments, flood risk mapping and for the design of hydraulic structures, but the implementation of procedures for incorporating potential climate change effects are only now being considered. In particular, projects are considering climate change effects on dam safety and on flood hazard, with a focus on practical applications. (See 4. below for project details).

3.2 Merits and drawbacks of different methods

Current procedures do not consider environmental change.

3.3 Recommendations for users

With respect to climate change impacts, recommendations for including climate change impacts on flood runoff have been developed for six regions in Norway and are given in Lawrence and Hisdal (2011). Large, inland catchments in Norway are actually projected to have a decrease in flood hazard in the future due to decreased winter snow storage leading to a reduction in the peak spring runoff. Coastal, western and parts of northern Norway are projected to have an increased flood risk, due to increased autumn and winter rainfall flooding. The newly revised version of the guidelines for flood frequency estimation in Norway (NVE, 2011) recommend that design flood estimates consider the potential effect of climate change according to the guidance given in Lawrence and Hisdal (2011).

4. Case studies

Examples of practical applications

Norway is currently involved in the EU Interreg IV SAWA (Strategic Alliance for Water Management Actions; http://www.sawa-project.eu/) project, which is focusing on the implementation of the EU Flood Directive. In conjunction with this project, NVE has been involved in developing a summary of how partner countries plan to take climate change into account in flood risk management planning (Lawrence *et al*., 2012). Within this project, work on developing hydrological projections for expected changes in the 200-year flood has been undertaken for Norway (further details in sections 1.3 and 1.5 above).

NVE has also been involved in the Climate and Energy Systems (CES; http://en.vedur.is/ces) project funded by Nordic Energy Research. A comparison of methods used for dam safety analyses in Norway, Finland and Sweden was undertaken as part of this project, and this includes a comparison of projected changes in flood magnitudes in transnational catchments (Bergström, *et al*., 2012). The results indicate significant differences in the projected magnitude (and in some cases direction) of changes in the design flood, reflecting differences in 1) the local adjustment methods (e.g. bias correction *vs*. delta change) used to transfer the climate signal to the hydrological models, and 2) the methods used for estimating the design flood in the three countries.

5. Plans for future development

Plans for future development of flood frequency assessments involve adjusting final water levels/flows to account for projected climate changes (discussed above). There are currently no plans to modify flood estimates for other types of environmental changes, or to modify the analytical methods used. However, there is considerable interest in assessing, for example, the relative impacts of increased urbanisation *vs*. climate change on flood hazards in urban areas, in addition to other issues presented in sections above.

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Review of applied methods for flood-frequency analysis in a changing environment in Poland

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1. Description of methods

1.1 Detection of trends and shifts in time series of hydrological extremes (at-site and regional procedures)

Recent floods in Poland (e.g. in 1997, 2010), which caused huge damages in life and property lead to the suggestion that flooding has become more frequent and more severe on many rivers. This statement can be explained by several reasons ranging from development in high-risk areas (floodplains) through land use change in the catchment and natural and anthropogenic modifications of river systems up to climate change and shifts. Statistical analysis of changes in the magnitude and frequency of flooding and development of tools for non-stationary flood frequency analysis (NFFA) is challenging because of the limited length of most hydrologic records, insufficient documentation of river beds, engineering activities and structures in rivers and their floodplains. Another aspect is to distinguish and quantify the impact of the individual causes mentioned above on flood regime as they can operate simultaneously.

In many Polish research works (e.g. Markiewicz *et al*, 2006; Strupczewski *et al*, 2000, 2001abc, 2009, 2011; Kochanek *et al*, 2011; Kundzewicz 2010, 2011) one can find the results of temporal analysis of meteorological and hydrological extreme events and values showing increasing or decreasing trends. Some of the results indicate at-site and regional changes like altering precipitation patterns, increasing mean and extreme temperature, increasing frequency of circulation types affecting high wind speeds, shortening the time of ice phenomena on rivers, trends in annual and seasonal series of minimum discharge and of peak flows. However, the research do not cover all available stations neither the whole of the Polish territory.

In hydrological practice NFFA is rarely taken into account but the awareness of its importance is constantly growing. Non-stationarity of peak flows series affecting the results of standard FFA is tested as part of calculating design flood. The homogeneity testing procedure includes several tests both genetic and statistics (see Castellarin et al., 2012). Examination of homogeneity of maximum discharge series by means of statistical methods consist of:

- investigation of outliers with the use of the Grubbs-Beck test,
- investigation of independence of elements of series with the use of the test of series,
- investigation of stationarity of the series of maximum discharges with the use of three non-parametric tests: the Kruskal-Wallis test, the Spearman rank correlation coefficient test for trend of mean value and the Spearman rank correlation coefficient test for trend of variance.

In case of recognising non-homogeneity of the series, such series are rejected from farther processing, i.e. it cannot be used as a basis for calculating upper quantiles at a given non-exceedance probability ($Q_{max,p}$).

1.2 Non-stationary flood frequency analysis NFFA (at-site and regional procedures)

Regardless of the reasons of flood regime changes, when dealing with hydrological non-stationarity in flood frequency modelling and hydrological design, it is necessary to account for trends in upper quantile estimates. Assuming a distribution function to be time-invariant, the trends in quantiles result from time-variability of distribution parameters. For a given probability distribution function (PDF) with time dependent parameters $f(x;\boldsymbol{\theta}(t))$ one can calculate the design flow discharge with the probability of exceedance P_T during a service-life period T of a hydraulic structure and then to determine its confidence interval. In other words, taking into account risk at the accepted level one can either estimate the maximum flood (i.e. quantile $Q_{max,p}$) that the hydro-technical structure would withstand during its service life-time (T) or vice-versa, according to the estimated expected extreme floods design a construction that could resist to the flood magnitude within the assumed time-span (T).

Dealing with a set of alternative distributions in a discrimination procedure, e.g. maximum likelihood (ML) ratio, one can find that even in the stationary case, the selected PDF can vary both with time series (even addition of the current year observation can affect the choice of best-fitted model) and along a river channel, giving unexpected changes of upper quantile estimates. To adjust quantiles along a river the multi-model approach is being developed.

Usually, in the non-stationary approach, the location and scale parameters of a distribution are considered to be time-dependent. In order to unify various PDFs in terms of their parameters, it is convenient to replace the original set of parameters of each PDF by the statistical moments, so the trend in the mean and the standard deviation can be analysed and estimated. To do so, the ML method in the presence of covariates is applied. Currently, the only readily available covariate is the time index which is used to approximate the time dependence in mean and standard deviation. Note, that ML estimates of trend in statistical moments are distribution specific. For the normal distribution and the linear trend in the mean, one gets the linear regression. For trend in the both parameters of normal distribution ML-estimation becomes equivalent to Weighted Least Squares (WLS) method (Strupczewski *et al*, 2000, 2001abc).

The main interest in hydrological time series analysis under changing environment is attached to time-changes of the mean and standard deviation. Using the ML method in presence of the time covariate, the estimates of these time- changing moments depend on assumed distribution. Therefore, fitting different distributions to the time series one gets the different trend estimates, which can be confusing. To overcome this problem, the WLS method is used. It gives asymptotically unbiased time-dependent estimates of the mean and standard deviation for a wide class of three-parameter distributions with constant shape parameter. For this reason the two-stage NFFA, i.e. combined technique is applied. Using the WLS method output, the time series is made stationary and the best fitting 3-parameter distribution is selected. The *L*-moments method serves for estimation of parameters. Finally, using the time-dependent moment estimates, the estimates of time-dependent quantiles are obtained (Strupczewski *et al*, 2009).

1.3 Rainfall-runoff modelling

In Poland, rainfall-runoff modelling approaches are rarely used to design purposes. In the stationary case some attempts are made to applied Gradex method enabling estimation of annual maximum flow with T-year return period on the basis of short, 10 to 15 years, series of annual maximum river discharge and long i.e. 40 or more years of annual maximum precipitation and its modification for ungauged basins (Ozga-Zielinski, 2010)

Also Probable Maximum Precipitation (PMP) concept is taken into account. Some ongoing projects deal with its application. The future plans include research on non-stationarity of PMP and its consequences to design flow characteristics.

1.4 Multivariate frequency analysis (e.g. storm surge, river flooding, urban flooding)

Due to their complex mathematical features, multivariate methods are applied only on the assumption of series stationarity.

1.5 Uncertainty and risk analysis

The uncertainty and risk analyses have been not applied as standard procedure in hydrological practice, yet.

2. Data

2.1 Availability and use of streamflow/precipitation data and proxy data for change detection and frequency analysis

Stage and flow data are stored in the Central Historic Data Base (CHDB) in the Institute of Meteorology and Water Management. Daily data and values of instantaneous extremes according to the accepted standards of data processing are available for about 800 hydrological stations, a big part of them from 1951. Several stations with longer time series of annual maxima (starting from 1921) are also available.

Apart from runoff data, daily precipitation data in CHBD starting from 1966 for about 1000 stations are also achievable, but only few series for shorter rainfall durations.

There is no special data base for complete flood characteristics.

An agreement with the collecting institutions should be established.

2.2 Availability and use of data to assess changes in hydrological regime and river infrastructure development

This kind of data is rather difficult to access. There is no special data bases and the information is distributed among many institutions due to their responsibilities.

2.3 Availability and use of climate change projections from general circulation models and regional climate models, including statistical downscaling

In preparation for Polish territory.

3. Applications

3.1 Purpose and areas of application (design of hydraulic structures, dams, urban hydrology, flood-hazard mapping, etc.)

Non-stationary methods are not yet applied in hydrological practice.

3.2 Merits and drawbacks of different methods

The IDT (Identification of Distribution and Trend) software package (Kochanek & Strupczewski, 2010; Feluch *et al*, 2010) containing a variety of alternative distributions combined with various trend models, applied to Polish data revealed small differences of AIC values for different distribution/trend models which often lead to a great differences in time-dependent quantile estimates. The above mentioned unification of distributions in terms of parameters allowed to expose a weakness of statistical approach to trend investigation for hydrological (usually small) size of samples (the results of this research are being prepared for publication). Hence, there is much greater uncertainty than in stationary case. The question arise, whether the trends, detected in relatively short time series, would stay the same for the design period of a hydraulic structure which can be over 100 hundred years and whether it is not too risky to accept the design quantile obtained from a non-stationary approach when its magnitude is lower than those obtained by classical FFA. Two-stage NFFA is already under testing.

3.3 Recommendations for users

As the two-stage method proved to be more reliable and accurate in terms of time-dependant upper quantiles, it should be used in practical solutions rather than more complex and failure-prone ML-estimation technique. The preliminary results of comparison of these two approaches point clearly that two-stage technique produces smaller bias and mean square error of the time-dependant flood quantiles than its counterpart; its percentage of failures is much lower too. (Strupczewski *et al*, 2009; Kochanek *et al*, 2010; Feluch *et al*, 2010). See also section 5.

4. Case studies

Examples of practical applications.

The methods have not been applied in practice, yet. However, preliminary calculations on data from 38 Polish gauging stations have been carried out recently. The results are being post-processed and soon will be prepared for publication.
(e.g. Strupczewski *et al*, 2009)

5. Plans for future development

While some authors consider the GEV distribution option only, we suggest making the time series stationary by the WLS method and then selecting a proper distribution function using the L-moment technique for parameter estimation.

Annual peak flow series of Polish rivers are mixtures of summer and winter flows. Change of land cover, channel modifications, drainage works and presumably climate change can all have an impact on the flood regime which can be manifested differently for summer and winter floods, and for each gauging station. Consequently, in order to mitigate inaccuracies in results, a non-stationary flood frequency analysis (NFFA) should be carried out for each season separately and made at least on regional scale.

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Review of applied methods for flood-frequency analysis in a changing environment in Slovakia

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1. Description of methods

1.1 Detection of trends and shifts in time series of hydrological extremes (at-site and regional procedures)

Detection of trends and changes in time series of hydrological extremes is not systematically evaluated in Slovakia and no official methodology has yet been established for non-stationary flood frequency analysis. However, there are several studies on changes in annual and monthly trends. Methodologies are based on classical statistical methods for evaluating data homogeneity, identifying linear and nonlinear trends and testing trend significance, e.g. using the AnClim software (Stepanek, 2007). Trends in atmospheric precipitation in the mountainous regions in Slovakia were investigated by Faško and Šťastný (2002). Analysis of time series of annual and summer precipitation totals for the period May–September from 47 rain gauges indicates a decrease in summer precipitation in the last 3 decades. Majerčáková et al. (2004) compared the development of runoff and precipitation characteristics in Slovakia for the periods 1931–1980 and 1961–2000. In the period 1961–2000 runoff has decreased 20% in regions denominated as high sensitive and vulnerable. In Pekárová et al. (2008) a statistical analysis of changes in the maximum volumes of flood waves of the Danube River within two time periods, 1876–1940 and 1941–2005 was done.

1.2 Non-stationary flood frequency analysis (at-site and regional procedures)

Methodologies for flood frequency analysis in Slovakia are based on an assumption of stationarity. The procedures consist of at-site frequency analysis and regional frequency analysis. The regional methods involve frequency analysis based on envelope curves, which is a historically used method, and nowadays the index flood method. Also the region of influence approach was tested for application on the whole territory of Slovakia. In Slovakia, there is no systematic evaluation for considering the impact of environmental changes in flood frequency analysis.

1.3 Rainfall-runoff modelling

Conceptual and physically-based rainfall-runoff models are used for a wide range of applications, including the prediction of the effects of climate and land use changes. In studies on climate change impact on hydrological characteristics conceptual water balance models with monthly time steps were applied: the DAIR – MEHYBY, WBMOD, WatBal, KVHK, BILAN and the raster-based Turc model. For estimating impacts due to land use change physically-based models were used: Wetspa, AGNPS and Wasim. These kinds of hydrologic models have the advantage of reflecting the effects of spatially distributed model parameters such as land use on stream flows. Changes in design floods for regions in Central Slovakia due to land use changes were simulated using the WetSpa distributed hydrological model (Papánková, et al., 2005).

1.4 Multivariate frequency analysis (e.g. storm surge, river flooding, urban flooding)

Multivariate frequency analysis is not systematically applied in the approaches for flood frequency analysis in Slovakia but it is used in expert opinions and assessments; for example in joint frequency analysis of maximum discharges and volumes of flood waves by Copulas (Gaál, 2010).

1.5 Uncertainty and risk analysis

Uncertainty and risk analysis is not systematically applied in flood frequency analysis in Slovakia.

2. Data

2.1 Availability and use of streamflow/precipitation data and proxy data for change detection and frequency analysis

For flood frequency analysis and detection of changes in Slovakia annual maximum discharges and mean daily discharges from approx. 400 gauging stations are available, with record lengths of approx. from 15 to 108 years (time span covered: 1901–2008). Precipitation data is available from approx. 600 precipitation and climate stations in daily resolution and period of observation from 1951. Validation and accessibility of data: Slovak Hydrometeorological Institute. Availability of data is restricted; precipitation and flow data is free for scientific purposes only on request. For testing purposes in WG 4 a good data set for the Hron River basin (area of 1756 km^2) in Slovakia is available: daily precipitation totals (23 stations); daily air temperature, air humidity, cloudiness, wind velocity (5 climate stations), mean daily discharges (6 gauge stations) from the period 1981-2010.

2.2 Availability and use of data to assess changes in hydrological regime and river infrastructure development

For regional methods of flood frequency analysis and detection of changes in environment DEM (grid 20x20m) and land use and soil maps in digital form are available. Different climatic and physiographic catchment characteristics are derived from these layers: catchment area, length of the river network, mean catchment slope, mean stream slope, catchment shape coefficient, mean hangs orientation, mean catchment elevation, percentage of forested area, hydrogeological index, soil capacity infiltration index and time of concentration. Data on changes in river infrastructure is not systematically documented.

2.3 Availability and use of climate change projections from general circulation models and regional climate models, including statistical downscaling

Usually, three types of climate change projections have been used in previous impact studies in Slovakia: analogue scenarios based on an analogy with warmer periods and periods with a specified variability in the climate in the past (WP and SD); regionally downscaled outputs of GCM scenarios (CCCM, GISS, CGCM3.1, ECHAM and HadCM2) with typical time horizons of 2010, 2030 and 2075; and incremental climate change scenarios. Modified model input time series have usually been constructed from the baseline data by adding the differences in mean air temperature and precipitation prescribed by the scenarios for the given time step. Observed runoff series from 1931 – 1980 or 1951−1980 have usually been considered as baseline periods.

