Estimating the impact of global change on flood and drought risks in Europe: a continental, integrated analysis

Bernhard Lehner*, Petra Döll, Joseph Alcamo, Thomas Henrichs, Frank Kaspar

Center for Environmental Systems Research, University of Kassel, Kurt-Wolters-Straße 3, 34109 Kassel, Germany

*Email: lehner@usf.uni-kassel.de

Abstract

Studies on the impact of climate change on water resources and hydrology typically focus either on average precipitation and flows or, when analyzing extreme events such as floods and droughts, on small areas and case studies. At the same time it is acknowledged that climate change may severely alter the risk of hydrological extremes over large regional scales, that changes in precipitation are likely to be amplified in runoff, and that human water use will put additional pressure on future water resources. In an attempt to bridge these various aspects, this paper presents a first continental, integrated analysis of possible impacts of global change – i.e. climate and water use change – on future flood and drought frequencies at a pan-European scale. The global integrated water model WaterGAP is evaluated regarding its capability to simulate high and low flow regimes and is then applied to calculate relative changes in flood and drought frequencies. The results indicate large 'critical regions' for which significant changes in flood or drought risk are expected under the proposed global change scenarios. The regions most prone to a rise in flood frequencies are northern to northeastern Europe, while southern and southeastern Europe show significant increases in drought frequencies. In the critical regions, events with an intensity of today's 100-year floods and droughts may recur every 10-50 years, or even more often. Though interim and preliminary, and despite the inherent uncertainties in the presented approach, the results underpin the importance of developing mitigation and adaptation strategies for global change impacts on a continental scale.

Keywords: Floods; Droughts; Climate change; Global change; Europe; Large-scale modeling

1. Introduction

Assessments of available water resources and their temporal and spatial distribution, as well as the analysis of flood and drought risks are of great importance to preserve the health of human societies and environmental systems. When looking at global change scenarios, these types of assessments are severely constrained by limited data availability, uncertain model results, and incomplete scenario assumptions. As long-term average values are generally considered the more reliable outputs of climate and large-scale hydrological models (Hulme et al., 2001), many climate impact studies have focused on mean renewable water resources and average flow conditions (e.g., Arnell et al., 2000; Parry, 2000; Alcamo et al., 2003b), while assessments of seasonal changes and extreme flows have been rare (Prudhomme et al., 2002; Voss et al., 2002). Beyond the average trends, however, changes in the frequencies of extreme events, such as floods and droughts, may be one of the most significant consequences of climate change (Katz and Brown, 1992; Karl et al., 1993; Frei et al., 1998; Jones, 1999). Moreover, during extreme low and high flow events the threats to human societies and the environment are likely to be most critical, and the conflicts between competing requirements to be most intense. Thus growing attention has recently been drawn, both from a scientific and political perspective, on understanding the risks of extreme hydrological events with regard to global change.

Evidently, extreme flood events can cause tremendous damage to economy and ecology and, in the worst case, bear enormous risks for life. In contrast, droughts are often perceived by society to play a less dominant role when thinking of natural hazards. This perception may be influenced by the typical characteristic of droughts to build up slowly, whereas floods are immediately seen and felt. Nevertheless, droughts regularly cause serious damage to economy, society and the environment. In the early 1990s, Europe experienced severe droughts, and the damage in Spain, where the drought affected about 500,000 hectares of irrigated land alone in the Guadalquivir river basin, was estimated at several billion Euro (Garrido and Gómez-Ramos, 2000). Various studies conclude that in the last decades the drought situation in many European regions has become more severe (Arnell, 1994; DVWK, 1998; Demuth and Stahl, 2001).

Climate change is expected to alter average temperature and precipitation values and to increase the variability of precipitation events. This may, in many regions, lead to more severe and frequent floods and droughts (Jones, 1996; Watson et al., 1997; EEA, 1999; Arnell et al., 2000; Parry, 2000; IPCC, 2001a, Voss et al., 2002). As general trends in Europe, increases in average precipitation and its variability are expected for northern regions, suggesting higher flood risks, while less rainfall, prolonged dry spells and increased evaporation may increase the frequency of droughts in southern areas.

Floods and droughts are phenomena that are not constrained by watershed or international boundaries, and they can grow to afflict large areas and many countries simultaneously. Examples are the severe 2002 floods, which were induced by the same meteorological event and affected a region reaching from Germany and Austria over the Czech Republic to Romania and Russia; or the European drought of 1976 which stretched from Spain over France, Germany, and Britain to Scandinavia (Bradford, 2000). Consequently, it has been recommended that droughts should be studied within a regional context (Demuth and Stahl, 2001; Tallaksen, 2000). Floods, whose critical peak flows are often determined by small to meso-scale processes, are typically analysed in basin-specific approaches, focusing on single watersheds. This, however, may hamper regional comparisons of climate change impacts, as differing results of future flood frequencies may be caused by differing climate change scenarios, differing hydrological models, or differing statistical methods of deriving the frequencies from the simulated discharge time series. Even applying the same hydrological model in multiple basins may not solve this problem, as small to meso-scale models are normally developed for certain areas and conditions and often need strong tuning or model modifications when transferred e.g. from cold humid to hot semiarid areas.

In response to these arguments, we present a spatially consistent methodology to analyze the possible impacts of global change – with a particular focus on climate change – on future flood and drought frequencies throughout the whole of Europe, based on the results of a single large-scale discharge model. Due to this broad objective, the approach inherently disregards some important hydrological processes and, in consequence, cannot aim to provide detailed quantitative results in terms of explicit discharges of single events, their timing and exact location. Instead, the main intent of this study is to draw a comprehensive picture of conceivable changes in extreme flow occurrences at a pan-European scale, which can serve as an initial, interim assessment until better information becomes available. The core question of this study is: In which ‘critical regions’ of Europe may, according to different global change scenarios, floods and droughts occur more often in future, and of what magnitude are these changes?

Floods and droughts are typically analyzed in separate hydrological and statistical approaches to better reflect their distinct underlying processes and causes. However, as this study aims to provide an overview of possible risks rather than a detailed process analysis, we investigate floods and droughts following the same statistical concept to determine their frequency of recurrence. This may to some extent compromise the accuracy of the results, but allows for better comparison of the changes in future risks.

Besides climate change, human interactions in terms of water storage and abstractions are expected to show significant effects on future river flows. To account for this, the global integrated water model WaterGAP is applied for all calculations, which combines river discharge simulations with estimates of current and future water use.

Within this study, floods and droughts are strictly defined in terms of river discharge. It is not determined, however, to what extent a given flood discharge is related to real flooding, in terms of bursting river banks and setting a considerable area under water. To answer this complex question, additional information would be required, in particular a highly accurate elevation model, which is currently not available on a continental scale. According to Tate and Gustard (2000), drought assessments typically focus on climatology (deficit in precipitation), agro-meteorology (deficit in soil water), groundwater (deficit in groundwater storage), river flows (deficit in discharge), or operational issues (conflict of water shortage and water management demands). Within this study the concept of 'river flow drought' (or hydrological drought) is adopted, because (i) discharge integrates both climatological anomalies and additional influences (plant transpiration, soil, water abstractions) and (ii) any type of drought is likely to show a concurrent reduction in streamflow.

2. Methods

2.1 Applied models and scenarios

2.1.1 The WaterGAP model

The analysis of flood and drought frequencies presented in this paper is based on discharge calculations as provided by the integrated global water model WaterGAP (Water – Global Assessment and Prognosis) (for a more detailed description of the applied version 2.1 see Alcamo et al., 2003a; Döll et al., 2003). This model transforms current and future climate and water use conditions into time series of river flows. It thus allows for a combined analysis of the effects of climate change as well as demographic, socioeconomic and technological trends on large-scale discharge regimes.

WaterGAP comprises two main components, a Global Hydrology Model and a Global Water Use Model. The Global Hydrology Model simulates the characteristic macro-scale behavior of the terrestrial water cycle and estimates natural water availability defined as total river discharge, i.e. combined surface runoff and groundwater recharge. The Global Water Use Model consists of four submodels which compute water use for the sectors households, industry, irrigation, and livestock. WaterGAP calculates daily vertical canopy and soil water balances for grid-cells at a spatial resolution of 0.5º longitude x 0.5º latitude. The European continent, with a total area of approx. 10 million km^2, is covered by more than 6000 cells at a typical size of about 35 km x 55 km, depending on latitude, which represent approx. 500 first-order river basins. The model routes the derived cell runoff along a global drainage direction map (Döll and Lehner, 2002), taking lakes, reservoirs, wetlands, and human water abstractions into account, and finally computes monthly discharge values for every grid-cell of the river network. For simulations of historic and present conditions, climate input data are applied as monthly time series (max. 1901-

95) of observed temperature, precipitation and radiation (derived from cloudiness), provided at 0.5-degree grid resolution (New et. al., 2000).

2.1.2 Scenarios of future development

In order to derive future discharge values, WaterGAP is driven by climate change projections (temperature and precipitation) as calculated by General Circulation Models (GCMs), and by a set of scenario assumptions for changes in human water use (for a more detailed description see Henrichs et al., 2002; Alcamo et al., 2003a, b). The applied scenarios are largely consistent with the no-climate-policy IPCC-IS92a scenario estimates of the Intergovernmental Panel on Climate Change (IPCC, 1992) and the intermediate Baseline-A scenario as developed by the Dutch National Institute of Public Health and Environment (RIVM) (Alcamo et al., 1998). They represent a set of 'business-as-usual' assumptions about population growth, economic growth and economic activity, and imply an average annual increase of carbon dioxide emissions of 1% per year. This global emission pathway is also within the range of marker scenarios of the updated IPCC-SRES scenarios, and slightly above their intermediate 'A1B' scenario (IPCC, 2000). The 'A1B' scenario anticipates an increase in global carbon dioxide concentrations from about 360 ppm to 600 ppm, and a temperature rise of about 2.3°C by 2070, while other scenarios project temperature rises between 1.3°C and 5°C (IPCC, 2001b). For comparison, global carbon dioxide emissions from use of fossil fuels actually increased by over 1.2% per year between 1980 and 2001 (EIA, 2001), despite significant reductions in eastern Europe and the former Soviet Union in the 1990s due to their economic downfall. The applied emission scenario is thus considered to describe a medium to slightly optimistic future development.

