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How will climate change modify river flow regimes in Europe?

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Abstract

Worldwide, flow regimes are being modified by various anthropogenic impacts and climate change induces an additional risk. Rising evapotranspiration rates, declining snow cover and changing precipitation patterns will interact differently at different locations. Consequently, in distinct climate zones, unequal consequences can be expected in matters of water stress, flood risk, water quality, and food security. In particular, river ecosystems and their vital ecosystem services will be compromised as their species richness and composition have evolved over long time under natural flow conditions. This study aims at evaluating the exclusive impacts of climate change on river flow regimes in Europe. Various flow characteristics are taken into consideration and diverse dynamics are identified for each distinct climate zone in Europe. In order to simulate natural and modified flow regimes, the global hydrology model WaterGAP3 is applied. All calculations for current and future conditions (2050s) are carried out on a $5' \times 5'$ European grid. To address uncertainty, climate forcing data of three different global climate models are used to drive WaterGAP3. Finally, the hydrological alterations of different flow characteristics are quantified by the Indicators of Hydrological Alteration approach. Results of our analysis indicate that on European scale, climate change can be expected to modify flow regimes significantly. This is especially the case in the Mediterranean climate zone (due to drier conditions with reduced precipitation across the year) and in the continental climate zone (due to reduced snowmelt and drier summers). Regarding single flow characteristics, strongest impacts on timing were found for the boreal climate zone. This applies for both, high and low flows. While low flow magnitudes are likely to be stronger influenced in the Mediterranean climate, high flow magnitudes will be mainly altered in snow climates with warmer summers. At the end of this study, typical future flow regimes under climate change are illustrated for each climate zone including a validation on robustness.

1 Introduction

In the last century, natural flow regimes have been heavily modified by different anthropogenic impacts (Malmqvist and Rundle, 2002). Worldwide around 50 000 large dams and an estimated number of 800 000 smaller dams exist usually generating a less variable flow with elevated low flows and dampened flood peaks (Nilsson et al., 2005). Water demands of an exponential growing world population leads to reduced river discharge due to withdrawals for irrigation, electricity production, manufacturing, domestic and other purposes. In addition, population growth has caused significant land-use changes. Large sealed areas through urbanization and deforestation alter flow magnitudes and timing through lower evapotranspiration rates and faster runoff (Sahin and Hall, 1996). Many rivers have also been artificially altered by construction works such as channelization, embanking, straightening, widening or deepening with further impacts on flow and flow velocity.

In the future, climate change constitutes another factor for flow regime alteration and will interact with other anthropogenic flow modifications. Climate change "*is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level*" (IPCC, 2007). Owing to the higher temperatures, evaporation from surfaces and transpiration by plants will be increased nearly everywhere leading to a reduction in runoff (Frederick and Major, 1997). Additionally, in snow or glacier affected river basins, runoff is altered by a decline in melt water (Verzano and Menzel, 2009). Regionally and seasonally differing developments are simulated for precipitation amounts and patterns (IPCC, 2007) causing higher or lower runoff values in the future (Alcamo et al., 2007). Moreover, it is expected that climate change accelerates the hydrological cycle with an increasing intensity of rainfalls and frequency of extreme weather events (Milly et al., 2008). All these implications will interact in different ways at different climatic locations inducing unfavourable alterations in the river flow regimes with large geographical disparities in directions and causes.

The consequences of these alterations are manifold. In 2000, approximately 2.4 billion people lived in water-stressed river basins and this number is supposed to rise in the future (Arnell et al., 2011). An increase in water stress can be caused by a reduction in total flow amounts or just by changes in flow seasonality. For example, irrigated agriculture, the largest water user worldwide, depends on the available water resources in the summer season during times of low flows. Even some basins may attain higher annual runoff values under climate change, the surplus of water is likely to occur during high flow seasons which will not solve dry season problems (Arnell, 2004; Arnell et al., 2011). Another issue is that higher runoff values in the wet season can enhance the risk of flooding (IPCC, 2007). Next to water quantity issues, water quality is also fundamentally linked to the flow regime as described by Nilsson and Renöfält (2008), especially when rivers are impaired by sewage water or non-point source pollution. Here, flow regime modifications influence transport and concentration of chemicals, nutrients, salts, oxygen and organic matter, but also water temperature which can be crucial for hydroelectric power cooling (Flörke, 2012). Furthermore, the shape of rivers can be altered as build-up of sediments and erosion processes change.