Within the CECILIA EU project (CECILIA, 2007) the ALADIN regional climate was developed for dynamical downscaling of climate change projections for the territory of Slovakia. The climate characteristics, such as precipitation totals, air temperature and relative air humidity were projected by the ALADIN climate model in daily time steps with a grid resolution of 10 km up to time horizon of 2100.

3. Applications

3.1 Purpose and areas of application (design of hydraulic structures, dams, urban hydrology, flood-hazard mapping, etc.).

In Slovakia, flood frequency analyses is applied especially for the design of hydraulic structures, assessments of dam safety, integrated river basin management and mapping of flood risk. In the current flood frequency analysis the impacts of climate and land use changes are not considered.

3.2 Merits and drawbacks of different methods

Flood frequency analysis in Slovakia is based on progressive methods for at-site and regional analysis but changes of environment are not systematically considered in these methods. There are no practical results on how extremes are changed under complex environmental changes, including climate change.

3.3 Recommendations for users

Users would consider the uncertainties of current approaches for estimating design floods which are based on an assumption of stationarity. It is required to adapt the effects of joint climate and land use change in the management of surface water resources with special emphasis on runoff extremes. In Slovakia, there are no national recommended practices or guidelines for including uncertainties due to environmental changes in design flood estimation.

4. Case studies

In Hlavčová et al. (2008) the potential impact of climate change on the mean monthly runoff in the upper Hron River basin, which was chosen as a representative mountainous region in Central Slovakia, was evaluated. A conceptual hydrological water balance model calibrated with data from the period 1971–2000 was used for modelling changes in runoff with monthly time steps. Changes in climate variables in the future were expressed by two different climate change scenarios, constructed using the pattern scaling method from the outputs of transient simulations made by 2 GCMs, ECHAM4/OPYC3 and HadCM2. The runoff scenarios for the selected basin in the future time horizons of 2025, 2050 and 2100 show changes in the runoff distribution within the year.

The potential impact of climate change on river runoff in a mountainous basin in Slovakia was evaluated using a conceptual spatially-lumped water balance model and a regional climate model (Hlavčová et al., 2010). The climate characteristics were simulated by the ALADIN climate model in daily time steps with a grid spacing of 10 km. The conceptual water balance model was calibrated in monthly time steps with data from the 1971-2000 period and validated with data from the 1961-1970 period. Based on the outputs of the ALADIN climate model, possible changes in the mean monthly runoff for the time horizons of 2021-2050 and 2071-2100 were estimated. The simulated results of the long-term mean monthly runoff indicate future changes in the seasonal runoff distribution in the mountainous basins of Slovakia.

In order to estimate possible changes in the flash flood regime in the mountainous regions of Slovakia, a simple physically-based concept for climate change induced changes in extreme short-term precipitation totals was proposed in Hlavčová et al. (2007). It utilizes regionally downscaled scenarios of the long-term monthly means of air temperature, specific air humidity and precipitation projected for Central Slovakia by three Global Circulation Models (CCCM1997, CCCM2000 and GISS1998). A simplified physically-based model for the calculation of short-term precipitation totals at changing air temperatures was proposed, which is used to drive a conceptual rainfall-runoff model. Changes in extreme mean daily discharges due to climate change were compared with original floods and discussed.

Changes in the runoff regime due to land use changes for the Hron river basin were simulated using the WetSpa distributed model (Liu and Smedt, 2004). In order to account for the flood regime changes due to land use changes in the simulated land use scenarios, a design flood analysis was undertaken (Hlavčová, et al., 2005). For each land use scenario and for the actual state design maximum mean daily discharges were calculated. The DVWK (1999) method was applied for estimation of design values of maximum mean daily discharges. The Generalised extreme value (GEV) distribution with parameter estimation using the method of probability weighted moments was the best and most applied one in the study.

5. Plans for future development

Assessment of climate and land use change feedbacks and prediction of the joint effects of climate and land use on river flow in Slovakia.

Adapting effects of joint climate and land use changes in the management of water resources with special emphasis on runoff extremes.

Using remote sensing data in hydrological modelling with the aim of improving the model's performance through an enhanced land cover representation and corresponding model modifications.

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Review of applied methods for flood-frequency analysis in a changing environment in Slovenia

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1. Description of methods

1.1 Detection of trends and shifts in time series of hydrological extremes (at-site and regional procedures)

Trends are important indicators of the temporal variability of discharges. By analysing the historical time series of discharges, the hydrological behaviour of the rivers and the assessment of the magnitude and significance of the temporal variability can be done. Deviations of characteristic discharges from the periodic averages indicate the changes in runoff regime. Global warming was recognized since the mid of 20th century. As a consequence of climate change greater differences in discharges of Slovenian rivers are seen since 1980 when the mean annual discharges are almost continuously below the average, but the flood peaks occur regularly (Figure 1). In recent years some catastrophic floods happened in different parts of the country and some of them claimed fatalities besides enormous economic damage (Kobold, 2009).

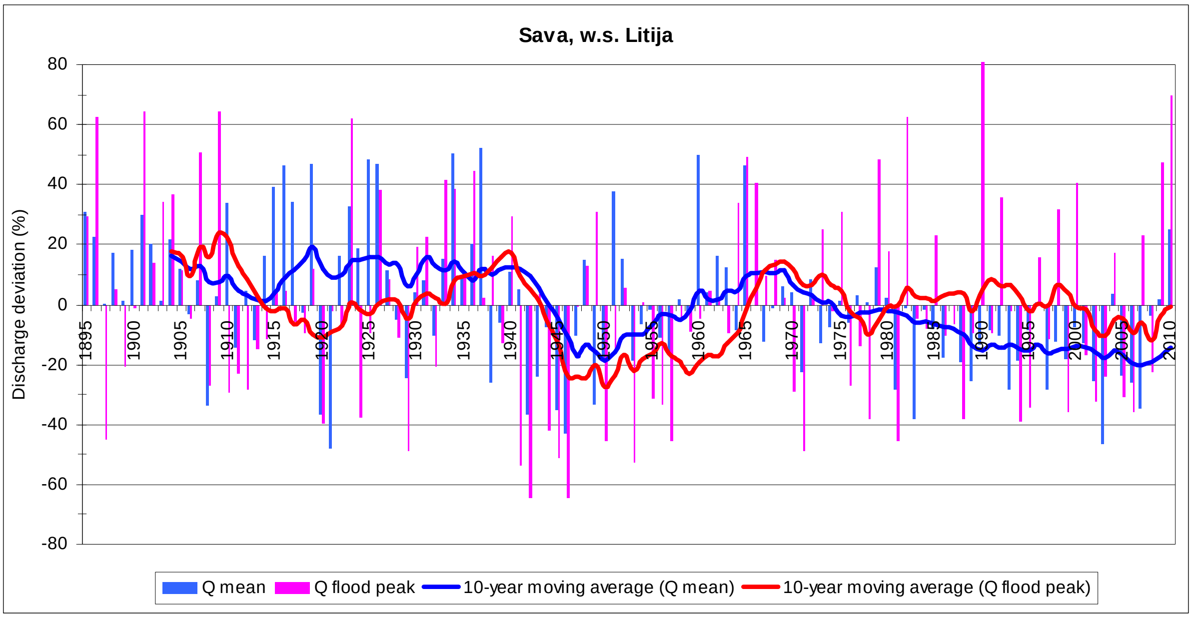

Figure 1. Relative deviation of mean annual discharges and annual flood peaks from the long-term mean values and 10-year moving averages for water station Litija on the Sava river, the longest Slovenian river.

Statistical analysis of streamflow trends for the low, mean and high discharges were examined using mean daily discharges and the Hydrospect software, which was developed under the auspices of WMO for detecting changes in hydrological data (Kundzewicz and Robson, 2000). The Mann-Kendall and linear regression tests were applied for the estimation of trends. The Mann-Kendall test is frequently applied to detect trends. It is a distribution free rank based test. Rank based tests assume that data are independent and identically distributed. They are robust and usually simple to use and less powerful than parametric approaches (Kundzewicz and Robson, 2000). Another simple test statistic for the depiction of a trend is the slope of the regression line that shows how distinct the trend is. If there is no trend, the value of the regression gradient is close to 0. If the trend is significant, the value of the regression gradient is (considerably) different from 0 - positive for an increasing trend and negative for a decreasing one. The statistical significance of discharge trends was assessed with the 90% significance level. Values above 90% were adopted as statistically significant.

More trends analyses of discharges on a limited number of water gauging stations were done from the year 2000 in Slovenia (Frantar et al., 2008). Recently, more detailed analysis was carried out for 77 water stations representatively distributed across Slovenia with sufficiently long and reliable continuous data sets (Jurko, 2009). The average length of the selected data sets was about 50 years. Different indices were used to assess the temporal variation of discharges: annual mean daily discharge, annual maximum daily discharge, two magnitude and frequency series defined by the peak-over-threshold (POT) approach (POT1 and POT3), and two low flow indices describing low flows for different durations (7 and 30 days). The clustering method was used to classify the results of trends into regional groups.

The annual mean daily discharges of the analysed water gauging stations show a significant negative trend for the majority of the stations (Figure 2). Similar results, but with lower statistical significance are found for annual minimum 7-day and 30-day mean discharges (Figure 2). For flood indices, there are generally slightly more stations showing a significant negative trend than a significant positive trend. Significant negative trends were seen for gauging stations with predominantly high-mountain and karstic catchment areas (Figure 3).

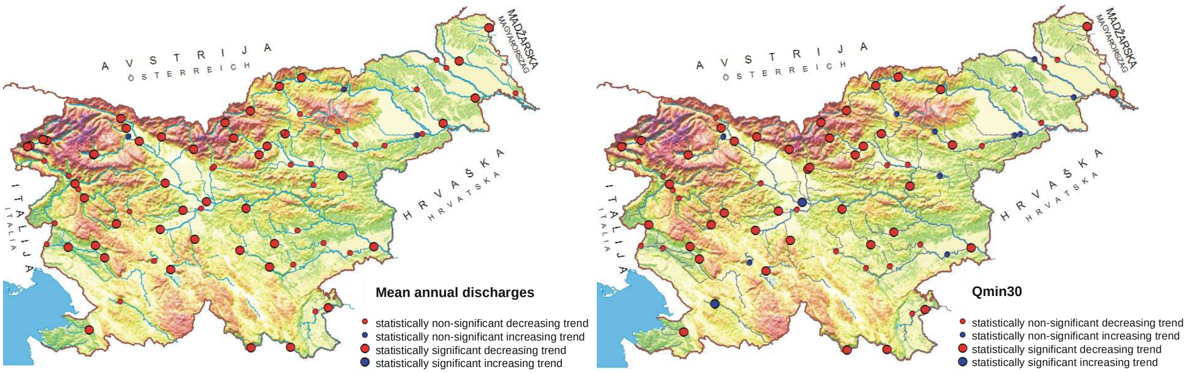

Figure 2. Trends of annual mean daily discharges and 30-day annual minimum discharges (Qmin30).

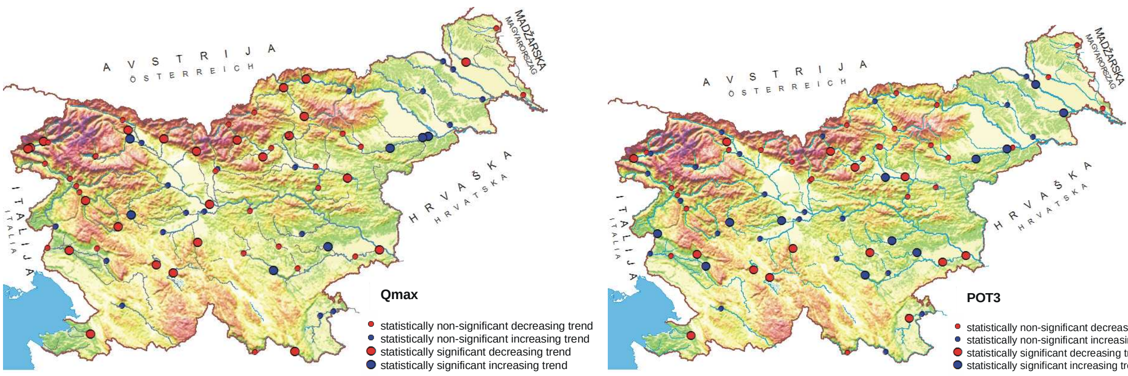

Figure 3. Trends of flood discharges considering annual maximum daily mean discharges (Qmax) and three (POT3) values per year.

The classification into groups was done representing the different stations on the principle of similarity so that the data sub-sets share a common characteristic (Jurko, 2009). On the basis of mutual distance of stations and flow behaviour five regional groups can be seen for all flow indices (Figure 4).

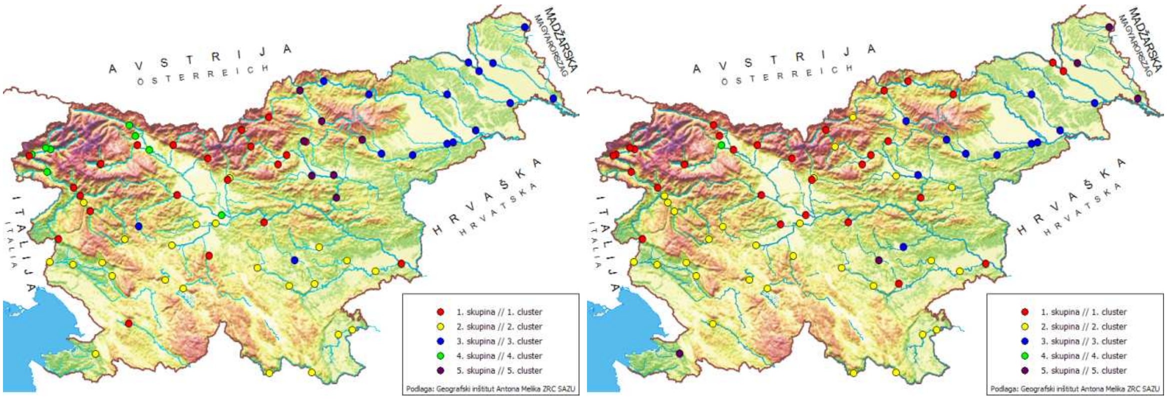

Figure 4. Clustered gauging stations for annual maximum and 30-day annual minimum discharges.

1.2 Non-stationary flood frequency analysis (at-site and regional procedures)

Non-stationary flood frequency analysis has not been carried out in Slovenia yet.

1.3 Rainfall-runoff modelling

The HEC-1 model (Feldman, 1995) and the HBV model (IHMS, 1999) were used in the studies of impact of climate change. The HEC-1 flood hydrograph package was developed by the US Army Corps of Engineers. It is designed for surface runoff simulation. It is primarily a flood hydrology analysis tool to model the rainfall-runoff process. The HBV model is a semi-distributed conceptual model for continuous calculation of runoff. It was originally developed in the 1970's at SMHI, the Swedish Meteorological and Hydrological Institute. The wide usage of the HBV model around the world has demonstrated its practicability under different physical conditions and/or climate conditions. With these models different scenarios have been performed (Kobold and Sušelj, 2005; Kobold and Brilly, 2006) using increased intensity of precipitation and rainfall amount in Slovenia as foreseen by climate projections.

1.4 Multivariate frequency analysis (e.g. storm surge, river flooding, urban flooding)

Multivariate frequency analysis is not available and it is planned for the future.

2. Data

2.1 Availability and use of streamflow/precipitation data and proxy data for change detection and frequency analysis

Trend analysis requires long records of observation to distinguish climate change-induced trends from climate variability. The problems of missing values, seasonal and other short-term fluctuations or anthropogenic impacts and lack of homogeneity of data due to changes in instruments and observation techniques are frequently present in existing hydrological data sets.

The Slovenian Environment Agency (ARSO) takes care of the national meteorological and hydrological data archive. About 170 traditional rainfall stations with 24-hour observation and 37 recording rain gauges with continuous registration are currently in operation in Slovenia. But there exists more historical data in the archives for the stations which operated during other periods. The coverage with recording rain gauges is insufficient, especially in mountainous areas where the spatial variability of the precipitation amounts is usually the highest. Precipitation and other meteorological data are available in the meteorological archive, from fixed term data to aggregated data, such as daily data, monthly data, annual data, and annual series of monthly data. Data are also accessible through the web site of the Slovenian Environment Agency (http://meteo.arso.gov.si/met/en/app/webmet/).