River discharge. WaterGAP simulates the effects of present and future climate on both river discharge and irrigation water demand. In addition, the effect of changing water consumption is accounted for by modeling and subtracting human water use from natural discharge. In order to represent ‘present’ climate conditions, the 30-year monthly time series of the baseline period 1961-90 is applied. Future monthly time series are then constructed from the observed data by scaling the time series of temperature and precipitation. Scaling factors (monthly means) are derived by comparing GCM runs for present and for future time slices (e.g. GCM runs for 1961-90 and 2021-30). As future time slices, the representative decades of the ‘2020s’ (mid-term future) and the ‘2070s’ (long-term future) are analyzed. Temperature is scaled in an additive approach: future temperature = present observed temperature + difference between future (e.g. 2021-2030 mean) and present (1961-90 mean) GCM temperature. Precipitation is scaled in a multiplicative way: Future precipitation = present observed precipitation · ratio between future and present GCM precipitation. Following these scaling approaches and based on the observed data of 1961-90, 30-year monthly time series of future climate are constructed, which are then applied in WaterGAP to represent the conditions in the 2020s and 2070s. Yet with the same emission scenarios, climate projections and especially precipitation estimates vary considerably between GCMs – not only in magnitude but even in their direction (IPCC, 2001a). Therefore, in order to allow for comparisons, we analyze WaterGAP runs with climate projections derived from two different state-of-the-art GCMs: the HadCM3 model (Gordon et al., 2000) and the ECHAM4/OPYC3 model (Röckner et al., 1999).

Water use. The population of Europe is projected to grow from 745 million in 1995 to 882 million in 2075. The Gross Domestic Product (GDP) per capita, as an indicator for economic growth, is assumed to increase at a rate between 1.7% and 4% for European countries, which is slightly lower than historically. Population and economic growth lead to an expansion of electricity demand and, in consequence, a rise in cooling water requirements. A regional breakdown shows drastic increases in electricity production for eastern Europe, where growth rates in the energy sector of 500% or more are anticipated in the scenario by 2100. At the same time, WaterGAP considers structural and technological changes based on extrapolations of historic trends that reflect a change in behavior, industry and water supply infrastructure, as well as the effect of improved water use efficiencies over time. The extent of irrigated area is assumed to remain more or less constant within Europe throughout the century (Henrichs et al., 2002). The impact of climate change on irrigation, which represents the dominant water use sector in southern Europe, is simulated as a shift of the growing season and a changed daily irrigation requirement (Döll, 2002).

2.1.3 General limitations

Scenario assumptions and climate model results as applied in WaterGAP calculations are coarse and inherently uncertain on both spatial and temporal scales. This problem is addressed in the evaluation of WaterGAP in section 2.3, which focuses on high and low flows. Additionally, the following general limitations should be kept in mind when interpreting any of the presented results:

- The analysis of possible impacts of global change on flood and drought frequencies is generally limited by the quality of the applied input data. With regard to climate scenarios, the major limitations in current GCM output are that their spatial resolution is much coarser than required for most river basin studies, and that the modeling of precipitation is considerably less reliable than temperature and pressure (Jones and Woo, 2002). Furthermore, while annual or monthly time steps may be adequate for analyzing the effects of climate change on average water resources, impact studies on floods require at least daily data, and climatic changes need to be expressed at this resolution (Prudhomme et al., 2002). Although recent generations of GCMs have brought considerable improvements (Mitchell and Hulme, 1999) and sequences of daily weather are now available from these models, the results are not considered reliable for time scales shorter than one month (Kilsby et al., 1999). As a consequence, 'downscaling' techniques have emerged as an efficient means of generating smaller-scale regional climate-change scenarios (for a review see e.g. Wilby and Wigley, 1997; Xu, 1999; Prudhomme et al., 2002; Burlando and Rosso, 2002a). Within this study, GCM results are disaggregated to fit WaterGAP's 0.5-degree resolution and simple downscaling algorithms are applied to derive daily climate series from the original monthly means. Implications of this approach are further discussed in section 2.3.

- Besides general model uncertainties, the important process of possible land use and land cover change has not been accounted for in the analyzed model runs, due to the absence of a reasonable macroscale land use change scenario.
- In low flow and drought situations, the contribution of groundwater discharge (baseflow) largely determines the remaining flow and its fluctuations. WaterGAP distinguishes groundwater recharge from fast surface and subsurface runoff in a heuristic approach (Döll et al., 2002), and applies a simple linear storage equation to calculate the baseflow. However, the accuracy of the baseflow module has not been fully evaluated yet.
- For both flood formation and the occurrence of droughts, the storage and retention of water in lakes, reservoirs and wetlands is of high importance. In WaterGAP, these processes are

addressed by 'local' lake, reservoir and wetland storage within each cell, and by applying a global drainage direction map along which the discharge is routed downstream from cell to cell. On this passage the discharge can re-enter 'global' lake, reservoir or wetland storage. However, WaterGAP implements only simple storage approaches as no further data on reservoir control or retention behavior is available. As a consequence, the model results are likely to locally underestimate the human influence of reservoir management and flood control.

- The scaling algorithm of the monthly climate time series as outlined in section 2.1.2 does not account for changes in the inter-annual variability of precipitation and temperature. Only the long-term trend and changes in the seasonal (inner-annual) climate are reflected. However, as the year-to-year variability is unlikely to remain constant in a changing climate, the results may underestimate this additional influence on flood and drought occurrences.
- Due to the different seasonal behavior and distinct processes involved, flood and drought studies typically discriminate into spring/summer vs. autumn/winter events. In our presented interim assessment we disregard this separation, which may significantly influence the statistical calculations.
- Besides the uncertainties regarding climate change, the applied water use scenario is only one selected projection of future socioeconomic developments. Other legitimate projections are possible and may lead to different results.

2.2 Flood and drought calculations with WaterGAP

The general objective of flow frequency analyses is to relate the magnitude of extreme low or high flows to their frequency or probability of future occurrence. As a result, e.g. the water levels of a '100-year flood', or the severity of a '100-year drought' can be identified, which are statistically exceeded once every 100 years. The analysis commonly starts by selecting either the most extreme event in each year (annual maximum series), or all events that exceed a certain threshold, independent of their time lag (partial duration series). To finally derive a basin's flood or drought frequency distribution, the selected extreme values are ranked and fitted to a model statistical distribution, or probability density function (pdf), which allows for inter- and extrapolation of the frequency distribution. Several distribution functions have been developed to serve this purpose but no single statistical distribution has been found that fits all data (Jones, 1997; Tallaksen, 2000).

In this study, the annual maximum series is applied as the same statistical method for both flood and drought frequency calculations. Thus, for each year the most extreme flood and drought event needs to be selected. Due to their fundamentally different characteristics, however, we discriminate in identifying flood and drought events. Floods are defined through their peak flows, representing the state of maximum inundation or potential damage. Droughts, on the other hand, are defined as persistent periods of shortfalls in river discharge.

Floods. Typically, floods are determined by extreme but relatively short-term peak flows, and for the calculation of flood events at least daily precipitation values are required. To provide this resolution, most current climate impacts studies on floods use monthly GCM outputs and rely on simple downscaling techniques to derive daily time series (e.g., Prudhomme et al., 2002; Burlando and Rosso, 2002a). There are many methods of temporal downscaling, including empirical approaches, multiple-regression models, and weather generator techniques, but it is not clear which method provides the most reliable estimates of daily rainfall (Prudhomme et al., 2002). In WaterGAP, pseudo-daily precipitation values are generated from monthly values by utilizing the provided information on the number of observed wet days per month, such that there are days with and without precipitation. The monthly rainfall volume is then equally distributed over all wet days. In order to include information on rainfall persistency, the distribution of wet days within a month is modeled as a two-state, first-order Markov chain. This simple temporal downscaling approach excludes the option of simulating single flood events, as there is no 'real' daily precipitation input into the model. Nevertheless, when looking at long time series, the overall stochastic sequences of wet and dry spells are, to some degree, reflected in the model. To what extent WaterGAP is able to simulate statistical flood frequency distributions from the pseudo-daily values is investigated in section 2.3.3. In the scenario calculations, the number of wet days remains at the present-day value, and a change in monthly precipitation as simulated by the GCMs is translated into a homogeneous increase or decrease of daily precipitation. The expected increase of climate variability at the daily scale is not taken into account.

Droughts. Droughts are typically induced by mid to long-term low flows with slowly growing water deficits. For the calculation of droughts, the standard output of WaterGAP in the form of monthly discharge values is considered adequate, as it eliminates daily fluctuations, which are often arbitrary or artificial in low flow periods, while being short enough to represent single drought events. Unlike floods, which were defined through their peak flows, droughts are considered as ongoing situations where the discharge stays below a reference minimum flow. In this 'threshold level method', each drought spell is characterized by its time of occurrence, duration, minimum flow, and deficit volume (or severity) (Tallaksen, 2000; Smakhtin, 2001) (Figure 1). Besides the option for a constant threshold value for all data over time (as illustrated in Figure 1) or a variable threshold (e.g. oscillating on a seasonal basis), the general magnitude of the threshold level is highly significant. Marginal differences can decide between termination and continued growth of a drought event. A threshold level which is too low might lead to a high number of no-drought years making the few identified drought events statistically uncertain to evaluate. In contrast, with a high threshold level the likelihood for a series of small single drought events being combined into one severe multi-year drought increases. As a compromise, this study applies the median of monthly discharges, based on the time series 1961-90, as a constant threshold value for all data over time (i.e. both for the present and the future). Because the monthly median is a relatively high threshold value, drought events start soon on the falling hydrograph and the deficits reach rather high volumes. Although arguable, this may still correctly mark the beginning of a 'relative' drought event, i.e. a period when streamflow is not sufficient to supply established uses under a given water management system (Demuth and Stahl, 2001), as these may have been adapted to long-term means.

Frequency distributions. To determine the annual maximum series, the highest flood and drought records per year are selected, i.e. the highest daily discharge for floods, and the highest deficit volume for droughts. Due to the applied method, multi-year droughts may be identified more than once. The annual maximum series are calculated for all cells of the WaterGAP grid and, for evaluation purposes, for the data of selected gauging stations. The frequency distributions are then derived by fitting the Log-Pearson Type III distribution, a widely applied distribution function in both flood and drought assessments, to the ranked annual maximum series. This procedure delivers an individual frequency distribution for each cell.

2.3 Evaluation of WaterGAP focusing on floods and droughts

The WaterGAP model has been tuned for 126 drainage basins and sub-basins within Europe, which cover approx. 65% of Europe's land area, by adjusting a runoff coefficient such that the simulated long-term average discharge differs by less than 1% from the measured discharges (data of gauging stations provided by GRDC, 1999). For all other basins the runoff coefficient has been regionalized based on selected physical basin characteristics (Döll et al., 2003). In a global-scale evaluation the model demonstrated its capability to provide robust simulations of present long-term average discharges, and to estimate annual discharges and monthly high and low flow statistics within reasonable limits, in particular for the tuned basins and for large areas (> 20,000 km^2, Döll et al., 2003). However, the quality of the results decreases for shorter time periods and for smaller basin sizes.

In this section, the performance of WaterGAP is further investigated with respect to flood and drought frequency calculations. For this purpose, model simulations of high and low flow events are compared to discharge measurements of selected gauging stations. Most of the available observed data, however, were also used for tuning the model in the first place, as it was aimed to include all suitable GRDC stations in the tuning process. Despite this limitation, the following evaluation intends to analyze the general reliability of high and low flow calculations which are derived from a large-scale model that (i) uses downscaled monthly values of precipitation and temperature as input, and (ii) is calibrated to long-term average discharges only. All comparisons refer to the 1961-90 baseline period.

2.3.1 Monthly high and low flows

First, as a general indicator, WaterGAP's performance in simulating statistical monthly high and low flows in Europe is evaluated, both in terms of timing and magnitude. For the comparisons, the monthly discharge series of 39 GRDC stations have been selected in equal distribution over Europe (34 of the stations were also used for calibration, compare Figure 2).

As for timing, the highest and lowest month within the long-term seasonal regime are identified for every station. Looking at the highest seasonal flows, WaterGAP simulations agree with 31 of the GRDC stations within ±1 month. The largest difference within the remaining stations is 4 months (maximum possible difference: 6 months). For the lowest seasonal flows, WaterGAP agrees with 26 stations within ±1 month, and the largest difference is 5 months. The slightly weaker correspondence in the low flow simulations can be attributed to the generally smaller and more steady monthly discharge values during the low flow season, where small errors can lead to a mismatch of several months. We also found that in some cases WaterGAP simulates the lowest flows in winter, due to precipitation being stored as snow, while the observed values show the lowest flows in late autumn. This error is most likely caused by the simple snow module of WaterGAP combined with its downscaling algorithm to derive daily temperatures from monthly means (see also Lehner et al., 2001).

As for magnitudes, characteristic indicator values are analyzed: the monthly Q_{90} (i.e. the discharge that is exceeded in 9 out of 10 months) as a typical low flow indicator, and analog the monthly Q_{10} as a high flow indicator (Figure 3). The correlation of observed and modeled high and low values is good, with modeling efficiencies (Nash-Sutcliffe coefficients) of 0.79 and 0.98, respectively. If specific discharges are used, i.e. the Q_{90} and Q_{10} values are divided by the basin area, the modeling efficiencies are still acceptable at 0.56 and 0.86. Again the low flow values show a weaker correspondence, with similar reasons as discussed above. The three most significant outliers are gauging stations along the Danube river, downstream of the confluence with the Alpine Inn river. The Inn shows an observed Q_{90} of 359 m^3/s, whereas WaterGAP simulates only 129 m^3/s. Errors in the snow module or effects of reservoir operation along the Inn may be responsible for this error, which is then passed on to the downstream stations.

Overall, WaterGAP demonstrates a reasonable performance in simulating timing and magnitude of average monthly high and low flow values in Europe. However, some significant errors occur for certain stations and conditions.

2.3.2 Frequency distributions

Next, WaterGAP's capability to compute basin characteristic flood and drought frequency distributions is tested. For the drought analysis, which is based on monthly discharge values, the same 39 GRDC stations as before are applied. For the flood analysis, only those 21 European GRDC stations were selected which provide a complete daily discharge measurement series for 1961-90 (Figure 2). This criterion excludes mainly southern European stations. Of the 21 stations, 19 were used for calibration.

Before looking at actual frequency distributions, the main characteristics of the simulated annual maximum series, i.e. the annual maximum daily discharges for floods, and the annual maximum deficit volumes for droughts, are analyzed for a selected example. Figure 4 illustrates a comparison of GRDC observed data and WaterGAP model results for the Czech part of the

Elbe river at gauging station Decin (approx. 51,000 km^2). This station was selected because it represents a relatively unimpaired basin in central Europe, and although the results may not be transferable to other locations, they allow for a discussion of the main arguments.

As for the deficit volumes, the general behavior of the Elbe river is reasonably reproduced by WaterGAP. Exceptions like the years 1978-79, where WaterGAP overestimates the drought severity, may be attributed either to errors in the model calculations, to human influences (abstractions, reservoir management, etc.), or to the sensitivity of the method regarding the applied threshold value. For the maximum daily flows, however, there is only poor correspondence between observed and modeled time-variation curves. This result is not surprising considering the fact that WaterGAP operates with pseudo-daily precipitation values, downscaled from monthly averages. Additionally, in the illustrated case of the upper Elbe basin, the tendency of the model to overestimate the peak flows is likely to be caused by the simulation of too much snow storage in winter, leading to a snowmelt with unrealistically high peak flows in spring.

Despite this discrepancy, the statistical distribution of flood events may, to a certain degree, be reflected in WaterGAP, as it simulates stochastic sequences of wet and dry spells and models the main physical basin characteristics, which are important for flood formation. Figure 5 illustrates the flood and drought frequency distributions for the Elbe river at station Decin as derived from the annual maximum series presented in Figure 4. For drought frequencies, the agreement of observed and modeled curves is within reasonable bounds, e.g. showing a difference of approx. 10% for the 100-year event. For flood frequencies, WaterGAP significantly overestimates the GRDC results, with an error in the 100-flood discharge of over 50%. A striking result, however, is that despite the strong discrepancy in absolute values the overall shape of modeled and observed distribution functions are similar, differing only by a more or less constant factor (the same is observed for the drought frequencies, but here the better overall agreement can be expected to lead to closer shapes).

For a better interpretation of this behavior, we applied the index-flood method to the flood frequency distributions. The index-flood procedure was originally introduced as a simple regionalization technique and has a long history in flood frequency analysis. The concept underlying the index-flood method is that the distribution of floods at different but comparable sites in one region is the same except for a scaling or 'index-flood' factor which reflects the size, rainfall and runoff characteristics of each watershed (Maidment, 1993). This means that the shape of the dimensionless flood frequency distribution, normalized to an index-flood value, is characteristic for a particular site. Generally, for normalization the mean discharge, or a flood flow of lower return period, e.g. 2 or 2.33 years, is employed as the index-flood value (Maidment, 1993; WMO, 1994; Dyck and Peschke, 1995).

Figure 6 shows the normalized frequency distributions of station Decin and of three other stations. Every discharge value has been divided by the index-flood value, here defined as the respective 2-year flood. The index-flood curves based on observed data and on modeling results show good agreement. The distinctive shapes of the curves reflect the different flood behavior of the four basins due to their physical characteristics as well as their typical rainfall or snowmelt patterns. In the case of the Elbe river, relative flood events seem to be preserved in the model although the single flood events do not occur at the correct times and in correct magnitudes. E.g. a flood that exceeds 2.2 times the 2-year flood occurs once in 100 years both in reality and in the model, yet not in the same year.

These results, however, should not be mistaken for proof of the accuracy of WaterGAP. From the 21 test basins, eleven showed good results when comparing their index-flood curves (including the four stations of Figure 6), six showed medium agreement and four an unsatisfactory correlation with differences in the discharge ratio of more than one unit for the 200-year floods. More studies need to be carried out using a wide spectrum of test basins before the accuracy of WaterGAP can be finally evaluated. Nevertheless, the example suggests that WaterGAP, despite its coarse input data downscaled from monthly resolution, can provide reasonable estimates of relative flood frequency distributions for large-scale watersheds.

Finally, to provide an overview of all investigated European stations, the absolute 100-year flood and drought values have been extracted from their respective frequency distributions and are compared in Figure 7. WaterGAP equally over- and underestimates the 100-year flood discharges and drought deficit volumes, thus indicating no systematic error. With a modeling efficiency of 0.88 for droughts, the correspondence of observed and modeled results is good. For floods the general correlation is lower, but considering the significant errors as illustrated in the example of the Elbe river, the overall modeling efficiency of 0.78 is still acceptable.

In summary, we conclude that for Europe WaterGAP is capable of reasonably estimating large-scale high and low flow regimes, general drought statistics, and, although to a limited degree, relative, basin-specific flood frequency distributions. However, WaterGAP shows less accuracy in the absolute values of flood discharges, and it is currently not able to simulate single flood events. With respect to these findings, only relative results of changes in flood and drought frequencies are further analyzed in this study, and no absolute discharges will be discussed.

3. Results and discussion

Figures 8 and 9 provide a continental overview of simulated changes in flood and drought frequencies for Europe. The results are based on a set of WaterGAP runs, employing model outputs of the two GCMs ECHAM4 and HadCM3 and the Baseline-A water use scenario for the time slices of the 2020s and 2070s. As a representative indicator, the changes in the 'recurrence of a typical 100-year event' are illustrated, both for floods and droughts. We chose the 100-year event because many approaches in engineering (design of reservoirs, flooding zones, etc.) employ this reference level. And we chose the 'recurrence' indicator over 'intensity' because we felt that a statement like "in future today's 100-year floods may recur every 40 years" is easier to rate than "… will increase by 10%". However, as the frequency distribution is known, a change in the return period of a certain event can be interpreted equivalently as a change in its magnitude or intensity (Figure 10). To allow for comparison, the legend of Figure 11 illustrates changes in the intensity of 100-year droughts. Although the transformation is not linear, a comparison of the legends of Figures 9 and 11 can thus be used to serve as an average translation between recurrence and intensity. For example, a reduction in the recurrence of a 100-year event to 40 years can be interpreted equivalently as an increase of its intensity by 10%. The same relation was found to be adequate for flood events.

All values are visualized at the cell level of WaterGAP's calculation grid at 0.5-degree resolution. For interpretations, however, only uniform regional patterns and trends are considered to be significant. We refrain from calculating basin or country statistics as the nature of flood and drought frequencies does not support the concept of spatial averaging or compensation.

As a general finding of the analysis, typical 100-year floods are projected to occur more frequently in large areas of northern and northeastern Europe (Sweden, Finland, northern Russia). In contrast, 100-year droughts show strong increases for large areas of southern and southeastern Europe (Portugal, all Mediterranean countries, Hungary, Bulgaria, Romania, Moldova, Ukraine, southern Russia). In the long-term projection for the 2070s, the current 100-year events are calculated to occur every 40 years or even more often in these areas – in the most extreme cases reaching return periods of 10 years and below. Complementary to the regions with rising flood and drought risks, large parts of southern Europe show a decrease in the 100-year flood recurrence, while northern Europe shows a reduction in 100-year droughts. Besides general changes in the precipitation amounts, alterations in the snowmelt pattern and in the evaporation processes due to rising temperatures are likely to be the most effective climate-related factors of change.

Smaller areas affected by a rise in 100-year flood recurrences are the Vistula basin in eastern Poland, the Irish Island, some river courses originating in the Alps, and parts of Portugal and Spain. The latter is rather remarkable as the climate scenarios generally predict a decrease in average precipitation amounts for the Iberian Peninsula. The increase in the 100-year flood recurrence must therefore be attributed to a seasonal change in the flow regime towards both more extreme high and, as a consequence of the lower average water availability, low flow months.