The active hydrological network for Slovenian rivers consists of 185 hydrological stations. There exists more historical data in the archives for the stations which operated in different periods, some of them in very short time. The data of water levels, discharges and water temperature for some stations are available in the database of the Slovenian Environment Agency. Daily data and monthly and yearly hydrological statistics are available on the web site http://www.arso.gov.si/en/water/data/. Continuous data sets of water levels and discharges are generally available for the period since 1955; however, few stations have longer sets of data. Very few stations have data sets longer than 100 years.

2.2 Availability and use of data to assess changes in hydrological regime and river infrastructure development

Precipitation and discharge data are free of charge and can be used for research purposes to assess changes in hydrological regime as well as for commercial purposes.

2.3 Availability and use of climate change projections from general circulation models and regional climate models, including statistical downscaling

The results of climate change projections from general circulation models and regional climate models are available in Slovenia. Observed and projected changes in climate as they relate to water are also given by the Intergovernmental Panel on Climate Change (IPCC). In 2008, the IPCC issued a Technical Paper on Climate Change and Water (IPCC, 2008), in which it is shown that observation records and climate projections provide abundant evidence that freshwater resources are vulnerable and have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems.

The downscaling and predictions were done for Slovenia using the projections from general circulation and regional climate models (Bergant and Kajfez-Bogataj, 2004). Predictions of climate change for Slovenia by the end of 21st century give a temperature rise of 3℃ and increase of the intensity of rainfall (Kajfez-Bogataj, 2006). This will raise the frequency of flash floods (Kobold, 2009). The largest response to intense rainfall is expected in the Alpine and hilly catchments where flood peaks can increase by 30%. In karstic areas the increase of flood peaks is predicted to 10% due to the underground reservoirs.

3. Applications

3.1 Purpose and areas of application (design of hydraulic structures, dams, urban hydrology, flood-hazard mapping, etc.).

The results of trend analyses and predictions of climate change are relevant for water management, water supply, hydropower generation and other water activities. The main message of all analyses is: we can expect more droughts and shorter and locally distributed intense rainfall periods in the future. The impact of projected climate change, that is further increase in air temperature and intensities of precipitation, will result in increased flood risk, landslides and soil erosion. But there are no clear universal trends in the water regimes of the analysed Slovenian rivers. Large differences in trends occur even in nearby catchments. Similarity in discharge fluctuation is seen in the discharge regime along the river stream. Any climate change impacts cannot be distinguished from other human impacts on water regime.

Mean annual river flows represent a water balance of catchments, and these are important for water management and water use. These are also good indicators of climate variability in the past century, if there are no significant impacts of water use for irrigation. However, increasing temperatures and decreased moisture supply require increases in irrigation for crop vitality. River flow variations depend on the precipitation and evaporation as input to the river basin system, and water storages in the basin represent a stage of the system. Variations in the input of the basin amplify the variations of river flow as output from the basin. The percentage of the variation in yearly flows is higher than the percentage of variation in precipitation, considering the same stage of the system (Kobold and Sušelj, 2005). Those variations are significant and characterise particular catchments.

Hydropower production is highly dependent upon water supply, thus large variations in flow will have significant economic impacts on energy production. Water use and water management are also highly dependent on annual variations. These impacts are stronger in areas where water use is fully developed. Variations in annual flows have large impacts on water use, water rights, and may even limit allocations for environmental protection of endangered species. Competition among consumptive use by agriculture, people and environmental needs becomes critical in periods of drought, hence long-term planning for water conservation and storage systems is needed.

Water balance of the Sava River and the Mura River were studied in detail in Brilly et al. (2011). The WatBal model for Sava River basin was calibrated for the period 1960 – 2000. Linear trends and ten year moving average were calculated for the period. There is a descending trend of discharges for the whole simulation period. The reason for the descending trend in discharges is decreasing precipitation and slightly increasing evaporation. The descending trend is not clear in all of the subcatchments. Discharge has decreased significantly in the Sava River in the past forty years. The trend is significantly lower in the past twenty years, and there are some tributaries such as the Ljubljanica River that have a steady trend of discharges in the past twenty years (Brilly et al., 2011). If the trend continues, it will have significant impacts on water supplies, hydropower generation, agriculture, and availability of potable water for municipal use. There are also significant differences on the Mura River watershed between lower and upper part. Recent years' discharges in the alpine part of the catchment has increased, and in the lower part decreased.

In order to reduce the risks from weather disasters an early warning system for dangerous hydrological events has been developed. Adaptation to climate change requires spatial and inter-sectoral coordination with adequate legal, financial and professional frameworks. In June 2009 the Government Office of climate change was established in Slovenia. Impacts of climate change vary from one region to another, thus the adaptation measures should be different. Currently, the most important measure of adaptation to climate change is informing about climate variability and climate change to improve public awareness about the consequences of climate change.

4. Case studies

According to scenarios of climate change projections which foresee an increase of the rainfall intensity (Kajfež-Bogataj, 2006) several model calculations were done for the Savinja catchment to determine the impact of precipitation increase (Kobold, 2009).

For the flood event with 100-year return period from November 1998 simulation with the HBV model was performed for a water gauging station close to the outlet of the basin (Kobold and Brilly, 2006). The increase in the intensity of rainfall of 10% causes a raise of peak discharge of the flood wave by 18%, and for an increase in rainfall intensity of 20% by 37% (Figure 5). In the case of 20% increase in rainfall the flood wave would represent the 1000-year return period of flood on the Savinja catchment. Similar results are obtained by the HEC-1 model (Kobold and Sušelj, 2005).

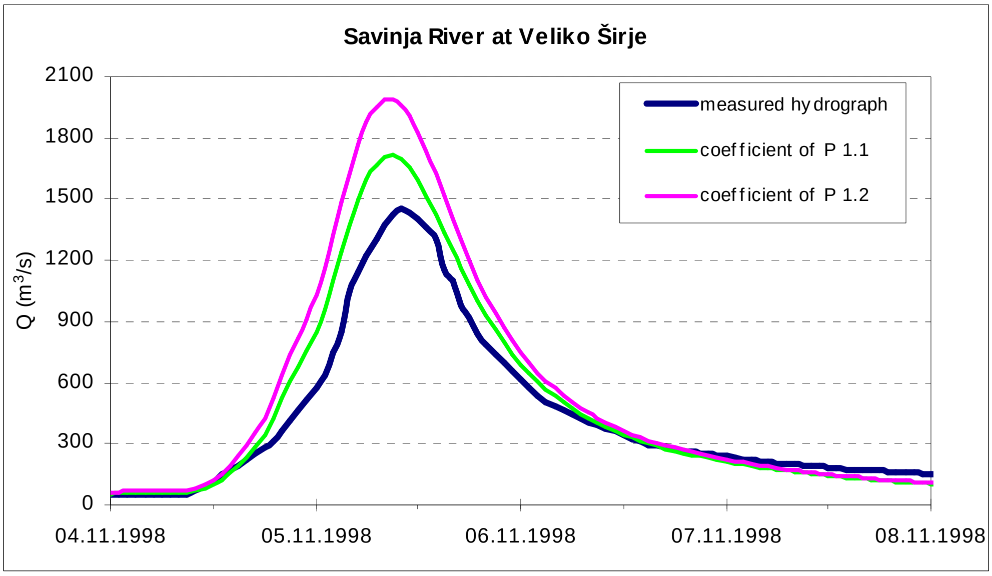

Figure 5. Modelled flood wave from the year 1998 using increased intensity of precipitation for 10% and 20%.

Areal rainfall in that flood event on the Savinja catchment amounted to 133 mm but was not the maximum event precipitation observed. The precipitation was larger (142 mm) in the flood event in October 1980, but at different initial hydrological state and smaller flood wave. In the 1990 event these rainfalls could lead to 1000-year return period of floods (Kobold, 2009). A larger intensity of rainfall on the Savinja catchment can be expected and major flooding on the Savinja catchment is therefore possible.

Also analyses of mean annual flow data for major Slovenian rivers (Sava, Drava and Mura) have been derived for the last thirty or sixty years, respectively (Brilly et al, 2011). In the last twenty years, significant trends in decreasing flows have been identified. Trends in water balance were also analysed by the WatBal model. Similar trends have been observed in other European rivers (Rhine) and US rivers (Colorado) (Brilly et al, 2011).

5. Plans for future development

In future, segmentation of streamflow time series will be done for different flow indices. Non-stationary flood frequency and multivariate frequency analyses are also planned to be carried out for Slovenian rivers.

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Review of applied methods for flood-frequency analysis in a changing environment in Spain

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1. Description of methods

Flood frequency analyses in Spain are based on Annual Maximum Discharges (AMD) series. AMD series are routinely inspected to find trends, shifts and outliers. Maximum discharge quantiles at ungauged sites are estimated by regression equations using climatic and physiographic characteristics (Stedinger and Tasker, 1985), usually the basin area, mean elevation and precipitation quantiles. Regression equations were carried out in each region for 2, 5, 10, 25, 100 and 500 years return periods.

1.1 Detection of trends and shifts in time series of hydrological extremes (at-site and regional procedures)

Trends and shifts are detected by the following techniques:

1) Firstly, a graphical analysis is carried out at a local scale by plotting the cumulative AMD (Figure 1). Shifts are detected by changes in the slope of the graphic. Shifts can be caused by changes in the location of the gauging station, construction of dams or development of irrigation areas. In these cases, the series is reduced by removing a part of the AMD series.
2) Secondly, a more robust analysis is carried out at each station by the Mann-Kendall test (Kendall, 1975).
3) The discordance measure of Hosking and Wallis (1997) is computed at a regional scale to identify stations that are grossly discordant with the group as a whole, taking advantage of the fact that incorrect trends and shifts in time series are reflected in the L-Moments of the sample.
4) Based on results of these three analyses further investigation is carried out for the stations with possible trends. It has been seen that anomalies in the tests can also be caused by outliers. Outliers are identified by the U.S. Water Resources Council method (USWRC, 1981). High outliers are removed from the AMD series and treated as historical data.

1.2 Non-stationary flood frequency analysis (at-site and regional procedures)

There are no standard methods currently applied for non-stationary flood frequency analysis. Some work has been published on long term climatic changes and their effects on flood frequency, based on paleoflood data (Benito et al., 1996, Potenciano et al, 2002, Benito et al., 2003). Results showed a clearly increasing trend over the last few centuries (Figure 2)

1.3 Rainfall-runoff modelling

To the authors' knowledge, no attempts have been made in the country to apply rainfall-runoff modelling to assess changes in flood frequency under a changing environment.

1.4 Multivariate frequency analysis (e.g. storm surge, river flooding, urban flooding)

To the authors' knowledge, no attempts have been made in the country to apply multivariate frequency analysis to assess changes in flood frequency under a changing environment.

1.5 Uncertainty and risk analysis

Sampling uncertainty of the quantile estimate by the probability-weighted-moment (PWM) method and the regional estimate of the shape parameter are assessed. Gumbel and GEV estimation uncertainty is quantified by the expressions given by Lu and Stedinger (1992). Expressions for the TCEV are currently being studied. Uncertainty of quantile estimation at ungauged sites is quantified by the residual variance of the regression equations.

2. Data

2.1 Availability and use of streamflow/precipitation data and proxy data for change detection and frequency analysis

Streamflow data used for flood frequency analysis are AMD series recorded at flow gauging stations. Discharge data for all gauging stations in the entire country (around 900 stations) are available at http://hercules.cedex.es/anuarioaforos/default.asp. The length of the series ranges from 25 to 80 yr. Some stations have daily mean flow series that are transformed to peak discharges by the formulae in Fill and Steiner (2003). Precipitation data for all rain gauges in the entire country (around 9000 stations) are available at the Spanish Agency for Meteorology (AEMET), but there is a fee for data distribution. Most stations were established between 1950 and 1980, and thus the length of the series ranges from 30 to 60 yr. Daily data for a reduced number of stations (113) is available free of charge at ftp://ftpdatos.aemet.es/series_climatologicas/valores_diarios/estacion/. The use of precipitation data for flood frequency analysis through continuous simulation is prescribed by the River Basin Administrations for large basins, but the methodology generally applied is weak and lacks calibration due to the alteration of streamflow data. Proper use of the methodology is currently limited to some universities and research institutions.

2.2 Availability and use of data to assess changes in hydrological regime and river infrastructure development

Most gauging stations in Spain are located downstream of important hydraulic infrastructure which has altered natural hydrologic regime through regulation and abstractions. Data on Spanish dams can be accessed through the ICOLD World Register of Dams, available for purchase at: http://www.icold-cigb.net/GB/World_register/world_register.asp. This database includes basic dam and reservoir characteristics, purpose and date of construction. The Spanish Ministry for the Environment, Rural and Marine Affairs maintains a Water Information System, which includes data on hydraulic infrastructure and water uses. It is available at:
http://servicios2.marm.es/sia/visualizacion/lda/socioeconomico/infraestructuras_presas.jsp.
Despite this abundance of data, little work has been carried out to characterize the alteration of peak flows produced by hydraulic infrastructure. Some attempts have been made at estimating the alteration of flood frequency curves produced by dams in a simplified way by (Sordo 2010).

2.3 Availability and use of climate change projections from general circulation models and regional climate models, including statistical downscaling

The Spanish Meteorological Agency (AEMET, 2008) produced regionalized climate change scenarios for Spain using a combination of techniques (regional models from the PRUDENCE project and several statistical downscaling techniques), mostly focused on precipitation and temperature. These results are fully available to all interested users at http://www.aemet.es/es/elclima/cambio_climat/escenarios. The University of Cantabria maintains a web portal to provide access to statistical downscaling techniques which produce output in simple format of a reduced number of variables, including precipitation. It can be accessed at: https://www.meteo.unican.es/downscaling/ensembles. The CEDEX is currently undertaking research to characterize impacts of climate change on water resources based on the AEMET scenarios. The work, which is not yet published, has a chapter on hydrologic extremes, which is mostly focused on changes in daily precipitation maxima and drought occurrence. Changes in the frequency curve of daily precipitation maxima have been analyzed for several Spanish regions, finding mixed results. See, for instance, Figure 3, taken from the PhD thesis of Barranco (2011). No specific study on the impact on discharge maxima has yet been undertaken.

3. Applications

3.1 Purpose and areas of application (design of hydraulic structures, dams, urban hydrology, flood-hazard mapping, etc.).

A methodology has been applied for the development of peak flow maps (Jimenez-Alvarez and Mediero, 2009; Garcia-Montañes et al., 2008), which are a series of raster maps for different return periods (2, 5, 10, 25, 100 and 500 years) that give the instantaneous peak flows in each cell of the river network of Spain for basin areas greater than 50 km^2 (Figure 4). For smaller basins, a software tool based on a modification of the rational method is supplied, but its parameters must be defined by the user.

3.2 Merits and drawbacks of different methods

The peak flow mapping methodology has been a breakthrough in the hydrological field in Spain, as it is the first attempt to develop a general method to estimate the quantiles of the peak flow frequency distribution at a regional scale. This analysis over all AMD series recorded in Spain will make further improvements and studies easier. The peak flow mapping is very recent and drawbacks will be known in the future.

4. Case studies

To the authors' knowledge, there are no case studies reported in the literature focusing on changes in flood frequency under a changing environment in Spain.

5. Plans for further development

The CEDEX is currently working on the institutional evaluation of climate change impacts on water resources for Spain, based on regionalised climate change scenarios provided by AEMET. The results obtained so far are not conclusive regarding the impact of climate change on annual maxima of daily precipitation, and therefore an institutional focus on research in this area cannot be anticipated. The authors are planning to undertake a project on the estimation of flood frequency curves from stochastic rainfall simulation and rainfall-runoff modelling, focused on the evaluation of hydrologic dam safety. It is anticipated that, within this framework, a methodology to evaluate the effect of upstream reservoirs on flood frequency curves can be developed and tested.