It should be noted, however, that especially in arid and semiarid areas the calculation of flood frequency distributions is very critical, as typically very few extreme flood events determine the statistics and make the extrapolation of return periods highly susceptible to errors. A similar statistical artefact occurs for the drought calculations in Scandinavia. Here, some dark cells suggest a rise in the 100-year drought risk. A more detailed evaluation of the model results, however, revealed an actually strong increase in average discharges so that in most years the applied threshold value is exceeded, leaving only a few years with deficit volumes other than zero. The statistical frequency distributions derived for these singular data are not valid any more and deliver meaningless results.

The model runs, based on the two different GCMs, agree in their estimates of more pronounced changes for the 2070s. While the results with ECHAM4 seem to be relatively consistent over time, the projections based on HadCM3 are contradictory for the 2020s and 2070s in several regions (e.g., eastern Spain, Alps, Italy for floods; Scandinavia, Bulgaria for droughts). Also, depending on which of the two climate models is applied, some areas show opposite developments or different magnitudes of change. Only few regions show a steady, consistent improvement in their flood or drought risk situation throughout both GCMs and both time slices (e.g., parts of Germany, the Balkan, Ukraine and Turkey for floods; Finland and northern Russia for droughts).

The identified regions of strongest change are generally in accordance with areas for which the ACACIA report (Parry, 2000) indicates significant future increases or decreases, respectively, in average annual river discharge. Also, the magnitude of changes is comparable to that of smaller-scale studies (e.g., Prudhomme et al., 2002). However, these comparisons are of limited significance because different climate scenarios and time slices have been applied in the various studies. Other analyses disagree with the presented results. Bergström et al. (2001), for example, found a tendency of decreasing future flood risk in Sweden, in particular for spring events. Burlando and Rosso (2002a, b) point out that in their analysis sensitivities for high and low flow risks changed when different spatial scales were applied. They conclude that, for example, changes in the patterns of summer storms towards shorter and more intense convective rainfall events – which can be accounted for in small-scale models but are often disregarded in large-scale approaches – may lead to diverging trends in the simulated flood frequencies.

Local water abstractions for households, industry or agriculture are not considered to have a major effect on the typically short and extreme flood events. In contrast, during low flow periods water withdrawals can reach or even exceed the dimension of water availability. In order to evaluate the significance of water use changes for future drought severity, a separate WaterGAP run was performed applying the same Baseline-A water use scenario as in the other scenario realizations, but combined with present climate conditions (1961-90). As the Baseline-A scenario assumes no changes in the extent of irrigated areas or their efficiency rates in Europe, the irrigation water demand remains constant and the changes in total water use are caused by industry and households only.

Figure 11 (right map) illustrates the results for the long-term projection of the 2070s. The distinct spatial zoning into western (no change) and eastern Europe (strong change) reflects the applied scenario assumptions: while rather stable water use trends are expected for western European countries, strong increases are projected for eastern Europe due to largely expanding economic activities (Henrichs et al., 2002). The influence of population density and their classification (rural vs. urban) leads to variations within countries (e.g. northern vs. southern Russia). A remarkable transboundary effect occurs for the Elbe river basin: The rising water use in the Czech Republic increases the deficit volumes of the upper Elbe, which are then passed along the downstream river course and finally affect northern Germany (the distinct dark cell-line in northern Germany represent the Elbe river course in WaterGAP's routing scheme).

The comparison of both maps in Figure 11 indicates that the change in drought severity for western European countries is primarily caused by climate change. For eastern Europe, however, the change in water use plays a significant role in the future low flow regimes. Additionally, in the southern parts the superimposed climatic changes even worsen the situation, whereas in the northern regions the increased water demands are balanced by higher water availability.

Finally, the impact of global change on regional flood and drought characteristics is not only manifested through changes in the magnitude of discharges, but also in terms of temporal shifts of the seasonal flow regimes. WaterGAP results based on the HadCM3 climate model indicate that in the 2070s the maximum average discharge may occur about one month earlier than today in large parts of northern and central Europe. This can be explained by the general rise in temperature inducing an earlier snowmelt – a major cause for flood events in these areas. These results are largely consistent with findings of Arnell (1999) for the 2050s. Similar seasonal changes in the same order of magnitude are observed for the low flow regimes. These findings suggest a significant temporal shift of the overall high and low flow regimes, which may severely affect the established water needs of society as well as the integrity of freshwater ecosystems.

4. Conclusions

Previous studies on the impact of climate change on water resources and hydrology have typically focused either on average flows or, when analyzing extreme events such as floods and droughts, on small areas. They have concentrated either on floods, on droughts, on climate change impacts on water availability, or on the impact of socioeconomic changes on water use. In contrast, this paper outlines a first continental, integrated approach of how to analyze the impacts of global change – i.e. climate and water use change – on future flood and drought frequencies at a pan-European scale.

The applied global integrated water model WaterGAP has been evaluated regarding its capability to simulate high and low flow regimes by comparing its results to observed discharges. WaterGAP revealed a different quality for assessing floods as opposed to droughts. Despite its coarse spatial and temporal resolution, WaterGAP delivered reasonable results for the simulation of drought events, which are typically expressions of low flows persisting over several months and large areas. In contrast, the model is currently not qualified for explicit, single-event flood calculations, because the determining daily precipitation values are downscaled from large-scale monthly averages and do not reflect actual day-to-day patterns. Only relative measures, e.g. the ratio of a 100-year flood to a 2-year flood within a given basin, derived by applying normalized, basin characteristic frequency distributions, showed acceptable correlation with observed data. With respect to these findings, WaterGAP was applied to calculate relative changes in flood and drought frequencies, instead of providing absolute discharge values.

To demonstrate both agreements and divergences of different model runs, a set of WaterGAP simulations was performed, based on two GCMs (ECHAM4 and HadCM3) and the Baseline-A water use scenario for two time slices. In largely concurring trends, the regions most prone to a rise in flood frequencies are northern to northeastern Europe (Sweden, Finland and northern Russia), while southern and southeastern Europe show significant increases in drought frequencies (Portugal, Spain, western France, Italy and most of southeastern Europe). It should be noted, however, that these results do not reflect the entirety of possible effects of climate change, and that therefore the extent or intensity of rising flood and drought risks may have been underestimated. For example, expected increases in the variability of daily precipitation have not been accounted for. As this process is of high relevance for flood analyses, its inclusion may lead to a significant rise in flood frequencies also in parts of southern Europe.

The WaterGAP model results can be used to highlight 'critical regions', for which significant changes in flood or drought occurrences are conceivable under the proposed global change scenarios. If we define critical regions as areas where either floods or droughts with an intensity of today's 100-year events may recur every 50 years or more often, large parts of Europe are identified in the long-term projections of the 2070s (Figure 12). However, to what extent these areas will experience an actual rise in risks and threats will additionally depend on the present situation within these critical regions.

Some smaller regions, like the Vistula basin in western Poland and parts of Portugal, show indications for a rise in both flood and drought frequencies. This behavior may be due to a change in the seasonal variability of precipitation and temperature in these areas that lead to both more extreme high and low flow months. Similar trends have been observed in smaller-scale analyses for other European regions (e.g., Pilling and Jones, 2002). However, within the presented continental scale approach, these distinct and rather detailed results are considered very preliminary and may also reflect model inaccuracies.

A separate analysis, which looked at the impact of a change in water use at stable climate conditions, indicated that the direct anthropogenic influence on future droughts through water consumption is in the same order of magnitude as the simulated impact of climate change. The anticipated strong increases in water use for eastern European countries due to their increased economic activity may thus cause or intensify severe hydrological or operational droughts.

The primary objective of presenting this study without rigorous analysis of all uncertainties is to demonstrate a technique for analyzing the impacts of global change on flood and drought frequencies on a continental scale. However, the accurate estimation of climate change impacts is difficult using this or any other approach. The climate system is governed by many interrelated factors, the change in climate variables, particularly precipitation, cannot be estimated reliably, and it is currently difficult to develop appropriate downscaling methodologies (Chiew and McMahon, 2002; Prudhomme et al., 2002). Furthermore, "the fluvial system contains many complex interactions and while climate may be the 'driving force' there is a considerable 'cultural blur' in the history of European and many other rivers ... , which can make it difficult to distinguish between changes in flood frequency that are climatically induced and those that are due to human activity. Often the changes are a mixture of the two" (Jones, 1997). Similarly, "the analysis of river flow drought suffers from the effects of artificial influences in many cases (urbanisation, effluents, abstractions) which makes drought severity calculation difficult" (Tate and Gustard, 2000).

While fully recognizing the potential errors inherent in the presented approach, emphasis should be made of the scope of this study: to serve as an initial, interim assessment until better information becomes available. The main modeling limitations have been highlighted, and a cautionary response is expected from professionals experienced in the analysis of flood and drought frequencies and its statistical background. Still, we believe that the mapped changes in flood and drought frequencies provide a useful visual portrayal of the spatial pattern and extent of conceivable global change impacts within the European river network. The findings can serve as a continental framework and as a basis for critical comparisons. Finally, the identification of extensive 'critical regions' and the dimension of changes suggest that beyond the trends in long-term average water resources a significant change in hydrological extremes needs to be accounted for in future water management plans. These results, though interim and preliminary, underpin the importance of developing mitigation and adaptation strategies on a pan-European scale.

Acknowledgements

This work was carried out with financial support of the German Federal Ministry of Education, Science, Research and Technology (BMBF) under research project 01 LA 9809/1 (EuroWasser). The authors wish to thank their colleagues at the Center for Environmental Systems Research, University of Kassel, for assistance with and discussions of the WaterGAP calculations.

References

Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T., and Siebert, S.: 2003a, 'Development and testing of the WaterGAP 2 global model of water use and availability', *Hydrolog. Sci. J.* 48 (3), 317–337.

Alcamo, J., Döll, P., Henrichs, T., Kaspar, F., Lehner, B., Rösch, T., and Siebert, S.: 2003b, 'Global estimates of water withdrawals and availability under current and future "business-as-usual" conditions', *Hydrolog. Sci. J.* 48 (3), 339–349.

Alcamo, J., Leemans, R., and Kreileman, E.: 1998, *Global change scenarios of the 21st century – Results from the IMAGE 2.1 model*, Elsevier, Oxford, UK.

Arnell, N.W.: 1994, 'Variations over time in European hydrological behaviour: a spatial perspective', in FRIEND, *Flow Regimes from International Experimental and Network Data*, IAHS Publ. 221, pp. 179-184.

Arnell, N.W.: 1999, 'The effect of climate change on hydrological regimes in Europe: a continental perspective, *Global Environ. Change* 9, 5-23.

Arnell, N.W., Grabs, W., Mimikou, M., Schumann, A., Reynard, N.S., Kaczmarek, Z., Oancea, V., Buchtele, J., Kasparek, L., Blazoka, S., Starosolszky, O., and Kuzin, A.: 2000*, Effect of climate change on hydrological regimes and water resources in Europe*, Summary report of projects EV5V-CT93-0293 and EV5V-CT94-0114, University of Southampton, UK.

Bergström, S., Carlsson, B., Gardelin, M., Lindström, G., Pettersson, A., and Rummukainen, M.: 2001, 'Climate change impacts on runoff in Sweden - assessments by global climate models, dynamical downscaling and hydrological modelling', *Climate Res.* 16, 101–112.

Bradford, R.B.: 2000, 'Drought events in Europe', in Vogt, J.V. and Somma, F. (eds.), *Drought and drought mitigation in Europe - Advances in natural and technological hazards research*, Vol. 14, Kluwer, pp. 7-20.

Burlando, P. and Rosso, R.: 2002a, 'Effects of transient climate change on basin hydrology. 1. Precipitation scenarios for the Arno River, central Italy', *Hydrol. Process.* 16, 1151–1175.

Burlando, P. and Rosso, R.: 2002b, 'Effects of transient climate change on basin hydrology. 2. Impacts on runoff variability in the Arno River, central Italy', *Hydrol. Process.* 16, 1177–1199.

Chiew, F.H.S. and McMahon, T.A.: 2002, 'Modelling the impacts of climate change on Australian streamflow', *Hydrol. Process.* 16, 1235–1245.

Demuth, S. and Stahl, K. (eds.): 2001, *Assessment of the Regional Impact of Droughts in Europe*. Final Report to the European Union, ENV-CT97-0553, Institute of Hydrology, University of Freiburg, Germany.

Döll, P.: 2002, 'Impact of climate change and variability on irrigation requirements: a global perspective', *Climatic Change* 54 (3), 269-293.

Döll, P. and Lehner, B.: 2002, 'Validation of a new global 30-min drainage direction map', *J. Hydrol.* 258, 214-231.

Döll, P., Kaspar, F., and Lehner, B.: 2003, 'A global hydrological model for deriving water availability indicators: model tuning and validation', *J. Hydrol.* 270, 105–134.

Döll, P., Lehner, B., and Kaspar, F.: 2002, 'Global modeling of groundwater recharge', in Schmitz, G.H. (ed.), *Proceedings of Third International Conference on Water Resources* *and the Environment Research*, Technical University of Dresden, Germany, ISBN 3-934253-17-2, Vol. I, pp. 27-31.

DVWK (Deutscher Verband für Wasserwirtschaft und Kulturbau e.V.): 1998, *How to work out a drought mitigation strategy*. Guidelines for water management 309/1998, an ICID (International Commission on Irrigation and Drainage) Guide, Bonn, Germany.

Dyck, S., and Peschke, G.: 1995, *Grundlagen der Hydrologie*, Verlag für Bauwesen, Berlin.

EEA: 1999, *Environment in the European Union at the turn of the century – Environmental Assessment Report No. 2*, European Environment Agency, Copenhagen.

EIA: 2001, *International Energy Annual 2001: Carbon dioxide emissions from use of fossil fuels, 1980-2001*, U.S. Energy Information Administration, Department of Energy. http://www.eia.doe.gov/emeu/iea/carbon.html

Frei, C., Schar, C., Luthi, D., and Davies, H.C.: 1998, 'Heavy precipitation processes in a warmer climate', *Geophys. Res. Lett.* 25 (9), 1431–1434.

Garrido, A. and Gómez-Ramos, A.: 2000, 'Socio-economic aspects of droughts', in Vogt, J.V. and Somma, F. (eds.), *Drought and drought mitigation in Europe - Advances in natural and technological hazards research*, Vol. 14, Kluwer, pp. 197-207.

Gordon, C., Cooper, C., Senior, C.A., Banks, H., Gregory, J.M., Johns, T.C., Mitchell, J.F.B., and Wood, R.A.: 2000, 'The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments', *Clim. Dynam.* 16, 147-168.

GRDC: 1999, *Long term mean monthly discharges of selected GRDC stations*. Global Runoff Data Centre, Koblenz, Germany.

Henrichs, T., Lehner, B., and Alcamo, J.: 2002, 'An integrated analysis of changes in water stress in Europe', *Integrated Assessment* 3 (1), 15-29.

Hulme, M., Doherty, R.M., Ngara, T., New, M.G., and Lister, D.: 2001, 'African climate change: 1900-2100', *Climate Res.* 17, 145-168.

IPCC: 1992, *Climate Change 1992 - The Supplementary Report to the IPCC Scientific Assessment*, Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.

IPCC: 2000, *Special Report on Emission Scenarios*, Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.

IPCC: 2001a, *Climate Change 2001: Impacts, adaptation and vulnerability – A report of Working Group II of the IPCC*. Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.

IPCC: 2001b, *IPCC Third Assessment Report - Climate Change 2001: The Scientific Basis*, Summary for Policymakers, Report of Working Group I. Intergovernmental Panel on Climate Change, Geneva, Switzerland.

Jones, J.A.A.: 1996, 'Current evidence on the likely impact of global warming on hydrological regimes in Europe', in Jones, J.A.A., Liu, C., Woo, M.K., and Kung H.T. (eds), *Regional hydrological response to climate change*. Kluwer, Dordrecht, pp. 87–131.

Jones, J.A.A.: 1997, *Global Hydrology: processes, resources and environmental management*, Longman, England.

Jones, J.A.A.: 1999, 'Climate change and sustainable water resources: placing the threat of global warming in perspective', *Hydrolog. Sci. J.* 44 (4), 541–557.

Jones, J.A.A. and Woo, M.K.: 2002: ‘Modelling the impact of climate change on hydrological regimes’, Editorial Special Issue, *Hydrol. Process.* 16, 1135.

Karl, T., Quayle, R.G., and Groisman, P.I.: 1993, ‘Detecting climate variations and change: new challenges for observing data management systems’, *J. Climate* 6, 1481–1494.

Katz, W.R. and Brown, G.: 1992, ‘Extreme events in changing climate: variability is more important than averages’, *Climatic Change* 21, 289–302.

Kilsby, C.G., Buishand, T.A., and Jones P.D.: 1999, *Production of precipitation scenarios for impact assessment of climate change in Europe (POPSCICLE)*, Final report to the EU, EU project EV5V-CT94-0510, p. 113.

Lehner, B., Döll, P., and Kaspar, F.: 2001, ‚Vergleich von hydrologischen Modellen auf unterschiedlichen Skalenebenen am Beispiel Elbe und Oder‘, in: Sutmöller, J. and Raschke, E. (eds.), *Modellierung in meso- bis makroskaligen Flußeinzugsgebieten*, GKSS 2001/15, GKSS Research Center, Geesthacht, Germany, pp. 160-171.

Maidment, D.R. (ed.): 1993, *Handbook of hydrology*, McGraw-Hill, New York.

Mitchell, T.D. and Hulme, M.: 1999, ‘Predicting regional climate change: living with uncertainty’, *Prog. Phys. Geog.* 23 (1), 57–78.

New, M., Hulme, M., and Jones, P.D.: 2000, ‘Representing twentieth century space-time climate variability – Part II: Development of 1901-1996 monthly grids of terrestrial surface climate’, *J. Climate* 13, 2217-2238.

Parry, M. (ed.): 2000, *The Europe ACACIA project: Assessment of Potential Effects and Adaptations for Climate Change in Europe*, Jackson Environment Institute, Norwich, UK.

Pilling, C.G. and Jones, J.A.A.: 2002, 'The impact of future climate change on seasonal discharge, hydrological processes and extreme flows in the Upper Wye experimental catchment, mid-Wales', *Hydrol. Process.* 16, 1201–1213.

Prudhomme, C., Reynard, N., and Crooks, S.: 2002, 'Downscaling of global climate models for flood frequency analysis: where are we now?' *Hydrol. Process.* 16, 1137–1150.

Röckner, E., Bengtsson, L., Feichter, J., Lelieveld, J., and Rodhe, H.: 1999 'Transient climate change simulations with a coupled atmosphere–ocean GCM including the tropospheric sulfur cycle', *J. Climate* 12 (10), 3004–3032.

Smakhtin, V.U.: 2001, 'Low flow hydrology: a review', *J. Hydrol.* 240, 147-186.

Tallaksen, L.M.: 2000, 'Streamflow drought frequency analysis', in Vogt, J.V. and Somma, F. (eds.), *Drought and drought mitigation in Europe - Advances in natural and technological hazards research*, Vol. 14, Kluwer, pp. 103-117.

Tate, E.L. and Gustard, A.: 2000, 'Drought definition: a hydrological perspective', in Vogt, J.V. and Somma, F. (eds.), *Drought and drought mitigation in Europe - Advances in natural and technological hazards research*, Vol. 14, Kluwer, pp. 23-48.

Voss, R., May, W., and Roeckner, E.: 2002, 'Enhanced resolution modeling study on anthropogenic climate change: changes in extremes of the hydrological cycle', *Int. J. Climatol.* 22, 755-777.

Watson, R.T., Zinyowera, M.C., and Moss, R.H. (eds.): 1997, *The regional impacts of climate change - An assessment of vulnerability*, IPCC Special Report, Summary for Policymakers, Intergovernmental Panel of Climate Change, ISBN: 92-9169-110-0.

Wilby, R.L. and Wigley, T.M.L.: 1997, 'Downscaling general circulation model output: a review of methods and limitations', *Prog. Phys. Geog.* 21, 530–548.

WMO: 1994, *Guide to hydrological practices - Data aquisition and processing, analysis, forecasting and other applications*, World Meteorological Organisation, No. 168.

Xu, C.Y.: 1999, 'From GCMs to river flow: a review of downscaling methods and hydrologic modelling approaches', *Prog. Phys. Geog.* 23 (2), 229–249.

Figure captions

Figure 1:

Definition of drought events and deficit volumes: A drought event is defined to start when the discharge falls below the threshold value and to end when the discharge exceeds the threshold. The deficit volume (or severity) of the identified drought event is calculated by accumulating the monthly differences between threshold and actual discharge values over time.

Figure 2:

Distribution of GRDC stations and associated watersheds as used for evaluation of WaterGAP, visualized upon WaterGAP's river network at 0.5-degree resolution (line thickness proportional to upstream basin area).

Figure 3:

Comparison of GRDC observed and WaterGAP modeled monthly Q_{10} (left) and Q_{90} (right) for 39 European gauging stations (1961-90).

Figure 4:

Comparison of GRDC observed and WaterGAP modeled annual maximum series of daily discharge (top) and deficit volumes (bottom) for the Elbe river at station Decin (51,000 km^2). Modeling efficiencies (Nash-Sutcliffe coefficients): top -0.80, bottom 0.60.

Figure 5:

Flood (left) and drought (right) frequency distributions for the Elbe river at station Decin (51,000 km^2), derived from annual maximum series of daily discharges (floods) and deficit volumes (droughts) of 1961-90 (Log-Pearson Type III distribution).