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Figures

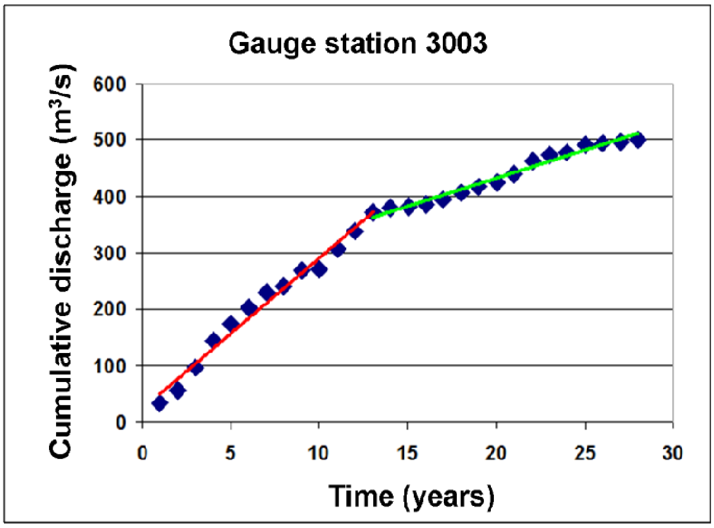

Figure 1. Graphical plot to identify shifts in AMD series

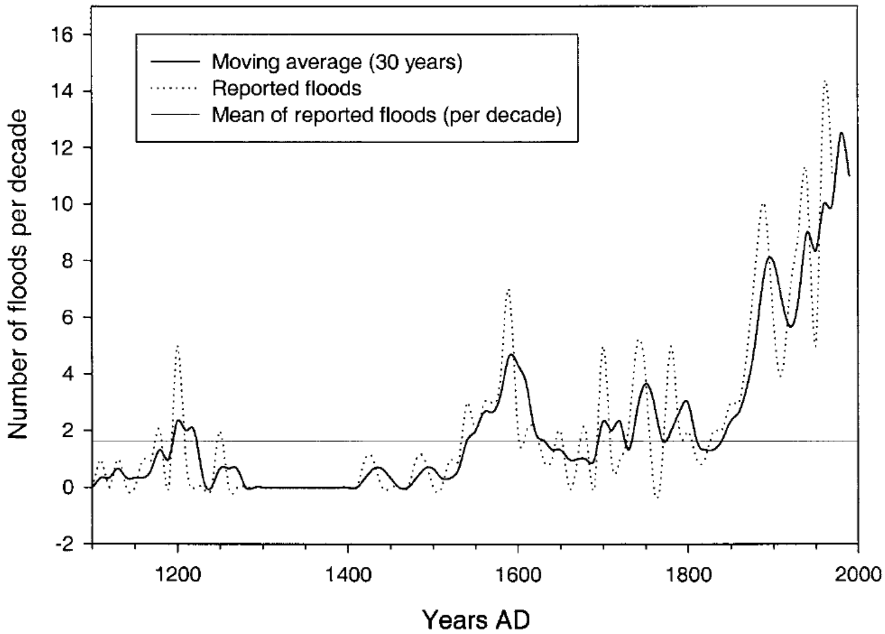

Figure 2. Distribution of the reported number of floods per decade and moving average analysis. Taken from Benito et al., 2003

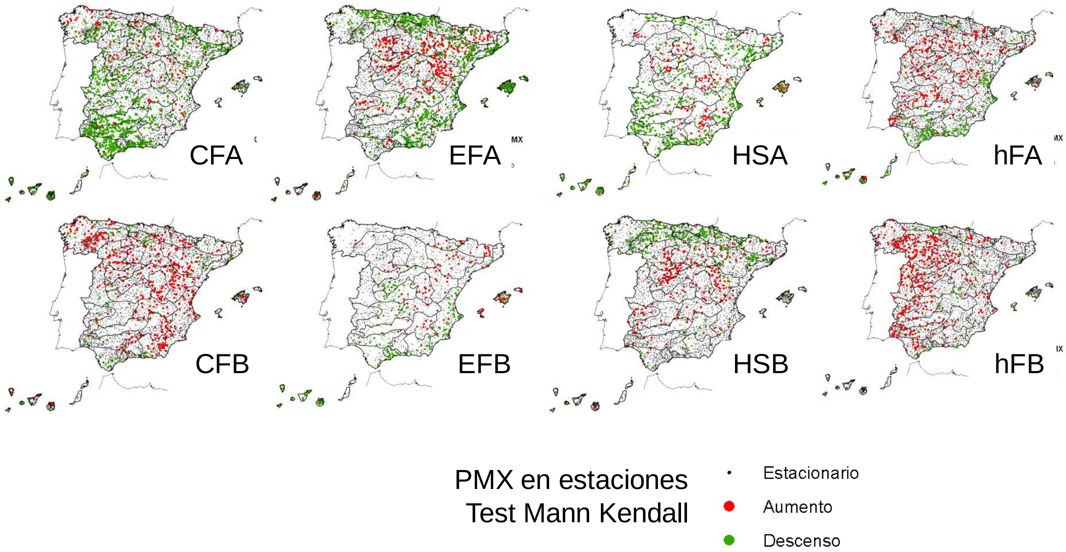

Figure 3. Trend detection in statistically-downscaled series of daily precipitation maxima for different climate projections. Red dots correspond to increasing trend and green dots correspond to decreasing trend. Taken from Barranco (2011).

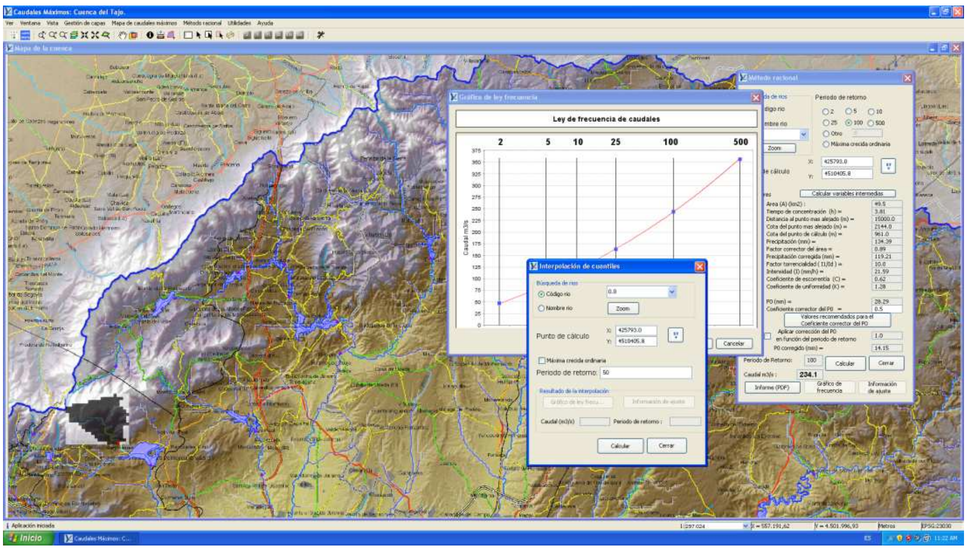

Figure 4. Capture of the peak flow mapping in the Tagus basin.

Review of applied methods for urban flood-frequency analysis in a changing environment in Sweden

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1. Description of methods

1.1 Detection of trends and shifts in time series of hydrological extremes (at-site and regional procedures)

Hernebring (2006) compiled extreme rain data from 15 Swedish municipalities and compared with existing IDF statistics derived from older data. The rain intensities in Gothenburg for the period 1973-2004 were about 95% of those published for the years 1926-1971. The last 20 years in Stockholm show essentially the same rain statistics as the older IDF curves (1907-1946), for the 5-year and 10 year events. In Malmö, the older curves (1928-1952) were in accordance with data from the project (1980-2004) for short rain durations (5-15 minutes), however, for longer rain durations there were higher rainfall intensities, about 15-20 % greater for the 1-year and 2-year storms respectively, in the recent data.

Hernebring (2008) analysed data from the rain gauge station Barlastplatsen in Gothenburg for the period 1926-2007. Compared to the period as a whole, and if the series is processed in fractions of about 20 years, the statistical result will vary a good deal. For the 1-year event the uncertainty is shown to vary within ±15%. For more rare events, i.e. 10 years, the uncertainty of the estimate increases to ±25%.

Hernebring and Salomonsson (2009) concluded that the extreme rain statistics of rain data from the West coast of Sweden was poorly correlated to yearly precipitation volumes.

Dahlström (2006, 2010) observed a strong reduction in the summer rainfall during the period 1971–2000 as compared with the period 1931–1960 in southern Sweden. The reduction is strongest in the western part of the south half of Sweden. The regional IDF model, developed by Dahlström 1979 (based on the period 1931–1960) had to be revised, which resulted in a single Swedish IDF-model (2006, and revised 2010). SWWA (2011) has adopted this (Dahlström, 2010) as one national intensity-duration-frequency (IDF) equation, if nothing else is known.

Bengtsson and Milotti (2008) and Bengtsson (2011) have analysed daily and short-term rainfall observations from southern Sweden by extreme value distribution fitting and linear trend analysis. In terms of daily maxima, no trend was found over the last 90 years. The short-term series extend over 25 years or less which was generally found too short for credible trend analysis. Some indications of increasing 10-min intensities were found in Malmö.

Concerning streamflow and water availability, linear trend analyses have been performed using data since the 1860s (Hellström and Lindström, 2008). Both the magnitude and frequency of high flows were found relatively stable.

1.2 Rainfall-runoff modelling

For urban applications, modelling typically combines a simple conceptual rainfall-runoff model with a hydraulic model of the sewer system, i.e. MOUSE and MIKE Urban, which have been used in several climate change impact studies (see Section 4). To take future climate changes into account, guidelines exist on the use of a climate factor for multiplication of design rainfalls (see Section 3).

For larger predominantly rural catchments the HBV model (Bergström, 1976; Lindström et al., 1997) is commonly used. Several climate change impact studies have been performed, often focusing on the large rivers and lakes and relevant for many cities affected by high flows and water levels (e.g. Andréasson et al., 2004; Olsson et al., 2011). The new HYPE model (Lindström et al., 2010) is being set up with a high spatial resolution (Sweden divided into ~40 000 sub-catchments) and is to be applied in climate change impact studies during 2012.

2. Data

2.1 Availability and use of streamflow/precipitation data and proxy data for change detection and frequency analysis

The Swedish Meteorological and Hydrological Institute (SMHI) manages the national observation network containing data from both meteorological (~230) and hydrological (~120) stations. The lengths of available time series vary with the longest series being 100 year or more. Some 120 stations observe rainfall with a 15-min time step since 1995. Further, short-term rain data are collected within municipalities, or sewerage organisations. The availability of data within or outside the organisations varies.

2.2 Availability and use of climate change projections from general circulation models and regional climate models, including statistical downscaling

The Rossby Centre at SMHI is one of the leading institutes for regional climate modelling. The RCA model (Kjellström et al., 2005) has been used to dynamically downscale a large ensemble of global projections, mainly over Europe, to spatial resolutions down to 6.25 km. Method development for further downscaling to urban scales is ongoing, using Delta Change approaches (e.g. Olsson et al., 2009) or more process-based approaches (e.g. Olsson et al., 2012b)

Further, many studies on climate change in Sweden have used regional climate model data from the PRUDENCE (http://prudence.dmi.dk/) and ENSEMBLES (http://ensemblesrt3.dmi.dk/) data archives.

3. Applications

Frequency analysis methods are most widely used in the design and analysis of urban drainage systems. The interaction between rainfall over urban areas, moisture conditions in upstream rural catchments, and, in coastal areas, sea water levels has gained increasing interest for more accurate assessment of flood risk in the light of climate change and current observed increases in both pluvial floods and floods caused by storm surges.

For the design and analysis of urban drainage systems, guidelines exist for use of a climate factor to multiply design rainfalls with 1.05 – 1.3 depending on the actual region. (SWWA, 2011)

4. Case studies

There are several case studies carried out based on climate scenario projections focusing on specifically urban hydrology. The scope is flooding, CSOs, inflow to wastewater treatment plants etc. Key studies have been performed for the cities of Helsingborg (Semadeni-Davies et al., 2008), Kalmar (Olsson et al., 2009), Stockholm (Olsson et al., 2010) and Arvika (Olsson et al., 2012a).

5. Plans for future development

A number of research issues related to frequency and risk analysis under climate change are presently being addressed:

- Evaluation of high-resolution RCM projections.
- Development of procedures for statistical downscaling and quantifying uncertainties in projected climate extremes.

- A project based on the collection of historical European IDF data with the purpose to project them into (future) Swedish conditions.
- EU-project SUDPLAN (*Sustainable Urban Development Planner for Climate Change Adaptation*) aiming at developing an urban Climate Service providing downscaled input for local climate change impact assessment.

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Review of applied methods for flood-frequency analysis in a changing environment in Turkey

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1. Description of methods

1.1 Detection of trends and shifts in time series of hydrological extremes (at-site and regional procedures)

In this section a review of the studies to date, on historical trends of precipitation and streamflow data in Turkey are presented.

Precipitation:

The studies that focus on long-term changes in Turkish precipitation generally agree on a decreasing trend (Partal and Kahya, 2006; Turkes, 1996; Turkes et al., 2009), but regional and seasonal differences exist (Figure 1). Many studies reported general decreasing precipitation trend over western (Dalfes et al., 2007; Toker, 2011; Partal and Kahya, 2006; Tayanc et al., 2009; Turkes, 1996; Turkes et al., 2009) and southern (Partal and Kahya, 2006; Turkes, 1996; Turkes et al., 2009) parts of Turkey that are dominated by the Mediterranean climate. In contrast, in northern regions and northern parts of Central Anatolia precipitation trend have been increasing (Dalfes et al., 2007; Yilmaz et al., 2010; Turkes, 1996; Turkes et al., 2009). In terms of seasonal changes, a decrease in winter precipitation over Turkey (Aksoy et al., 2008; Tayanc et al., 2009; Partal and Kahya, 2006; Turkes, 1996; Turkes et al., 2009) has been reported, which is more dominant in the western and southwestern parts (Dalfes et al., 2007; Turkes, 1996; Turkes et al., 2009). The winter precipitation is especially important for Tigris–Euphrates (TE) River flows which are mainly fed by snow melt. A decrease in the amount of snow and an increase in temperature will likely have negative consequences for energy and irrigation projects along the TE river system, in addition to the potential conflicts with the downstream countries. In spring and fall, an increase in precipitation has been generally reported throughout the country (Tayanc et al., 2009; Turkes, 1996; Turkes et al., 2009). In the northwest (European) part of Turkey, no coherent behaviour in long term precipitation trends have been reported. Focusing on the European part, Aksoy et al. (2008) reported insignificant trends at seasonal scale: a decreasing trend in winter and an increasing trend in fall. Precipitation data used in trend analysis are seasonal and annual average values.

Streamflow:

Most consistent pattern is the decreasing behaviour in streamflow in western parts (Marmara and Aegean) (Aksoy et al., 2008; Kahya and Kalayci, 2004; Dalfes et al., 2007; Topaloglu and Irvem, 2007; Yenigun et al., 2008; Yildiz and Sarac, 2008; Sensoy et al., 2008; Topaloglu, 2006). Similar behaviour has also been reported for Central Anatolia and southern parts (Kahya and Kalayci, 2004; Topaloglu, 2006; Yildiz and Sarac, 2008). In other regions of Turkey no consistent trend has been reported, except a few stations with increasing streamflow trend in the north (Dalfes et al., 2007; Yildiz and Sarac, 2008). You can see these trends in Figure 2. Few studies (Kahya and Kalayci, 2004; Yenigun et al., 2008) have reported significant decrease in low flow conditions for many stations in eastern Turkey. In the Upper Euphrates basin, insignificant decreasing trend in annual average runoff (Figure 3) and slight earlier melting of snow for the period 1994–2004 was detected (Yilmaz et al., 2010). Seasonal and annual average streamflow data are used in trend analysis.

Apart from the most assessments on average runoff conditions and few on low flows, regional studies that employ regional procedures to provide spatially broader assessments on flood extremes do not widely exist in Turkey. Most studies focused on case-studies and used at-site procedures for the local assessments of their specific interest. As an example of at-site assessments, the ARTEMIS (Assessment of Flood Frequency Estimation Procedures under Environmental Changes) Project (Artemis, 2010), supported under the COST program with relevance to the FloodFreq Action, focuses on two case-studies (Seyhan and Iyidere catchments) for assessing the uses of varying flood frequency estimation techniques and their competencies in estimating relevant impacts of environmental changes. The Seyhan Basin is located in southern Turkey, and the Iyidere Basin is in the Black Sea region and forms part of the Eastern Black Sea River Basin System. Following the selection of case-studies based on a typological characterization of catchment units, the project included a series of analyses conducted for the detection of trends/shifts in records of time-series obtained from the selected gauging stations in the two case-studies. Outlier detection and homogeneity tests were first performed in this respect prior to any attempt to search for the existence of any trend/shift in the investigation dataset. Potential existence of outliers was tested with the use of a number of different test methods including Chauvenet's method (applied on original and log-transformed data), Rosner test (applied on original and log-transformed data) and Pearson Type III test (applied on original data with significance levels of 0.05 and 0.10). Outlier detection was then followed by a homogeneity test based on the Runs test approach and observed that all sets of the data used in analyses are homogeneous. Autocorrelation tests performed by using the Pearson test method indicated the existence of autocorrelation (lagged correlation or serial correlation) only in the dataset obtained for the EIE1801 station in Seyhan River Basin for the period 1936-2006. As part of exploratory data analyses, trend analyses were finally implemented through the t-test, Mann-Kendal and Spearman Rho methods. The results indicated that all three methods, applied on the yearly maximum runoff series at 0.95 confidence level, point at decrease trends in the period 1969-2009 for the EIE1822 station in Seyhan and in the period 1965-2005 for the EIE2215 station in Iyidere River Basin (Figures 4-a and 5-a).