Figure 6:

Observed and modeled index-flood curves for 4 European basins: Elbe at station Decin (51,000 km^2), Danube at Bratislava (132,000 km^2), Thames at Kingston (10,000 km^2), and Rhone at Chancy (10,000 km^2), derived from time series 1961-90 (Log-Pearson III distribution).

Figure 7:

Comparison of GRDC observed and WaterGAP modeled 100-year flood discharges (left, 21 stations) and 100-year drought deficit volumes (right, 39 stations), derived from time series 1961-90.

Figure 8:

Change in recurrence of 100-year floods. Comparisons of results calculated with WaterGAP 2.1 for today's climate and water use (1961-90) and for the 2020s and 2070s (ECHAM4 and HadCM3 climate models and Baseline-A water use scenario).

Figure 9:

Change in recurrence of 100-year droughts. Comparisons of results calculated with WaterGAP 2.1 for today's climate and water use (1961-90) and for the 2020s and 2070s (ECHAM4 and HadCM3 climate models and Baseline-A water use scenario).

Figure 10:

Characteristic relationship for floods or droughts between a change in return period and the corresponding change in intensity.

Figure 11:

Change in intensity of 100-year droughts. Comparison of results calculated with WaterGAP 2.1 for today's climate and water use (1961-90) and for the 2070s (Baseline-A water use scenario). Left map: Climate of 2070s according to HadCM3 climate model. Right map: Climate of 2070s remains constant at today's climate.

Figure 12:

Critical regions as referred to (i) a decrease in the return period of the current 100-year drought to 50 years or less and (ii) a decrease in the return period of the current 100-year flood to 50 years or less. Calculated with WaterGAP 2.1, based on HadCM3 climate model and Baseline-A water use scenario for the 2070s.

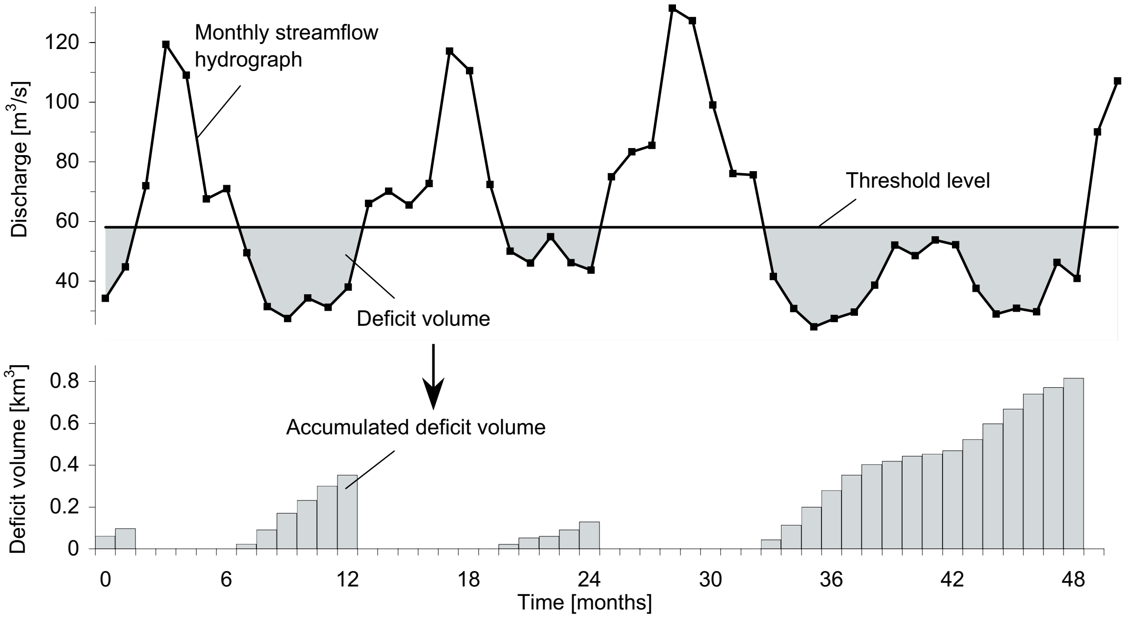

Figure 1

Definition of drought events and deficit volumes: A drought event is defined to start when the discharge falls below the threshold value and to end when the discharge exceeds the threshold. The deficit volume (or severity) of the identified drought event is calculated by accumulating the monthly differences between threshold and actual discharge values over time.

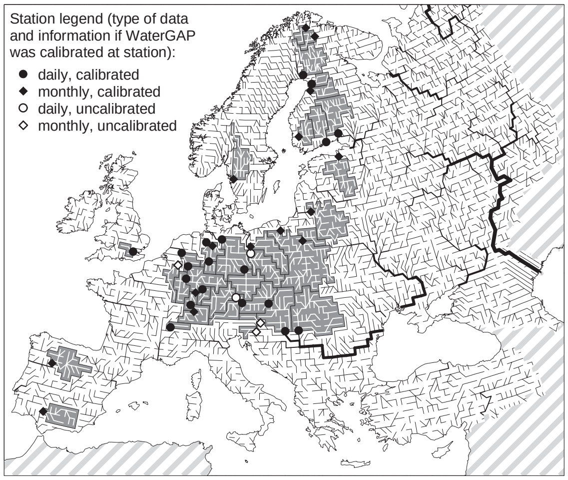

Figure 2

Distribution of GRDC stations and associated watersheds as used for evaluation of WaterGAP, visualized upon WaterGAP's river network at 0.5-degree resolution (line thickness proportional to upstream basin area).

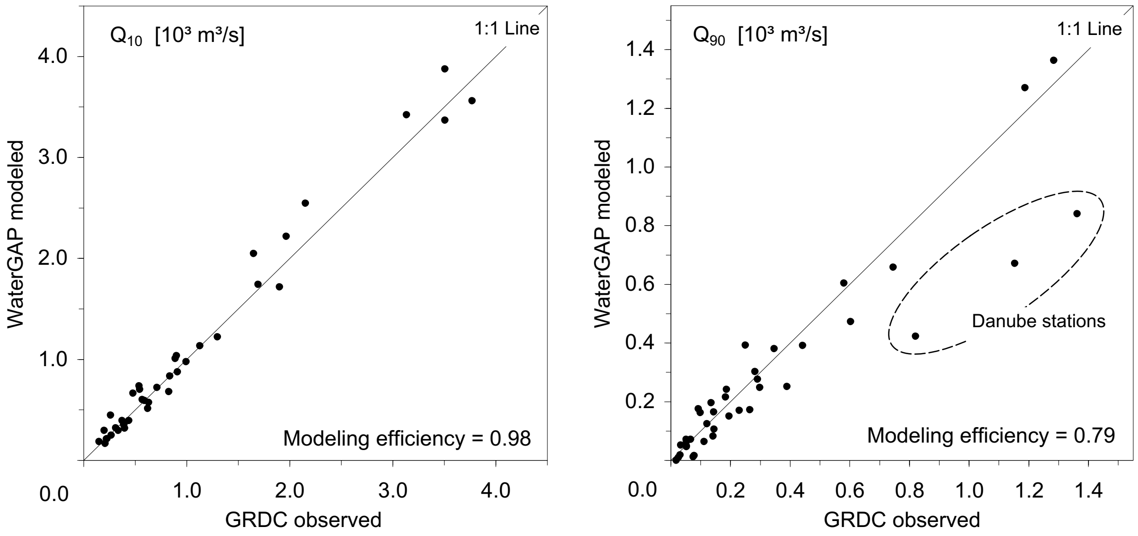

Figure 3

Comparison of GRDC observed and WaterGAP modeled monthly Q_{10} (left) and Q_{90} (right), for 39 European gauging stations (1961-90).

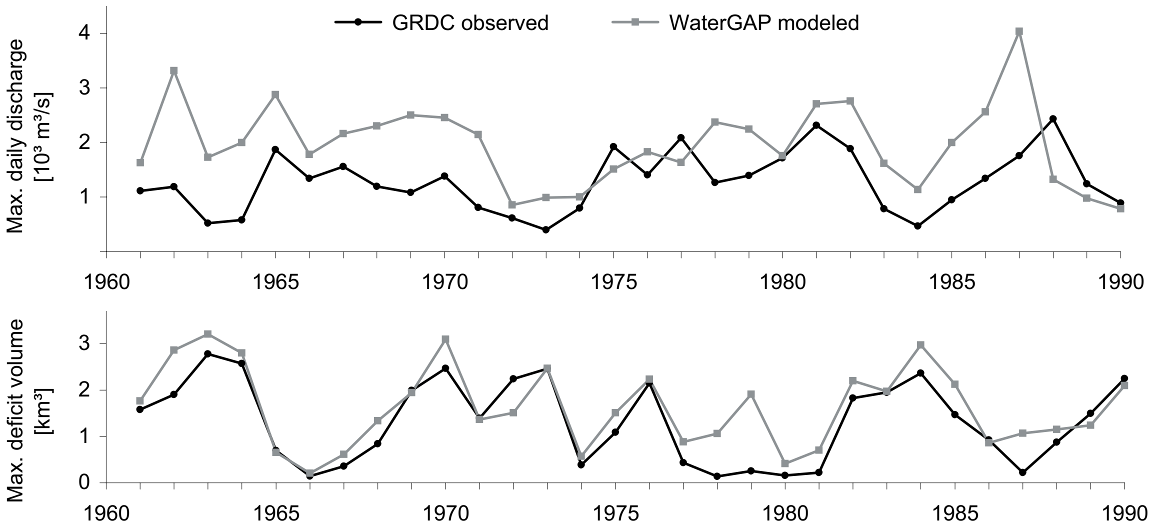

Figure 4

Comparison of GRDC observed and WaterGAP modeled annual maximum series of daily discharge (top) and deficit volumes (bottom) for the Elbe river at station Decin (51,000 km^2). Modeling efficiencies (Nash-Sutcliffe coefficients): top -0.80, bottom 0.60.

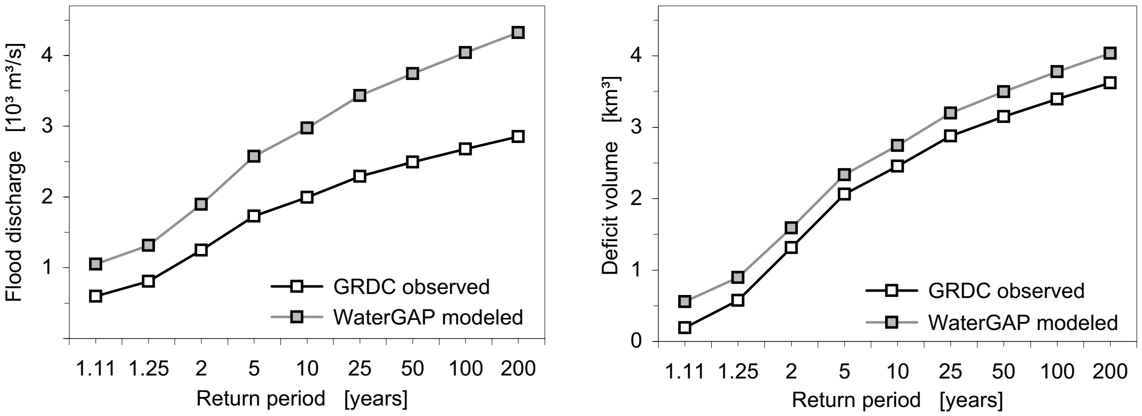

Figure 5

Flood (left) and drought (right) frequency distributions for the Elbe river at station Decin (51,000 km^2), derived from annual maximum series of daily discharges (floods) and deficit volumes (droughts) of 1961-90 (Log-Pearson Type III distribution).