1.2 Non-stationary flood frequency analysis (at-site and regional procedures)

Implementation of non-stationary flood frequency analyses is still not very well covered by the research studies in Turkey. The only example can be given from the ARTEMIS project, where non-stationary flood frequency analyses will be performed through at-site procedures implemented only on the data from the two gauging stations with decreasing trend patterns (i.e. EIE1822 station in Seyhan and EIE2215 station in Iyidere River Basins). The GEV-CDN model, which works on the R-software platform and is a statistical model developed for use in frequency analysis of non-stationary hydrological or climatological time series, was selected for use in the project to this end (Alex and Cannon, 2010). The analyses will have been completed in the fourth quarter of the project duration and results will only be available after the project completion.

1.3 Rainfall-runoff modelling

Despite the comprehensive knowledge and relative experience on modelling approaches and available tools, the studies by the research communities in Turkey that properly benefit from rainfall-runoff modelling capabilities are rather limited. Research efforts in recent years mostly concentrated on sub-regional assessments and remained in the context of testing the modelling capacities and developing frameworks based on different data uses and the use of alternative methodologies. Data insufficiencies, quality and precision problems seem to have led to the limited use, especially when combined with exhaustive data needs required by the new generation models. This is why national/international projects like the TEFER (Turkey Emergency Flood and Earthquake Recovery) project have been initiated for the review and re-design of the hydrometric and flood forecasting networks (including site evaluations, equipment recommendations and systems for data collection and dissemination) in Turkey.

Nonetheless, it is still possible to mention herein about some references that demonstrate different practices of rainfall-runoff modelling in Turkey. For example, Albek et al. (2004) used the mathematical modelling program called Hydrological Simulation Program—fortran (HSPF), developed by the United States Environmental Protection Agency (EPA), for the hydrological modelling of the Middle Seydi Suyu Watershed located to the northwest of Central Anatolia in Turkey. In an international congress on river basin management held in Turkey, Keskin et al. (2007) and Yener et al. (2007) presented applications of hydrologic modelling performed for the Yuvacik Dam Catchment which is roughly located in the eastern part of Marmara Region of Turkey. In the same congress, Cığızoğlu et al. (2004, 2007) presented a study that combined three neural network methods, feed forward back propagation (FFBP), radial basis function (RBF) and generalized regression neural network (GRNN), into rainfall-runoff modelling of Turkish hydrometeorologic data. In the study, the daily rainfall and daily mean flow data were coupled to form the basis of rainfall-flow modelling using different ANN configurations. Usul and Turan (2006) used the MIKE by DHI MIKE 11 model for modelling floods and computing their depths in a study performed within the Ulus river basin in the Western BlackSea region. Apart from these, a new EC FP7 project called FLOODSAT was launched in 2011 by a research team at the Middle East Technical University in Ankara, Turkey, with the primary goal of “advancing the utility of satellite-based rainfall estimates for hydrologic modelling, specifically for flood monitoring”, focusing firstly on the case-study of the Western Black Sea basin Toker (2011). Yucel and Keskin (2011) used the Hydrologic Modeling System (HEC-HMS) to simulate the catastrophic flood event that occurred in Sep 8-9 in 2009 in the Ayamama Basin of Istanbul, Turkey using rainfall forcing data from gauges, radar, satellite, and numerical weather predictions.

In the ARTEMIS project, a specific practice of rainfall-runoff modelling is performed for flood assessments by running the HEC-HMS model for two case-studies, Seyhan and Iyidere basins (Figures 4-b and 5-b). In the study, the precipitation data of the DMI (Turkish State Meteorological Services) and the streamflow data provided by the EIE (Electrical Works and Survey Administration) of Turkey are assessed together to acquire the user-specified unit hydrographs that will be used for rainfall/runoff transformation in the hydrologic modelling phase. Daily precipitation data was also collected from the APHRODITE project database (2006) which provides state-of-the-art daily precipitation datasets with high-resolution grids for Asia, and where the datasets are created primarily with data obtained from a rain-gauge-observation network. This gridded precipitation data was used in transferring precipitation records from the DMI stations onto the case-study basins in a distributed way.

1.4 Multivariate frequency analysis (e.g. storm surge, river flooding, urban flooding)

In the context of performance analysis for structural flood control measures, Onuşluel Gül et al. (2010) performed a study in the Bostanli river basin located in the highlands of the metropolitan city Izmir. The study covered hydrologic simulations with the HEC-HMS model followed by hydraulic simulations with the HEC-RAS system. The results indicated inefficient capacities of flood control measures (dam, river restoration, etc.) which were already built or officially planned to protect the Bostanli District in Izmir from the adverse impacts of flooding.

1.5 Uncertainty and risk analysis

Uncertainty and risk analysis constitutes one of the work packages in the ARTEMIS project, and it will be performed after the completion of the work packages on hydrologic modelling and hydrologic impact assessments due to environmental changes.

2. Data

2.1 Availability and use of streamflow/precipitation data and proxy data for change detection and frequency analysis

The spatial database of State Hydraulic Works (DSI) of Turkey from 26 basins indicates that there are a total of 2495 historical streamflow stations with daily data and varying periods of record. 1206 of these stations are currently active and approximately 50 provides real-time data reports.

Streamflow records are also available from the hydrometeorology division of EIE (previously Electrical Works and Survey Administration operating under the Ministry of Energy and Natural Resources; as of 02.Nov.2011, General Directorate of Renewable Energy) for the 26 basins, but corresponding to a different set of monitoring stations. The hydrometeorology division of EIE is now being operated by DSI, so all streamflow data can be operated and managed by DSI. Detailed information about the monitoring stations operated by the EIE in major river basin systems in Turkey can be accessed from the web sources *(in Turkish)*:

http://www.eie.gov.tr/turkce/YEK/HES/hidroloji/gozlemist.html

There are 424 operational meteorological stations that provide at least daily real-time precipitation reporting in the Turkish State Meteorological Office (DMI). Comments may have been added to a data record to describe a change that has taken place, such as changes in regulation, monitoring procedures or the discharge rating curve.

2.2 Availability and use of data to assess changes in hydrological regime and river infrastructure development

Daily precipitation and streamflow and water level data are readily available to assess changes in the hydrological regime. Data on river infrastructure development are also available with a special request from DSI.

2.3 Availability and use of climate change projections from general circulation models and regional climate models, including statistical downscaling

The studies focused on climate predictions over Turkey utilized the dynamical downscaling methods, in which regional climate models (RCMs) are nested within a Global circulation Model (GCM). GCMs provide information on the response of the atmosphere to different scenarios of global GHG emissions. Among the standard GHG emission scenarios defined by IPCC, A2 and B2 scenarios are the most commonly used by the climate change studies focusing on Turkey.

3. Applications

3.1 Purpose and areas of application (design of hydraulic structures, dams, urban hydrology, flood-hazard mapping, etc.).

The trans-boundary Tigris-Euphrates (TE) River system located in eastern Turkey is fed by seasonal snowmelt and is critical for a series of socio-economic development projects in the irrigation and energy production sectors. The potential impact of climate change on the Seyhan River Basin is also investigated.

The ARTEMIS project aimed at assessing and comparing a series of statistical methods and modeling tools, which are used mainly for flood frequency estimation, under different climatologic and geographic conditions and with different levels of data availability in Turkey. A scientific framework for assessing the ability of these methods to predict the impact of environmental change on future flood frequency characteristics is developed and tested. Analyses on flood frequency estimations and about the comparative use of available techniques are performed in the upper catchments of the Seyhan Basin as well as the Iyidere Basin. These two case-studies are highly critical in terms of flood occurrence and the level of socio-economic damages/vulnerabilities recorded from past flood events.

3.2 Merits and drawbacks of different methods

Problems associated to the availability, precision and quality of hydrometric data and the lack of spatial data sets that are properly enhanced and validated for local/regional/national studies are among the major drawbacks faced in hydrologic simaulations.

3.3 Recommendations for users

Global warming will likely worsen already existing water scarcity and water allocation problems in Turkey, especially in the western and southern regions. To better assess the evolving impacts of global warming on – both quality and quantity of – water resources, basin-scale impact assessment studies that utilize coupled land surface and regional climate model outputs are needed together with a method for quantification of the prediction uncertainty. Studies that help to understand isolated influences of human impacts and natural weather patterns (and their interaction) on the observed climatic change are also needed.

4. Case studies

Examples of practical applications

A few studies utilized RCMs to investigate the potential role of global warming on the future climate of Turkey. Among others, Onol and Semazzi (2009) and Dalfes et al. (2007) used the regional climate model RegCM3 (30 km horizontal resolution) forced by the general circulation model NASA-fvGCM to simulate the future climate change projections (2071–2100) over the Eastern Mediterranean (EM) based on A2 emission scenario. Their projections have shown general warming over EM (2–8℃). Over Turkey, the increase in summer temperatures is predicted to be more pronounced (5–7℃) in western Turkey with a prolonged summer season, whereas the increase in winter temperatures is predicted to be more pronounced in the eastern parts. Their simulations predicted a significant increase (10–50%) in winter precipitation along the east coast of the Black Sea, whereas significant decrease (30%) in winter precipitation was predicted across western and southern Turkey. Note that these predictions are in line with the past observed trends.

Fujihara et al. (2008) dynamically downscaled the hydrometeorologic variables to 8.3 km using the TERC-RAMS regional model forced by two GCMs utilizing the A2 emission scenario over the Seyhan River Basin. The RCM output was also used to drive a hydrology model after bias correction. They concluded that the Seyhan Basin will be significantly impacted by 2070s, with the drastic decrease in annual runoff (52–61%) due to an increase in temperature (2.0–2.7℃) and a decrease in precip itation (25–29%). They, however, concluded that water scarcity will not be an issue in the future, given that the water demand stays constant.

Ozkul (2009) also investigated the impact of these changes on runoff using a simple downscaling method (alpha method) and a simple monthly water balance model. The runoff predictions indicated that, by the years 2030, 2050 and 2100, the surface waters in the basin will be reduced by 20%, 35% and 50% respectively.

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Selected Figures:

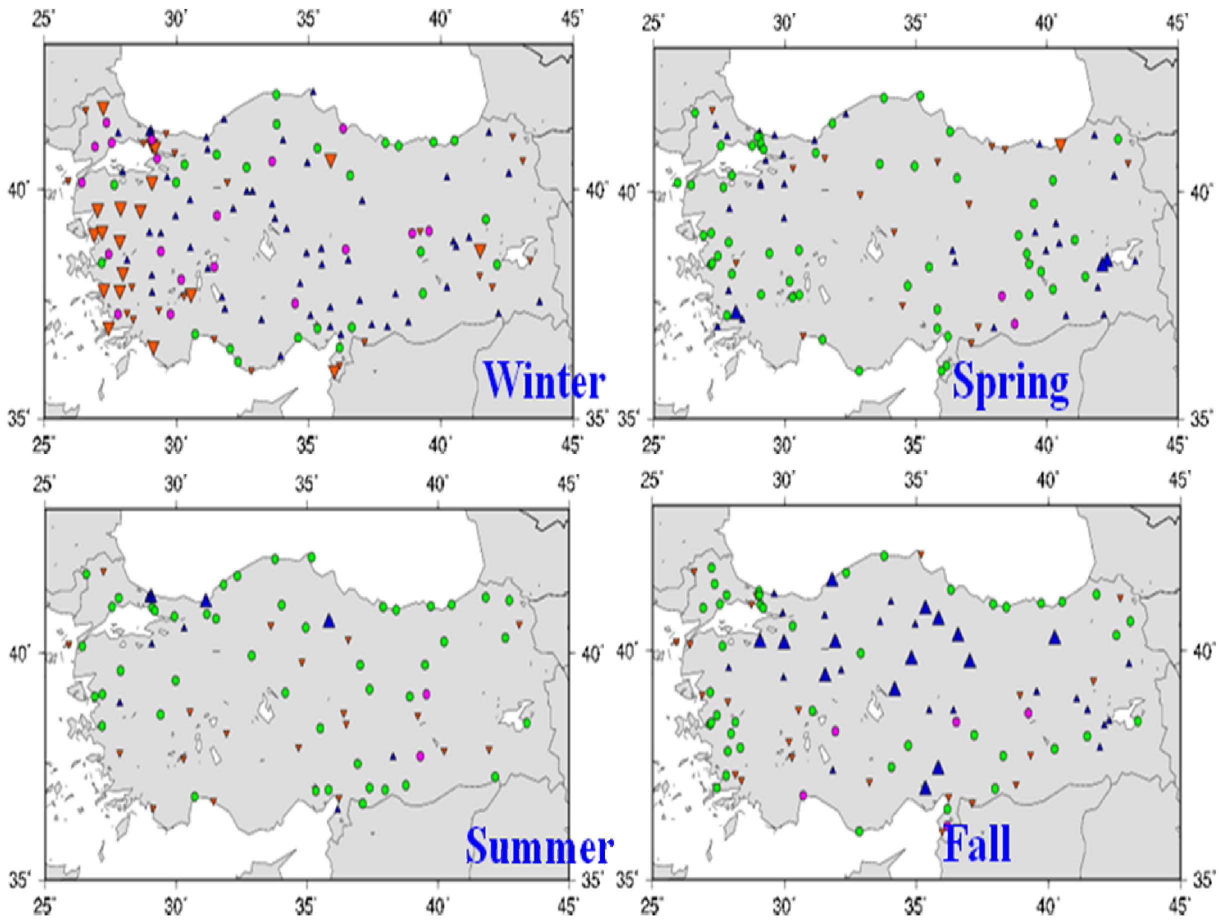

Figure 1. Observed trends in seasonal precipitation across Turkey calculated using the Mann Kendall Trend Test.

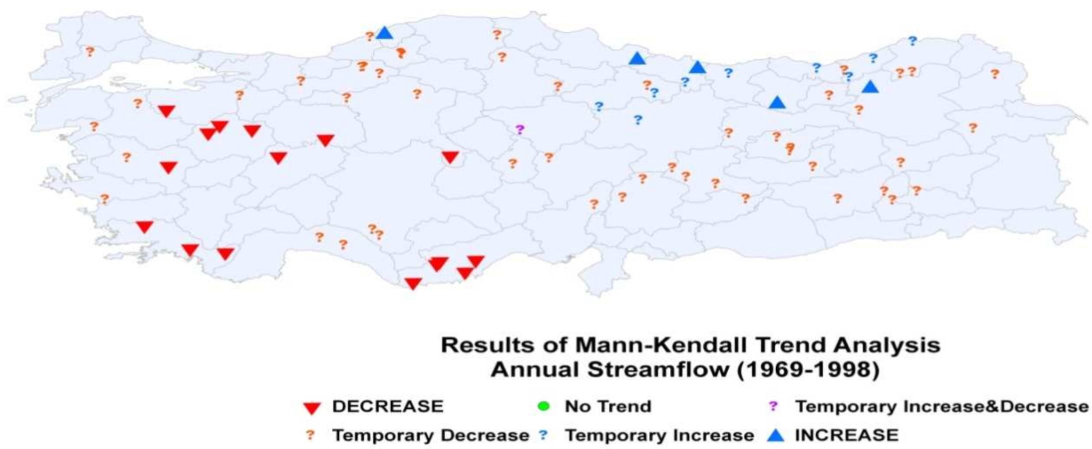

Figure 2. Observed trends in annual streamflow across Turkey calculated using the Mann Kendall Trend Test.