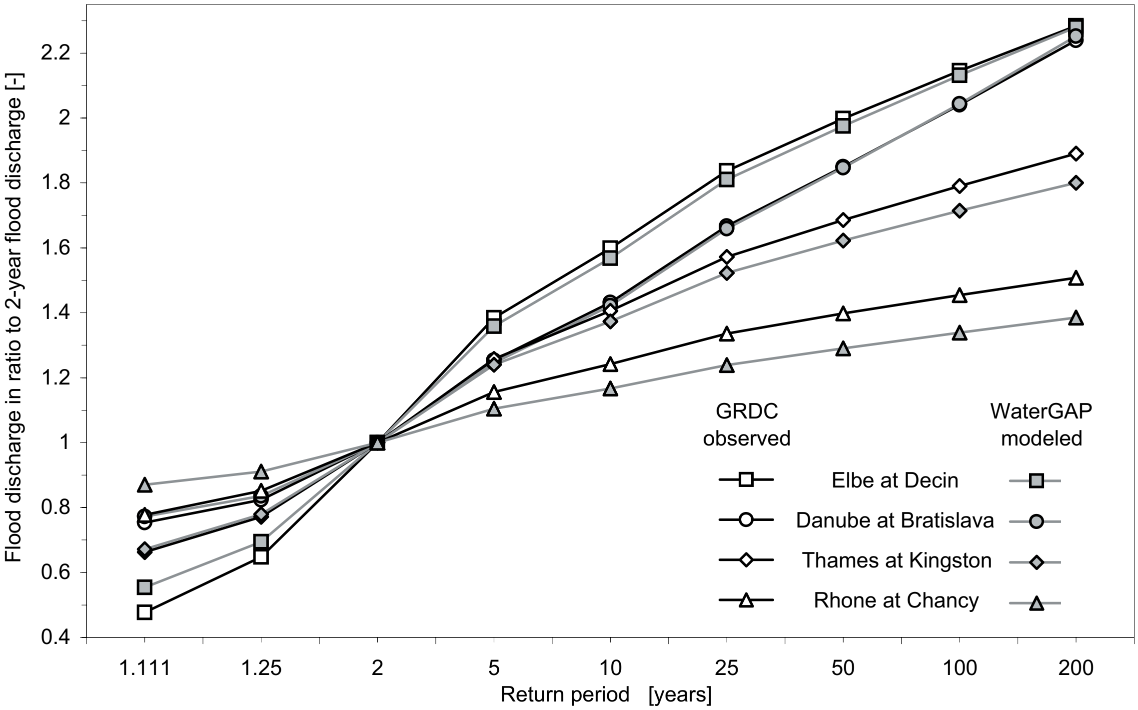

Figure 6

Observed and modeled index-flood curves for 4 European basins: Elbe at station Decin (51,000 km^2), Danube at Bratislava (132,000 km^2), Thames at Kingston (10,000 km^2), and Rhone at Chancy (10,000 km^2), derived from time series 1961-90 (Log-Pearson III distribution).

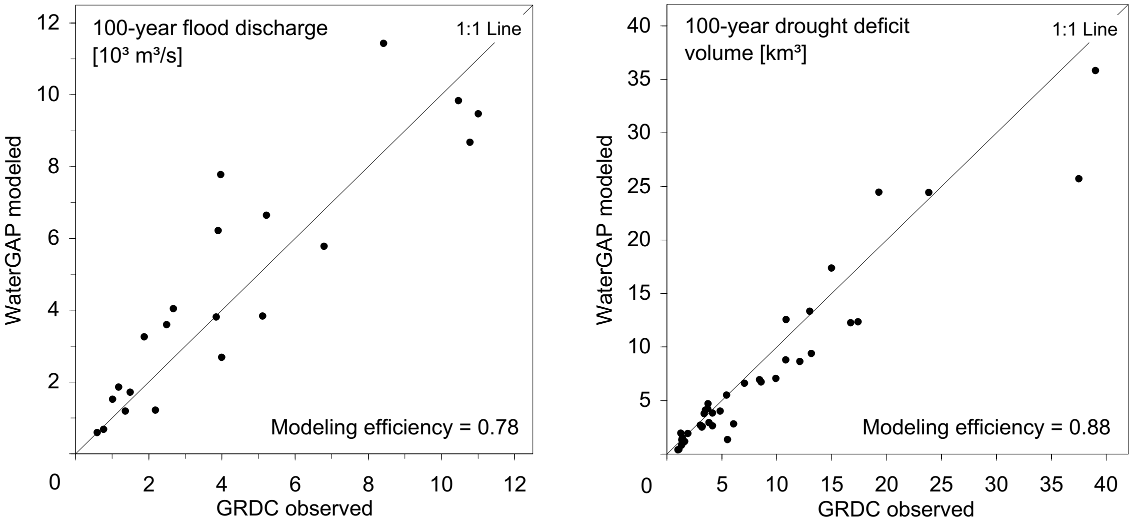

Figure 7

Comparison of GRDC observed and WaterGAP modeled 100-year flood discharges (left, 21 stations) and 100-year drought deficit volumes (right, 39 stations), derived from time series 1961-90.

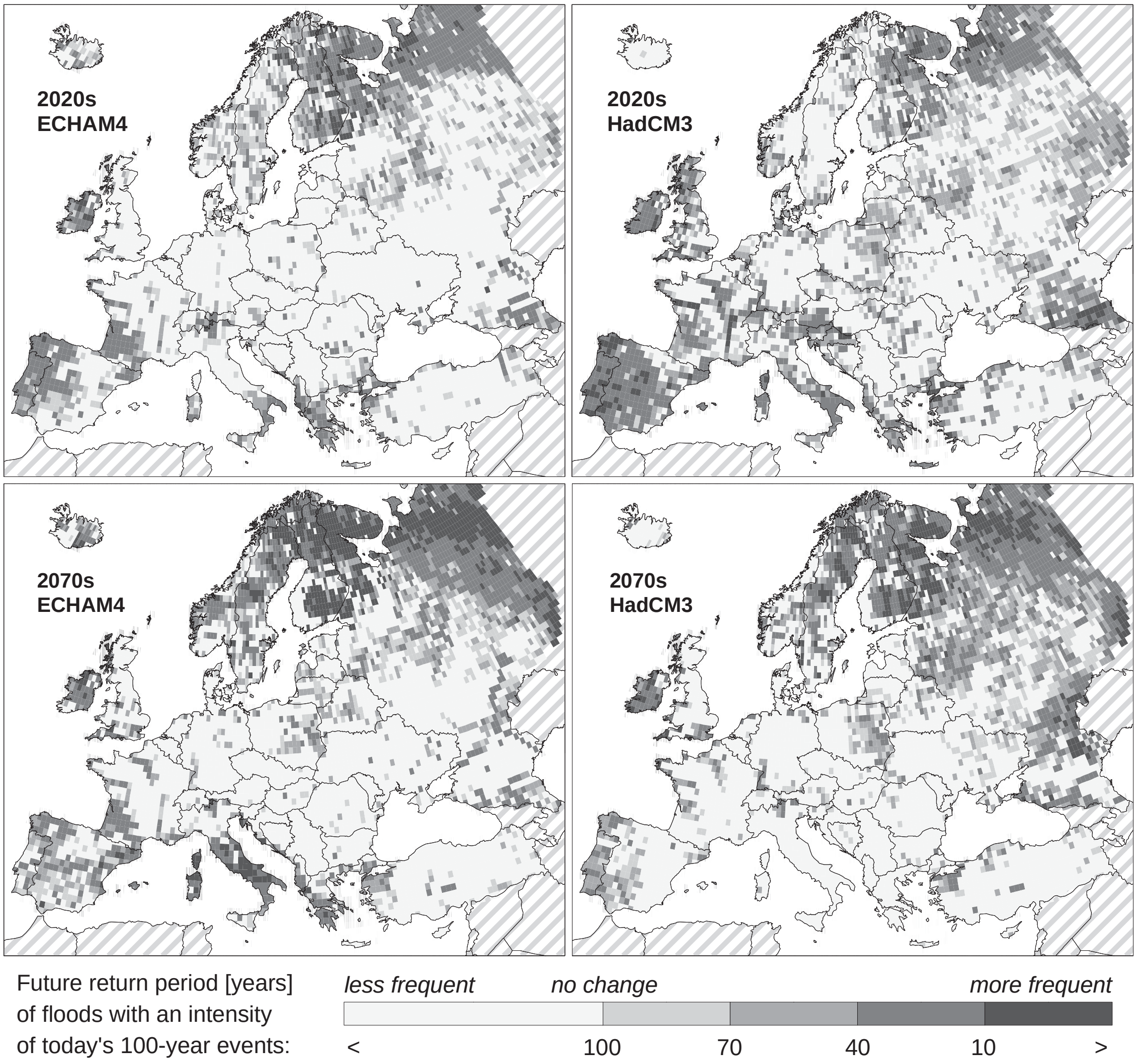

Figure 8

Change in recurrence of 100-year floods. Comparisons of results calculated with WaterGAP 2.1 for today's climate and water use (1961-90) and for the 2020s and 2070s (ECHAM4 and HadCM3 climate models and Baseline-A water use scenario).

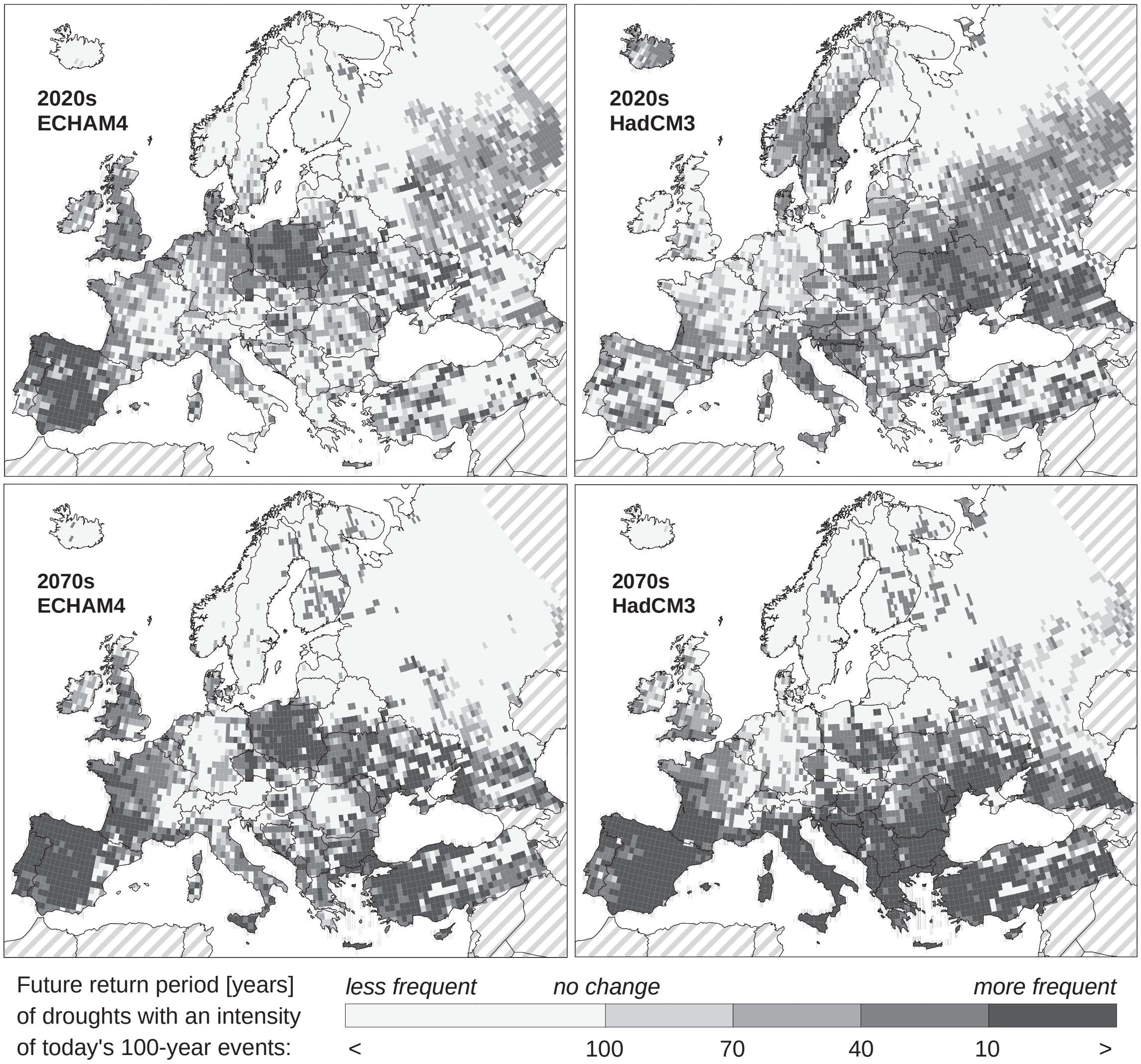

Figure 9

Change in recurrence of 100-year droughts. Comparisons of results calculated with WaterGAP 2.1 for today's climate and water use (1961-90) and for the 2020s and 2070s (ECHAM4 and HadCM3 climate models and Baseline-A water use scenario).

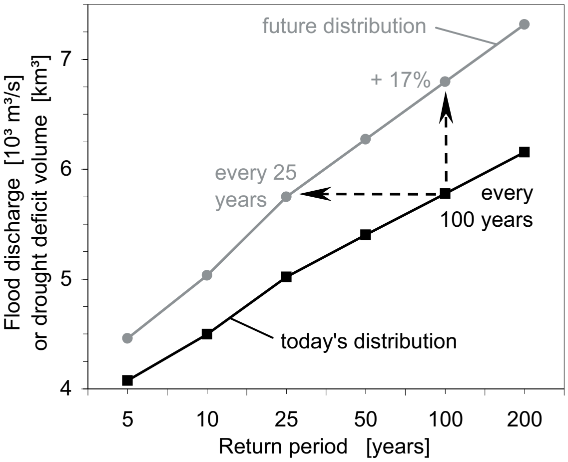

Figure 10

Characteristic relationship for floods or droughts between a change in return period and the corresponding change in intensity.

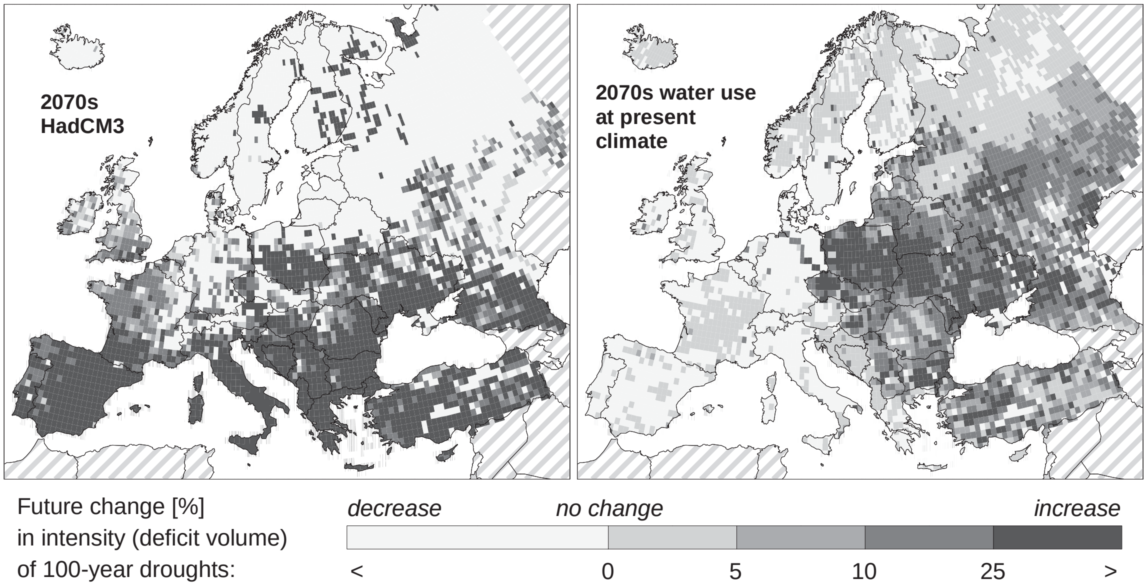

Figure 11

Change in intensity of 100-year droughts. Comparison of results calculated with WaterGAP 2.1 for today's climate and water use (1961-90) and for the 2070s (Baseline-A water use scenario). Left map: Climate of 2070s according to HadCM3 climate model. Right map: Climate of 2070s remains constant at today's climate.

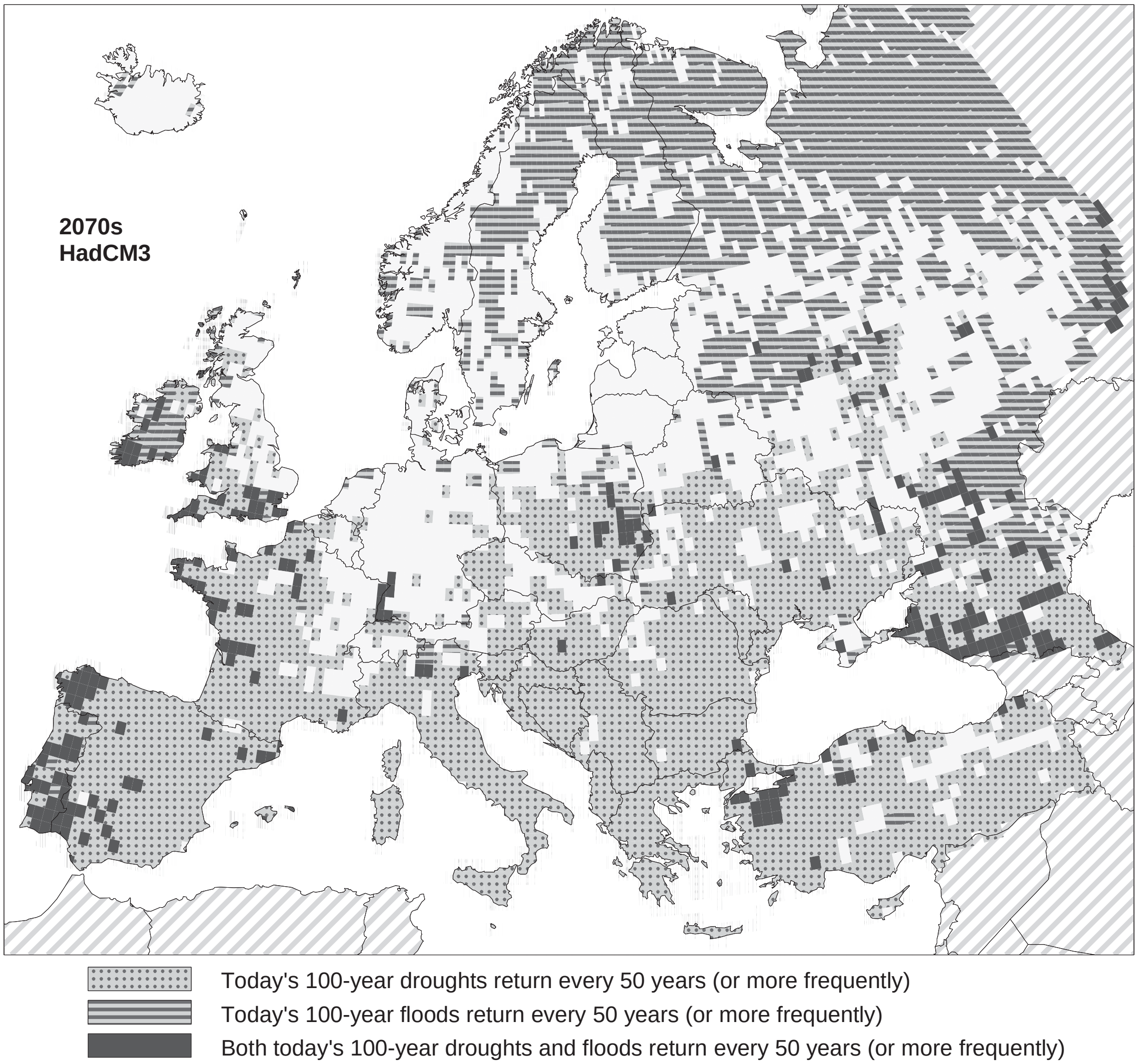

Figure 12

Critical regions as referred to (i) a decrease in the return period of the current 100-year drought to 50 years or less and (ii) a decrease in the return period of the current 100-year flood to 50 years or less. Calculated with WaterGAP 2.1, based on HadCM3 climate model and Baseline-A water use scenario for the 2070s.