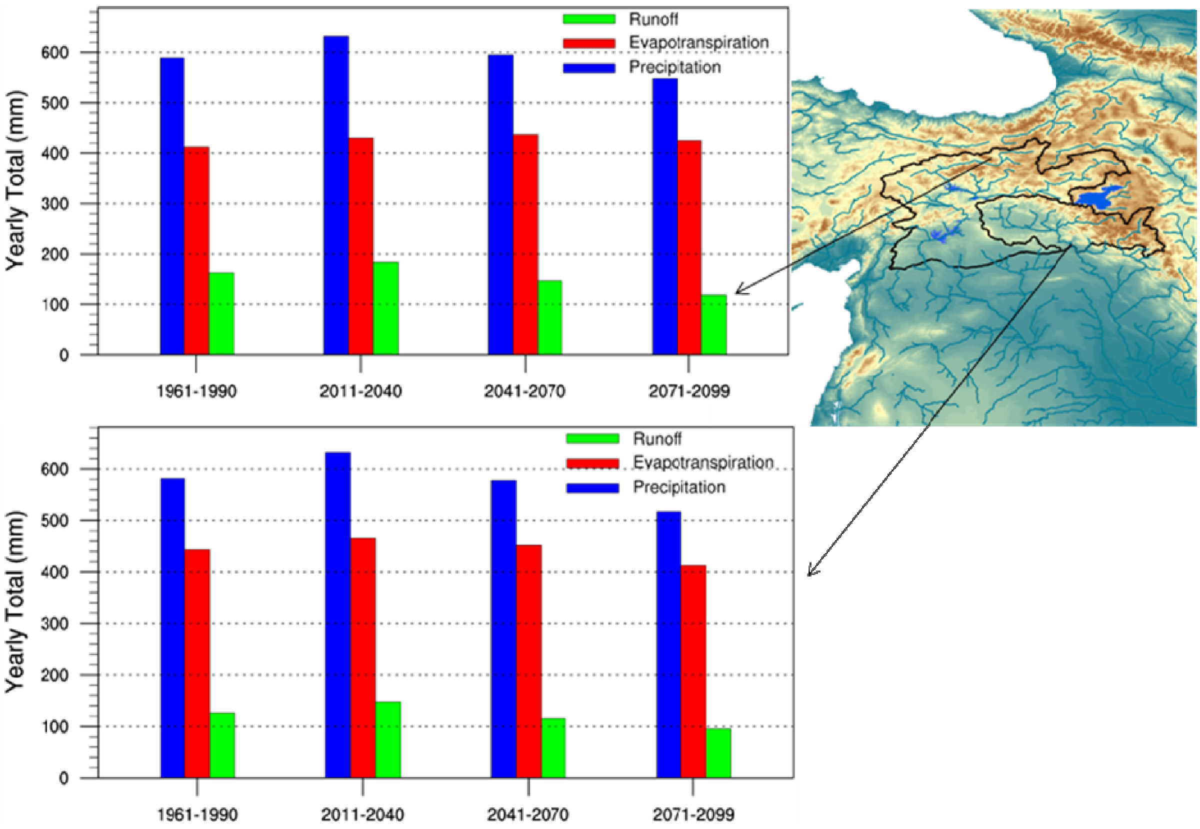

Figure 3. Climate projections using RegCM3 regional climate model based on the results of ECHAM5 global climate model and A2 scenario for Euphrates and Tigris river basins in Turkey.

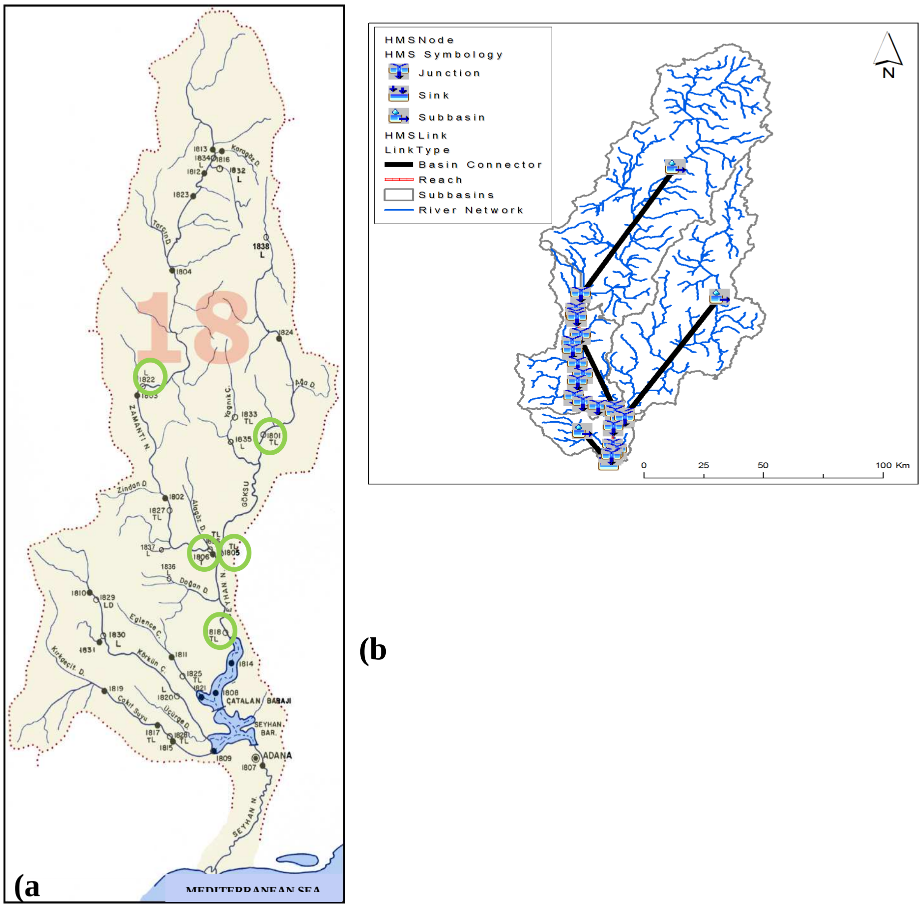

Figure 4. (a) Seyhan River Basin and locations of the stream gauging stations in the basin, (b) schematic diagram of the Seyhan Basin for hydrologic modelling in the ARTEMIS project.

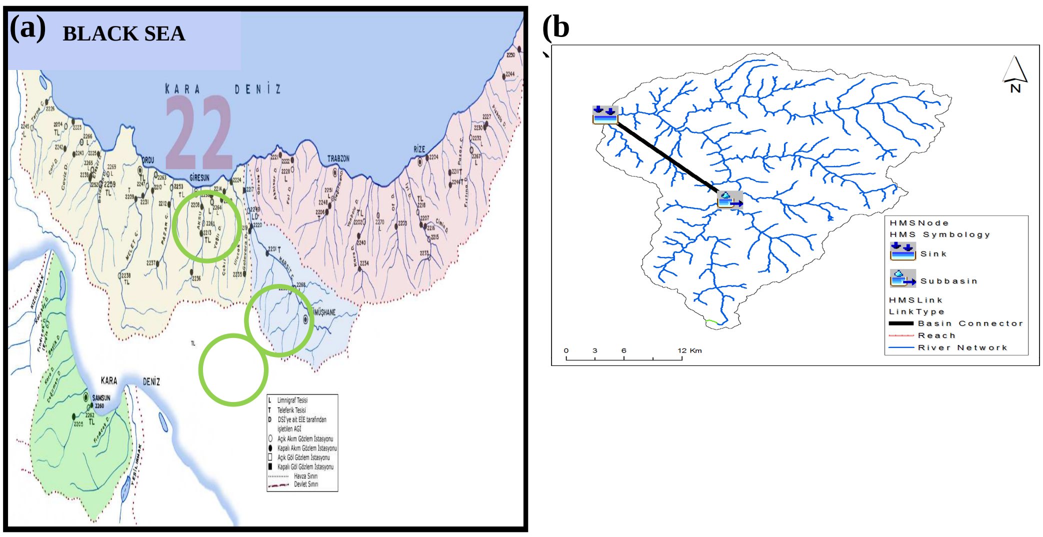

Figure 5. (a) Iyidere River Basin and locations of the stream gauging stations in the basin, (b) schematic diagram of the Iyidere Basin for hydrologic modelling in the ARTEMIS project.

Review of applied methods for flood-frequency analysis in a changing environment in the UK

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1. Description of methods

1.1 Detection of trends and shifts in time series of hydrological extremes (at-site and regional procedures)

A comprehensive assessment of trend in a national dataset of flood magnitude (annual maximum and peaks-over threshold series) and rate of occurrence (peaks-over threshold series) was reported as part of the Flood Estimation Handbook (Robson and Reed, 1999). The FEH concluded that inter-year and decadal variability are significant, but it was not possible to detect a systematic trend in the available flood data (Robson et al, 1998). Subsequent analysis by Hannaford and Marsh (1998) based on a subset of undisturbed catchments reported evidence of trend in upland and maritime-influenced catchments in northern and western areas of the UK, but little or no evidence for trend identified in catchments located in southern England. Detailed studies of flood flow in the river Thames reported by Marsh (2008) concluded that the flood series is characterised by substantial variability but no overall trend is identifiable.

Generally, it is not advised that flood series should be investigated for climate related trends before flood frequency analysis.

1.2 Non-stationary flood frequency analysis (at-site and regional procedures)

Statistical procedures for flood frequency analysis in the UK (Kjeldsen *et al.*, 2008) are currently based on assumptions of stationarity. However, a number of procedures exist to adjust design flow estimates for the perceived influence of climate change and land-use.

<u>Climate change:</u>
The standard procedure for considering the effect of climate change on design flood estimates in the UK is to first conduct a flood frequency analysis using standard methods based on the assumption of stationarity. Secondly, a safety margin of 20%, as recommended by Reynard *et al.* (2004) and Defra (2006) is added to the design flow. Finally, 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 impact factors (Prudhomme *et al.*, 2010), but these results have not yet found their way into official policy.

<u>Urbanisation:</u>
The impact of urbanisation on flood frequency relationships has been investigated based on observed annual maximum peak flow series from 200 urbanised catchments in the UK. The procedure reported in Kjeldsen (2010) developed a set of adjustment procedures allowing an adjustment of the as-rural estimates of the index flood and the two high-order L-moment ratios (L-CV and L-SKEW) to be made according to the level of urbanisation in the catchment under consideration.

<u>Agricultural land-use practice:</u>
A review of land and soil management and its impact on flood generation was published by Defra (2005) and concluded that there was little evidence of change in catchment flood peaks resulting from land-use changes. A follow-on project (Defra, 2008) used hydrological modelling techniques to investigate the effect of agricultural practise, but could not detect changes in catchment flood response resulting from land-use management. Macdonald and Black (2010) go so far as to suggest that the largest flood events resulting from extreme

precipitation, or snowmelt, are anticipated to over-ride land-use influences on flood magnitude. Consequently, there is currently no advice available on how to adjust flood frequency curves for the effects of changing agricultural practise.

1.3 Rainfall-runoff modelling

Climate change:
Numerous studies have been published in the UK investigating how climate change projections may translate into changing flood risk; see Table 1 below. While the studies are based on different combinations of catchments, models and climate predictions, the common message is a general increase in flood risk across the UK.

Table 1. UK studies of climate change impact on flood characteristics

Region	Climate model	Period	Key finding	Source
River Severn, Thames	HadCM2	2041-2070	50-year flood in the Severn and Thames increase by 20% and 16%, respectively.	Reynard *et al.* (2001)
5 UK catchments	7 GCMs	2041-2070	Increase in flood risk but generally within 95% confidence limits	Prudhomme *et al.* (2003)
15 UK catchments	HadRM3H	2071-2100	Decrease in flood risk in south and east England, 50%increase in north and west UK.	Kay *et al.* (2006)
25 UK catchments	HadRM3	2071-2100	An increase in design flood is generally reported (no percentage reported).	Bell *et al.* (2007)
154 UK catchments	16 GCMs from CMIP3; 11 versions of HadRM3	2071-2100	The 20% factor can no longer be considered precautionary.	Reynard *et al.* (2010)
National study (1km grid)	HadRM3	1950-2099 (transient)	Upward trend in flood risk nationally	Kay and Jones (2012)

Urbanisation:
The effect of urbanisation on catchment flood runoff is generally considered to be an increase in runoff volume (reduction in infiltration) and a decrease in catchment response time (or lag time). The revitalised FEH rainfall-runoff method (ReFH) is a lumped event-

based design flood model developed at CEH (Kjeldsen, 2007). The model enables users to simulate design hydrographs for any catchment in the UK. In the ReFH model, urbanisation will reduce the time-to-peak (Tp) of the UK standard instantaneous unit hydrograph thereby increasing peak flow. Subsequent development by Kjeldsen (2009) enabled urbanisation to be considered explicitly in the estimation of runoff volumes.

Agricultural land-use practice:
A system to adjust soil properties, as described by the Hydrology of Soils Types (HOST) system (Boorman *et al.*, 1995), to reflect changes in agricultural land-use management was developed by Packman *et al.* (2004). The HOST data is an important spatial dataset underpinning the Flood Estimation Handbook, and is used to determine the percentage runoff in the ReFH model. Following unsuccessful attempts to link catchment response time to land-cover, a more intuitive procedure was recommended; a one hour reduction in time-to-peak (Tp) to represent faster runoff expected for 'fully degraded' conditions, and a one-hour increase in Tp to represent local flow calming measures. The changes in Tp should be applied pro-rata based on the extent of degradation in the catchment.

1.4 Multivariate frequency analysis (e.g. storm surge, river flooding, urban flooding)

For complex cases involving flooding from multiple sources it is generally recognised that some sort of multivariate frequency analysis, or joint probability analysis, is required. However, the complexities of such methods have traditionally been a barrier towards practical uptake for routine application. A particular example where joint probability analysis has been applied includes a study of the statistical dependence between extreme sea surges and river flows around the coast of Britain (Svensson and Jones, 2004; Defra, 2005). More recently the Environment Agency (2010) published a framework for mapping of flooding from all sources containing a simplified framework for a probabilistic combination of existing flood risk maps. At present, no studies of the potential impact of environmental change on the dependence structures have been reported.

1.5 Uncertainty and risk analysis

The relative uncertainty included in different factors in climate change impact assessment for flood flows vary with catchments and time horizon of the projection in six contrasting UK catchments (Ledbetter, in prep.). For shorter future time scale (~2020), the hydrological model parameters and flood frequency estimates hold all the uncertainty in the changes. For longer future time scales (e.g. 2080s) uncertainty in flood frequency estimate and hydrological model parameters become irrelevant compared to uncertainty in climate model scenarios and emission scenarios. For medium time scales (~2050s), uncertainty in flood frequency estimate can be significant for some catchments and should be considered when undertaking a climate change impact assessment. Methods to assess the relative weight of climate variability compared to the climate change signal are suggested to better quantify uncertainty.

2. Data

2.1 Availability and use of streamflow/precipitation data and proxy data for change detection and frequency analysis

Annual maximum and Peak over threshold series for about 1000 UK catchments are readily available from the Environment Agency's HiFlows-UK online archive:

http://www.environment-agency.gov.uk/hiflows/91727.aspx

Unfortunately, proxy data for changes in catchment conditions are not available for routine analysis.

Precipitation data can be accessed from the British Atmospheric Data Centre (www.badc.nerc.ac.uk/) for stations from around the UK; gridded datasets are also available; though not freely accessible by all.

2.2 Availability and use of data to assess changes in hydrological regime and river infrastructure development

Each gauging station in the HiFlows-UK database includes a short description of artificial influences. However, this information is not standardised, and the level of detail vary between catchments.

2.3 Availability and use of climate change projections from general circulation models and regional climate models, including statistical downscaling

The UK Climate Impact Project has developed a set of probabilistic scenarios in the form of mean monthly climate change factors for a range of climatic variables and emission scenarios called UKCP09 (Murphy *et al.*, 2009). The factors are given for 10 time horizons relative to the 1961-1990 baseline on a 25-km^2 grid scale. The projections are designed to incorporate uncertainty due to Climate Model structure and parameterisation. A weather generator (Jones *et al.*, 2009) is also available that can generate point daily time series consistent with the UKCP09 scenarios. Alternative associated products are also available, including 150 years of daily transient climate projections from eleven variants of the HadRM3 UK Met. Office climate model (HadRM3-PPE). The data can be downloaded from http://ukclimateprojections.defra.gov.uk/ and http://badc.nerc.ac.uk/.

At CEH an ongoing 'Future flows and groundwater levels' project is developing a set of eleven daily river flow and groundwater level time series based on HadRM3-PPE transient projections using rainfall-runoff models for 200 sites across Britain. The climate input are bias-corrected and downscaled to reduce biases, and hydrological model calibrated on historical records. Data will be freely available to download from www.ceh.ac.uk (expected release: spring 2012).

3. Applications

3.1 Purpose and areas of application (design of hydraulic structures, dams, urban hydrology, flood-hazard mapping, etc.).

Flood frequency analysis is widely used in the UK for flood risk mapping (incl. insurance premiums), dam safety, design and operation of hydraulic infrastructure.

3.2 Recommendations for users

Current guidance for including potential climate change effects is to increase design flow estimates by 20% and investigate the potential effects on the design.

Procedures for adjusting design flood estimates for urbanisation are routinely used, as national data on urban extent are available.

5. Plans for future developments

Future work is required to develop non-stationary flood frequency models which will be able to operate within a regional flood frequency estimation framework, thus enabling estimation at both gauged and ungauged sites. Methods will be sought which will compliment the non-stationary signals in the historical records with the future changes predicted by GCM/RCMs.

Land-use changes can have a demonstrable effect on flood frequency characteristics. Future research will combine new data sources and modelling strategies to improve the ability of hydrological flood modelling tools to make more accurate predictions of land-use effects (e.g. urbanisation, agricultural practise) and how best to work with natural processes to reduce flood risk.

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Appendix B

Some world meteorological organization commission for hydrology information on river flood frequency estimation in changing environments

Introduction

Ann Calver
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At the time when the EU COST *FloodFreq* programme was developing, the World Meteorological Organization's Commission for Hydrology was considering the following item in its work programme: '*Prepare guidance material for factoring transient climates, the non-stationary nature of data sets and uncertainty analysis into the estimation of river design floods*.'

WMO is an agency of the United Nations specialising in the state and behaviour of the Earth's atmosphere and climate and the resulting distribution of water resources. WMO seeks in particular to serve the needs of the national meteorological and hydrological services of its member countries or the equivalent organisations in those countries. An important element of the role is the evaluation of emerging research in relation to the tasks these organisations are called upon to perform.

WMO has eight Technical Commissions, of which the Commission for Hydrology (CHy) is one. This commission works to a four-year work plan, the work item noted at the beginning of this introduction being initiated in the 2008-2012 programme under the theme of *'Water, Climate and Risk Management'*. As there was recognised to be considerable overlap in aim with *FloodFreq*, in particular work package 4, contact was made with the COST initiative with the outcome that the association of WMO with the partnership was welcomed. It was decided following liaison at the June 2011 Budapest *FloodFreq* meeting that CHy would seek some WMO country contributions on non-stationary flood frequency estimation developments, parallelling the reports being produced by *FloodFreq* European partners.

Much CHy work is undertaken by volunteer experts. Some WMO member countries were asked to consider contributing short papers along the same lines as those on which the major part of this report is based. This strand of work is expected to continue into the 2013-2016 WMO programme, extending information-gathering to a geographically wider area. Three early responses from contrasting environments beyond Europe – from Australia, India and the United States – are given below in this appendix.

From these papers, and from general discussion in CHy, it is apparent that there is widespread awareness of the potential implications for river flood frequency estimation of changing environmental, particularly climate, conditions. The degree of importance and urgency such issues are accorded by national hydrological services (or their equivalents) appears to depend on the climate conditions under which the services are operating, the degree to which these conditions are successfully catered for by flood management practices, and on access to relevant research outputs and to data. The issue of flood frequency estimation under changing conditions is one where research directions are starting to be considered in hydrological practice but it is recognised that much work needs to be done on this complex topic and that, worldwide, few guidelines or manuals for routine practical use are available.

The three country contributions are presented here very largely as received from their authors, following the general instructions that *FloodFreq* sent to its European members: the focus of interpretation differs a little between the countries. The WMO response has an emphasis of a use-in-practice standpoint rather than a primarily research perspective. The reporting in this appendix represents, therefore, a start in collating changing flood frequency estimation methodologies in areas beyond Europe, particularly in the sense of how research directions and outputs are making their way into national river flood management practice.

STATIONARITY ASSESSMENT OF AUSTRALIAN RAINFALL AND DERIVATION OF PRELIMINARY INTENSITY-FREQUENCY-DURATIONS

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1. Context

The Australian Bureau of Meteorology is currently undertaking a revision of the Intensity-Frequency-Duration (IFD) design rainfalls for the whole of Australia. The previous IFD estimates were developed over 20 years ago (Institution of Engineers Australia, 1987) and the current review is motivated by the quantity of additional data that is now available due expansions in the Bureau's network, the additional length of records available, and access to daily-read and continuous rainfall data collected by other organisations which supplements the Bureau's network.

2. Description of methods

It is intended that the IFD revision project will derive design rainfall data for two climate states – the first representing the current climate (i.e. climate of the 20th century) and the second to account for future changes to design rainfall due to anthropogenic climate change. The proposed methodology for deriving the current climate IFDs is to use station annual maxima series from continuous and daily rainfall stations to calculate regional parameters of the Generalised Extreme Value (GEV) distribution (Green et al., 2010a). At this stage it is intended to use the partial duration series only to correct the Annual Exceedance Probabilities (AEPs) estimates from the annual maxima for frequent events, as these are estimated more accurately using the partial duration series rather than annual maxima series (Institution of Engineers Australia, 1987).

For the stationarity assessment, a two phased approach has been used to analyse the annual maximum time series for trends. The first stage is to examine the records at individual stations. Tests include assessing trends in the time series of annual maximum rainfalls and changes in the probability distributions fitted to the annual maxima to estimate design rainfall quantiles. The Generalised Extreme Value (GEV) distribution has previously been found to best represent Australian AMS data (Green et al, 2010a) and has been adopted for the Preliminary IFDs.

The rainfall IFDs serve as inputs to the estimation of river floods of the same frequency.

Stationarity Assessment

Point based assessment of the stationarity of annual maxima

Two hypothesis tests have been conducted, namely:

- The Wilcoxon rank-sum test (also called the Mann-Whitney rank-sum test) which is a non-parametric test for difference in location (i.e. median) between two data samples.
- The two-sample Kolmogorov – Smirnov test which tests if two sets of data were drawn from the same, unspecified, distribution.

In addition to the split sample analysis approach, analysis has been carried out on the full data period at each station to test for trends. Two trend tests have been used:

- A t-test on the significance of the slope of a linear regression of the annual maximum time series, and
- The non-parametric Spearman's rank correlation to test for correlation of the annual maximum series with time.

Point based assessment of the stationarity of probability distributions and estimated rainfall quantiles

Using the daily and continuous rainfall data for each station and partitioning the record into two separate periods, it is possible to test if the data in the two periods belong to the same or different probability distributions. For the initial analysis, a Generalised Extreme Value (GEV) distribution has been considered. To test for difference in the distributions, a GEV distribution is fit to one of the data samples using the method of L-moments (Hosking and Wallis, 1997) and then a one sample Kolmogorov – Smirnov test is used to test if the data from the second sample is consistent with this distribution. The one sample Kolmogorov – Smirnov test compares the empirical and theoretical Cumulative Distribution Functions (CDF) and measures the maximum distance between the two. Confidence limits on the quantiles were estimated by creating 100 bootstrap samples of the data in each period.

Regional assessment of the stationarity of annual maxima

The second stage uses an area averaged approach to check for regional trends in annual maximum rainfalls. The approach is based on that carried out by Bonnin et al. (2010) to assess trends in rainfall events in the USA as part of the revisions by the National Oceanic and Atmospheric Administration (NOAA) to design rainfalls. For the NOAA analysis the historic record at each station in a region (either southwest US or Ohio River Basin) was treated as a partial duration series and for durations of 6 hours, 1, 2, 4, 7, 20 and 45 days a count was made of the number of times that the recorded rainfall exceeded the relevant design threshold at that station, for different Average Recurrence Intervals (ARIs). The average number of exceedances across all stations in the region was then calculated (the sum of all exceedances divided by the number of stations operating in that year). A time series was constructed of the average number of exceedances per year and tested for non stationarity using a number of non-parametric and parametric tests – namely the Wilcoxon rank sum test, Spearman's rank correlation test and parametric t-test. The NOAA methodology has been applied for both the continuous and daily rainfall stations in Australia. The analysis requires regional averaging of the exceedance time series; a way of grouping stations together is therefore required. For the daily stations, there is sufficient station density such that the analysis could be carried out Australia wide.

Preliminary IFD Estimates

Estimation of L Moments

Daily durations (24 hours to 120 hours)

L-moments were used to summarise the statistical properties of the AMS data at each station location. L-moments are commonly used in rainfall and flood frequency analysis (Hosking and Wallis, 1997) due to their efficiency in fitting the data and lack of bias in the sample estimates, particularly in the higher order moments, when compared to ordinary moments. The Generalised Extreme Value (GEV) distribution has previously been found to best represent Australian AMS data (Green et al, 2010a) and has been adopted for the Preliminary IFDs.

Sub-daily durations (1 hour to 12 hours)

At sites at which there was a continuous rainfall station with more than eight years of record, the mean, L-CV and L-skewness, were determined from the at-site AMS for each duration. The continuous rainfall stations were also used to derive prediction equations between site characteristics and the sub-daily L-moments. The prediction equations were derived using Bayesian Generalised Least Squares Regression (GLSR). Further details on the Bayesian GLSR approach can be found in Reis et al (2005) and Madsen et al (2002, 2009).

Regionalisation

Due to the generally short record lengths compared to the exceedance probabilities that are required, regionalisation has been used to estimate the L-CV and L-Skewness with more confidence. The regionalisation approach adopted is generally called the "index flood procedure" (Hosking and Wallis, 1997).

Gridding of GEV parameters

The regionalisation resulted in estimates of the GEV parameters at all station locations, which could be combined with the mean of the AMS at that site to estimate rainfall quantiles for any required exceedance probability. However IFD estimates are required across Australia, not just at station locations. Therefore the results of the analyses needed to be extended in some way to ungauged locations. ANUSPLIN (Hutchinson 2007) was chosen to grid the GEV parameters so that IFD estimates are available for any point in Australia.

Calculation of growth factors and rainfall depths

The outputs of the ANUSPLIN analysis were grids across Australia for each duration of index rainfall and the GEV shape (alpha) and scale (kappa) parameters. These were then processed to firstly estimate the growth factors for each grid location and then the rainfall depths for each exceedance probability.

Sub-hourly values

To derive IFDs for durations of less than one hour to one minute the 'simple scaling' model developed by Menabde et al (1999) was adopted. The model was calibrated using the AMS from the Bureau's continuous rainfall stations with more than eight years of data.

Smoothing across durations

In order to reduce inconsistencies across durations and smooth over discontinuities in the gridded data (unevenly spaced differences in design rainfall estimates at neighbouring durations) arising from application of the method, a smoothing process was undertaken. This was done by applying a 6^{th} order polynomial to each grid point to all the standard durations from 1 minute up to 7200 minutes.

3. Data

Stationarity Assesment

Daily rainfall stations

Data has been analysed for 17247 daily read rainfall stations across Australia. The data from each station has previously been quality-controlled with infilling of missing data from nearby stations and disaggregation of any aggregated multi-day rainfall totals. A time series of daily rainfall at each station was produced as a result of the quality controlling. To allow for spatial comparisons of the results, common analysis periods were adopted to test for stationarity. For a station to be included in the analysis, it had to have at least 20 years of data in each half of the analysis period considered. This is consistent with the requirement for 40 years of data that was used for the continuous rainfall stationarity analysis.

Continuous rainfall stations

Data has been analysed for 58 continuous rainfall stations. Stations were chosen to ensure that they have at least 40 years of data (with each year having at least 10 months with at least 75% of data values available). To determine the common period to be used for the field significance tests and distribution fitting, the starting and finishing dates for each station were compared and a 50 year period chosen that maximised the number of stations with records in the period. A common period of analysis of 1956 to 2005 was chosen.

Derivation of IFDs

The dataset adopted for the estimation of the Preliminary IFDs is the daily read and continuous rainfall data collected from the Bureau's network of rain gauges and archived in the Bureau's Australian Data Archive for Meteorology database. This comprises daily read rainfall data from nearly 20 000 stations (both open and closed) and nearly 1 500 continuous rainfall stations – using both Dines tilting syphon pluviograph (DINES) and Tipping Bucket Rain Gauge (TBRG) instrumentation. The Annual Maximum Series (AMS) was extracted from the quality-controlled database for all stations with more than eight years of record for continuous stations and thirty years of data for daily rainfall stations. This resulted in AMS from 8273 daily read stations and 683 continuous rainfall stations.

4. Applications

Stationarity Assessment

The stationarity analysis has found that although records at some stations show significant changes over time in both annual maximum time series and fitted GEV distribution and estimated design rainfall quantiles, there are no clear patterns to the changes spatially, with decreasing and increasing trends occurring in similar areas. Significant changes were found at between 2% and 30% of stations analysed depending on the period and method of analysis. Considering the results from both the continuous and daily read rainfall stations, it would seem that significant trends are more likely to occur for shorter duration events (sub-hourly). In general trends are also smaller than the uncertainty associated with the fitted probability distributions. This study has also applied the NOAA methodology to continuous and daily read rainfall gauges in Australia, grouped by rainfall district. Trends in average exceedances of design rainfall thresholds over time are generally not significant particularly for the daily duration events. Trends at the district level are strongly influenced by the period of analysis, indicating that multi-decadal climate variability may affect large rainfalls.

Conclusions are difficult to draw for the sub-daily rainfall events due to the sparse spatial distribution of continuous rainfall stations with long records. Overall it is concluded that the full historical record should be used in deriving IFD estimates.

Preliminary IFDs

Preliminary IFDs have been provided as gridded ASCII files. A summary of the data and method adopted in deriving the Preliminary IFDs is provided to give users of the Preliminary IFDs an overview of how they were estimated (Green et al., 2011).

In terms of the relationship between a rainfall Intensity Frequency Duration analysis and the estimation of design floods, the IFD estimates are used as direct inputs to the estimation of a river flood event of the same frequency. Therefore stationarity or nonstationarity of time series of hydrological parameters such as peak annual discharges are directly linked to nonstationarity of annual maximum series precipitation data.

5. Plans for future development

The method to be adopted for the Final IFDs is still being developed and will include further work including:

- The inclusion of the quality-controlled continuous rainfall data from non-Bureau operated rain gauges. Details of these non-Bureau gauges can be found in Green et al (2010b).
- Inclusion of historic rainfall data.
- An assessment of the appropriateness of the adoption of the partial duration series instead of the AMS.
- Additional trialling of the IFD resolution and consideration of adoption of a variable resolution across Australia.
- Assessment of alternative gridding approaches.
- Assessment of alternative regionalisation approaches.
- Further trialling of the order of polynomial that most appropriate for smoothing.
- An assessment of alternative approaches for the estimation of sub-hourly IFDs.
- Derivation of sub-hourly IFDs for durations of 5, 10, and 15 minutes instead of 6, 12, and 18 minutes.

For the future climate state IFD derivation, a range of information is required including time horizon, choice of emission scenario and technique to calculate future rainfall patterns. Two climate change workshops were held in 2010 to coordinate the integration of climate change projections across a number of the Australian Rainfall and Runoff revision projects and provide the required inputs for the derivation of the future IFD data. At this time, this process is continuing and thus future rainfall changes are not discussed in this report.

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Overview of methods used to consider the impact of environmental change (particularly climate change) on flood frequency in India

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1. Description of methods

1.1 Detection of trends and shifts in time series of hydrological extremes (at-site and regional procedures)

The design floods for hydraulic structures are estimated based on the BIS (Bureau of Indian Standards) 11223: 1985. The standard recommends the design flood as follows:

Dam Classification	Gross Storage	Hydraulic Head	Inflow design flood to be adopted
Small	0.5-10 Mm^3	7.5 m to 12.0 m	100 year return period
Medium	10- 60.0 Mm^3	12.0 m to 50.0 m	Standard Project Flood
Large	>60.0 Mm^3	> 50 m	Probable Maximum Flood

From the above it can be seen that the flood frequency methodology is generally adopted for small structures including minor cross drainage works where the risk associated with the failure is relatively low.

In view of the recommended procedure for estimating the Probable Maximum Flood (PMF) the complete flood hydrograph is derived using a hydrometeorological approach.

Due to a number of natural causes or human interference etc. there may be changes in the flow characteristics. There may be gradual changes in flow characteristics due to deforestation or afforestation or land management processes. The gradual aggradation or degradation of the river regime may cause changes in the rating curves and hence the water level estimates. Such systematic and continuous change over an entire sample in any parameter of a series is called trend which may be rising or falling in nature.

The data series has to be analysed to check for the presence of trend and appropriately corrected if the trend is significant before using the same for flood frequency analysis. Trend can be obtained either by regression analysis or by moving averages. An essential part of the concept of trend is that the movement over a fairly long period is smooth. It means that for all practical purposes, the trend component can be represented by a polynomial. Some of the tests for checking the significance of the presence of the trend are:

a. The difference sign test;

b. Kendall rank correlation test; and

c. Regression test.

In cases where the flood frequency approach is resorted to the trend analysis is carried out for the data of the specific location to check the stationary behaviour of the data before the data is subjected to frequency analysis.

If some trend is noticed the data are naturalised for changes in abstractions upstream of the data observation location. Efforts are made to understand and to assess the hydrological reasons for trends if any. In cases where the reasons are established the data series is naturalised and again tested for trends before flood frequency is applied. A regulated series is naturalised by maintaining continuity of the water balance, through either adding or subtracting changes in the reservoir water level and diversions in and out of the catchment upstream of the observation location.

1.2 Non-stationary flood frequency analysis (at-site and regional procedures)

Standard procedures for flood frequency analysis in India are based on an assumption of stationarity. There are currently no systematic analytical procedures for accounting for the effect of environmental change. In cases where trends are analysed in the data series to be used for flood frequency analysis and the series cannot be naturalised for known changes in the flow pattern upstream, efforts are made to assess the years beyond which the trend is observed. If the data series is long enough the series is split into to one prior to the years when the trend is observed and other when the trend is observed. The series free from trend is preferred for flood frequency analysis.

With research studies completed and ongoing, the science of climate has revealed the need for developing strategies for incorporating likely impacts of such changes in the planning of water resources projects. The preliminary assessment has recommended reviewing criteria for estimation of design flood incorporating the likely impact of climate change. Such issues are being taken up by the National Water Mission. The procedure for these estimates which largely depends on the data series remains by and large the same.

1.2.1 Likely changes in flood estimates

It is difficult to judge, at present, how the estimation of the Probable Maximum Precipitation (PMP) and Standard Project Storm (SPS) would change with climate change. That floods of given magnitude will become more frequent is not the same as the assumption that the maximum storm producing potential of a region may increase in the climate change scenario. This may or may not happen. Already the PMP and SPS are estimated by pulling together the experience of large storm events in the general region much larger than the catchment. This is necessary because the large storms are rare, and their limits cannot be judged without pooling of that inadequate information.

Though methodical documentation of the procedures by bodies like the WMO are in place, the exact determination of PMP (and SPS) remains somewhat subjective and even nebulous. Further judging the effects of climate change on these estimates, without hard data about the increased unusual precipitation events would become too subjective, and should perhaps be avoided.

In regard to the return period storms, some mathematical treatment based on the trend analysis of flood peak data of the past may be possible, even though the establishment of the significance and confidence limits for the trend would pose somewhat difficult problems. Research needs to be undertaken in this regard.

1.3 Rainfall-runoff modelling

Methodologies and tools are already available to some extent. NAM and MIKE–BASIN models already have some provisions for conversion of rainfall to runoff and for assembling runoff from different catchments. Modelling can be made distributed by considering large number of catchments. The SWAT model (which incidentally was used by the IIT, Delhi Group for studying climate change over India) is a distributed model in which the land use at each pixel can be specified. It works as a hydrologic model monitoring the water balance. However, the data requirements are very large and the calibration provisions appear somewhat inadequate. The ICID, as a part of their policy support programme (CPSP), developed a simple hydrologic model which depicted the different hydrologic behavior of each land use type. This model named as the BHIWA model is a lumped one, but was made partially distributed by modeling sub-catchments and their junctions separately. Calibration/verification could be done for a time series of five years monthly data. After calibration the models were used for water assessment under different likely future scenarios based on different development and management strategies. The results of such assessments have been published for the Sabarmati and the Brahmani basins.

Similarly, the IWMI worked on five basins of peninsular India to convert a monthly series of 15 years of observed flow data into a monthly time series of natural flows, by modeling the hydrological effects of all man-made changes such as surface storage filling, withdrawals for various purposes from surface and groundwater, anthropogenic evaporation and evapo-transpiration and returns to surface and ground water. The delays between the ground water recharge and the base flows due to the characteristics of the ground water reservoir were also modelled. This calibrated model was then used for assessing the future situation. The BHIWA model of ICID models the full hydrologic cycle for each land use, and has a capability of studying changes due to changes in rainfall and potential evapo-transpiration regimes as well as land use changes; however, the calibration process requires considerable time and experience. It seems to be well suited for assessments under future climate change situations. The IWMI model is faster, can accommodate longer time series but models only the anthropogenic changes and is not a complete hydrologic model. The SWAT model can also be used and its distributed nature is a big advantage. However, some simplification and meticulous data preparation may be required. The NAM – MIKE basin model, on a GIS platform can also be useful. The NIH and CWC together can even attempt to develop a tailor-made model for the Indian water assessments.

1.3.1 Predictive findings of scientists about likely climate change in India

Studies related to the impacts of climate change on various components of the hydrological cycle may be classified broadly into two categories: (i) studies using GCM/RCMs directly to predict impact of climate change scenarios (ii) studies using hydrological models with assumed plausible hypothetical climatic inputs.

The Indian Institute of Tropical Meteorology (IITM) is active in studying long-term climate change from observed and proxy data as well as model diagnostics and assessment of climatic impacts, with a particular focus on the Indian summer monsoon. IITM used the Hadley Centre RCMs for the Indian subcontinent to model the potential impacts of climate change.

The RCMs have shown significant improvements over the global models in depicting the surface climate over the Indian region, enabling the development of climate change scenarios with substantially more regional detail. High-resolution climate change scenarios have been generated for different states of India. Some of the major findings concerning water resources are:

1. The rainfall scenarios are dependent on climate scenarios.

2. There are substantial spatial differences in the projected rainfall changes. The maximum expected increase in rainfall (10 to 30%) is for central India.

3. There is no clear evidence of any substantial change in the year-to-year variability of rainfall over the next century.

4. Surface air temperature shows comparable increasing trends by as much as 3 to 4°C towards the end of the 21st century.

5. The warming is widespread over the country, and relatively more pronounced over northern parts of India.

1.4 Multivariate frequency analysis (e.g. storm surge, river flooding, urban flooding)

Climate change may change the frequency distribution of floods. There is a need for research in establishing these changes. On one hand these frequency distribution may change and on the other hand the economic gap between the rural and urban residents, as also the gap in their aspirations, would become smaller in the future.

1.5 Uncertainty and risk analysis

The criteria specified for the adoption of design flood for various sizes of hydraulic structures take into consideration the risks associated with the likely failure of these structures. However, estimation of specified return period flood has a degree of uncertainty which is the uncertainty associated with the data as all data are not naturalised data.

2. Data

2.1 Availability and use of stream-flow/precipitation data and proxy data for change detection and frequency analysis

IITM is active in studying long-term climate change from observed and proxy data as well as model diagnostics and assessment of climatic impacts, with a particular focus on the Indian summer monsoon. IITM used the Hadley Centre Regional Climate Models (RCMs) for the Indian subcontinent to model the potential impacts of climate change.

2.2 Availability and use of data to assess changes in hydrological regime and river infrastructure development

Daily hydrological data for about 866 stations are available across the country. The data at many of these locations are sufficiently long to assess and estimate the hydrological regime. The India Meteorological department collects meteorological data including precipitation at more than 9000 locations across the country which is supplemented with the flow data to estimate the design parameters for any water resources project. Information on infrastructure data such as irrigation projects, hydropower projects and other water utilisation projects is being compiled under national Water Resources Information System.

2.3 Availability and use of climate change projections from general circulation models and regional climate models, including statistical downscaling

Studies related to the impacts of climate change on various components of the hydrological cycle may be classified broadly into two categories: (i) studies using GCM/RCMs directly to predict impact of climate change scenarios (ii) studies using hydrological models with assumed plausible hypothetical climatic inputs.

The RCMs have shown significant improvements over the global models in depicting the surface climate over the Indian region, enabling the development of climate change scenarios with substantially more regional detail. High-resolution climate change scenarios have been generated for different states of India

Atmospheric Science Groups are working towards downscaling of GCM or RCM to basin/project level and also understanding the effect of climate change on monsoons.

3. Applications

3.1 Purpose and areas of application (design of hydraulic structures, dams, urban hydrology, flood-hazard mapping, etc.).

Flood frequency analyses are used in India for design small hydraulic structures such as small dams, cross drainage works etc. The design of urban flood estimates do call for frequency analysis but the daily data available at observation stations are not sufficient to estimate the design flood corresponding to the small duration of a day.

The incorporation of the likely impact of climate change is being studied by way of revising the acceptability criteria such as changing the return period for a given structure. For new small dams, which are currently designed for 100 year floods, it is suggested that a practice is started of designing these for 150 year return period floods, on an ad-hoc basis, until better methods of estimating the 100 year flood under the changed flood regime becomes available.

Plans for future development

Under National Action Plan on Climate Change it is planned to increase the analytical capabilities along with increased data collection to bridge the gaps wherever these occur.

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Review of applied methods for flood-frequency analysis in a changing environment in the United States

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1. Description of methods

The current guidelines for flood frequency analysis in the United States are described in Bulletin 17B, “Guidelines for Determining Flood Flow Frequency” (IACWD, 1982). The Bulletin 17B guidelines are used extensively for estimating flows with Annual Exceedance Probabilities (AEPs) ranging from 0.5 (1 in 2) to 0.01 (1 in 100). Probable Maximum Flood (PMF) methods are typically used to estimate floods for major structures, such as dams and nuclear facilities, but some U.S. agencies utilize flood frequency techniques for estimating extreme flood probabilities with AEPs ranging from 0.001 to 0.0001 (Swain et al., 2006).

1.1 Detection of trends and shifts in time series of hydrological extremes (at-site and regional procedures)

Bulletin 17B acknowledges that trends occur for both natural and anthropogenic reasons, including (IACWD, 1982 p. 6) “urbanization, channelization, levees, the construction of reservoirs, diversions, and alteration of cover conditions,” and that “special efforts should be made to identify those records which are not homogeneous.” However, B17B does not specify methods for detecting trends or for accounting for them in flood frequency studies.

With respect to “climatic trends,” B17B makes a strong assumption (IACWD, 1982 p. 6): “There is much speculation about climatic changes. Available evidence indicates that major changes occur in time scales involving thousands of years. In hydrological analysis it is conventional to assume flood flows are not affected by climatic trends of cycles. Climatic time invariance was assumed when developing this guide.” At the same time, Bulletin 17B recognizes that its failure to provide guidance on conducting flood-frequency analyses in changing environments limits the Bulletin’s applicability. Two of its eight recommendations for “future work” (IACWD, 1982 p. 27) relate directly to the questions posed here: procedures to incorporate flood estimates from precipitation into frequency analysis; and guides for defining flood potentials for watersheds altered by urbanization and by reservoirs. Stedinger and Griffis (2008) describe the list of additional studies recommended by IACWD (1982, pp. 27-28), and suggest that there is sufficient flood frequency research conducted since 1982 to update Bulletin 17B.

Bulletin 17B does not specify a standard method for detecting trends or shifts (change points) in parameters. The most commonly applied trend test is the Kendall-tau test (Helsel and Hirsch, 1992), which has been used extensively for detecting trends in streamflow (e.g., Lins and Slack, 1999) and precipitation (e.g., Bonnin et al., 2006, 2011) in the United States. Cohn and Lins (2005) present an adjusted likelihood ratio trend test which can account for long-term persistence (LTP) in flood-generation processes. The Pettitt test (Pettitt, 1979) has been used to investigate potential changes in mean flood peaks in the U.S. (Villarini et al., 2009).

1.2 Non-stationary flood frequency analysis (at-site and regional procedures)

There is currently no standard method for non-stationary flood frequency analysis in the United States. Stedinger and Griffis (2011) have recommended time-dependent parameters as one way to accommodate change.

1.3 Rainfall-runoff modelling

Rainfall-runoff models are often used in flood studies related to zoning and floodplain management, and for extreme flood estimation. Rainfall-runoff models can, in theory, account for changes in land-use, channel characteristics, or other hydrologically important factors that might affect flood flows. This is an area of ongoing research and development.

1.4 Multivariate frequency analysis (e.g. storm surge, river flooding, urban flooding)

Currently there is no standard method for assessing risk associated with non-independent hazards. However, at specific sites diverse scenarios are developed that can account for lack of independence of different types of flooding (Prasad et al., 2010).

1.5 Uncertainty and risk analysis

Flood risk for critical infrastructure such as dams and power plants is typically based on estimates of the Probable Maximum Flood for some U.S. agencies. The Bureau of Reclamation uses risk analysis to assess the safety of dams, prioritize expenditures, and evaluate potential modification alternatives (Reclamation, 2010), with hydrologic hazard curves as the main input (Swain et al., 2006). Currently, these extreme flood hazard techniques account for watershed changes such as upstream dams and reservoirs and extensively utilize long-term paleoflood records (e.g. Levish, 2002; England et al., 2010). The USACE is also investigating hydrologic hazard techniques for dam safety risk (USACE, 2008)

For sites where occasional flooding would not be considered catastrophic, probabilistic methods are usually applied. For example, the National Flood Insurance Program typically employs methods specified in Bulletin 17B for computing uncertainty and risk. The Bulletin 17B methods purport to account for both sampling and natural variability (aleatory and epistemic uncertainty). However, the methods have been criticized because they do not account for all sources of information and they assume that the estimation problem involves only two unknown parameters (Stedinger et al., 1993 p. 18-46).

2. Data

2.1 Availability and use of streamflow/precipitation data and proxy data for change detection and frequency analysis

The USGS operates approximately 7000 real-time streamgages throughout the Unites States, and maintains an archive of hundreds of thousands of annual peak flows. It also collects and maintains evidence of historic flood events.

The National Oceanic and Atmospheric Administration's Precipitation Frequency Atlas 14 (Bonnin et al, 2006) provides precipitation frequency, intensity and duration information that can be used in rainfall-runoff models, and provides basic precipitation data time series for frequency analysis, in addition to precipitation data at the National Climatic Data Centre (NCDC).

There is currently no U.S. national paleoflood database for use in estimating extreme floods. However, the Bureau of Reclamation routinely utilizes paleoflood data collected at the site of interest in estimating hydrologic hazard curves, and has collected paleoflood data at and near large dams, where the data are needed for hydrologic risk assessments conducted for individual sites. These data are currently stored in paper copies and in computer databases (Klinger and Godaire, 2002). The NOAA Satellite and Information Service provides a database of tree-ring widths and other paleoclimate and proxy information.

2.2 Availability and use of data to assess changes in hydrological regime and river infrastructure development

Continuous instantaneous records of streamflow are available at nearly 7000 streamgages across the United States. These data can be used to assess changes in the hydrological regime.

Information about land-use change, though periodically documented, are generally difficult to obtain except in places where detailed studies have been conducted. Some methods to accommodate watershed changes are presented in USACE (1994).

2.3 Availability and use of climate change projections from general circulation models and regional climate models, including statistical downscaling

While GCM models are available, at present there appears to be no consensus on how to employ climate-change projections and statistical downscaling in flood frequency estimation. Flood frequency estimates using statistical downscaling have been explored at 4 basins in the western U.S. (Raff et al., 2009) using projection information from Mauer et al. (2007).

3. Applications

3.1 Purpose and areas of application (design of hydraulic structures, dams, urban hydrology, flood-hazard mapping, etc.)

Flood-frequency estimates inform floodplain zoning in the United States and provide the basis for the National Flood Insurance Program. They are also used in the design of hydraulic structures, for land-use planning, ecosystem restoration, and many other local decisions. Hydrologic hazard estimates are also used in dam safety risk analysis by some U.S. federal agencies, with design flood techniques summarized by England (2011).

3.2 Merits and drawbacks of different methods

Current procedures in Bulletin 17B do not consider environmental change. Other recent methods have not been critically evaluated.

3.3 Recommendations for users

Federal agencies in the United States have received some criticism from the academic community for not taking climate change into account in the preparation of flood hazard maps. However, recent studies seem to indicate that there is no consistent or overall pattern of change in flood frequency throughout the United States (Villarini et al., 2009; Hirsch et al., 2011). In addition, because flood-risk estimates can be and often are challenged, it is problematic in the United States to employ operational procedures that employ qualitative or untested forecasts (as would be required to deal with climate change).

4. Case studies

Examples of practical applications

Some example practical applications to date include a set of methods that allow for the estimation of flood potential given a set of climate projections (Raff et al., 2009) and water-supply impacts in the western United States (Reclamation, 2011).

5. Plans for future development

Research on this topic is continuing, and in the future U.S. federal agencies may adopt procedures to address these shortcomings. There are several technical work groups that are investigating these issues.

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