Next to economic and social impacts, especially river ecosystems will be at risk due to altered flow regimes. In a river ecosystem, different flows have different ecological functions (Bunn and Arthington, 2000) and can be characterised by their magnitude, timing, duration, frequency, and their rate of change. Poff et al. (1997) describes the ecological functions of these parameters in detail providing numerous examples from the scientific literature. All in all, the various combinations of flow magnitude, timing, duration, frequency and rate of change shape different habitat features and hence, are important to support a high regional diversity (Allan et al., 2005). Scientists now understand that the total flow regime varying from hydrological droughts to floods is required to maintain biotic composition, integrity, and evolutionary potential of riverine ecosystems including associated floodplains and wetlands (Matthews and Richter, 2007; Richter et al., 1996). Another fundamental assumption of environmental flow research is the natural flow paradigm which states that the natural flow regime including natural fluctuations provides the optimum conditions for a river ecosystem (Poff et al., 1997). Over evolutionary time spans and in direct response to the natural flow regime, native biota has developed different morphological, physiological and behavioural traits as described by Lytle and Poff (2004). Provided habitats are exploited, all ecological niches are occupied and the natural range of flows can be tolerated by the endemic biota. Thus, increasing deviations from natural flow patterns lead to increasing ecological consequences favouring invasive species at the expense of adapted endemic species. Indeed, in a review of 165 papers, Poff and Zimmermann (2010) could clearly demonstrate that flow alteration leads to many ecological consequences. In 92 % of the case studies, impacts on river ecosystems were reported in response to modifications of certain flow parameters. Similar results were found by a review of Lloyd et al. (2004), were 86 % of 65 case studies recorded ecological changes.

Besides possible financial losses in the industrial sector, crop shortfalls and flood damages, the social costs of ecosystem damage will be high as well. Healthy rivers supply a large number of ecosystem services and goods to humanity. Their value has been estimated at $6.5 trillion USD globally (Costanza et al., 1997; Strayer and Dudgeon, 2010) and includes water purification, food production, raw material provision, flood mitigation, recreational values and genetic resources to name only a few of them. These vital functions are based on a rich biodiversity and species which are adapted to dynamic conditions of running waters variable in space and time (Giller and Malmqvist, 1998). However, on a global scale, approximately 65 % of all riverine habitats are under severe threat nowadays (Vörösmarty et al., 2010) and the loss of biodiversity has proceeded faster over the last 30 yr than in marine or terrestrial ecosystems (Jenkins, 2003) with loss rates comparable to historical events of great extinctions (Brown and Lomolino, 1998; Ricciardi and Rasmussen, 1999). Indicating changes of fish, bird, reptile, amphibian and mammal populations, the global freshwater living planet index declined by 37 % since 1970 (Grooten et al., 2012). These numbers are alarming and therefore the EU Water Framework Directive (200/60/EEC) demands from its Member

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

States to protect and restore water bodies in Europe aiming for a “Good Ecological Status” for most rivers.

Despite the various impacts on river flow, today only a tiny number of rivers are protected by any sort of environmental flow management (Richter et al., 2011) and according to current trends in riverine species loss, global warming, population growth and land-use change, freshwater ecosystems will remain threatened well into the future (Vörösmarty et al., 2010). Now there is strong consensus within the scientific community that natural flow regimes need to be protected to some degree and that further research on anthropogenic flow regime alteration is required (Richter et al., 2009). This paper aims at evaluating the sole impact of climate change on river flow regimes in Europe analysing the dynamics separately for each climate zone. In particular the following questions shall be addressed: (i) How will different driving forces such as precipitation, temperature and snowmelt alter in different climate zones? (ii) Where in Europe will flow regime modifications most severe? (iii) How will extreme flow characteristics be impacted in each climate zone? And (iv) how will typical flow regimes look like in the 2050s in the different climate zones?

2 Methodology

Assessment of river ecosystem health implies comparison to reference conditions (Norris and Thoms, 1999). In our study we compare future modified flow regimes to natural flow conditions. Thereby, we assume that the more characteristics of the flow regime are significantly changed, the more severe is the impact on the river ecosystem. Four different model experiments were carried out by the state-of-the-art global hydrology model WaterGAP3 (Verzano, 2009) to assess the impact of climate change on river flow regimes in Europe. The first model experiment sets the reference condition (baseline) and represents the flow regime that would have existed in the time period 1971–2000 without human impacts in terms of water withdrawals, return flows and dam management. However, climate conditions and land-use practices already prevailing at that time were considered. In the remaining three model experiments, WaterGAP3 was driven with climate data from three different General Circulation Models (GCMs) to consider future climatic conditions of the 2050s (2041–2070). Each model run provided a 30-yr time series of daily discharge data. Subsequently, for all simulated time series, general flow statistics were calculated to evaluate the rate of departure from the natural flow regime. Finally, the model experiments considering climate change were compared to the baseline.

2.1 Simulation of flow regimes

For the simulation of river discharge, we applied the latest version of the global water model WaterGAP (i.e. version 3) which has been refined since earlier studies (Döll et al., 2003) and performs its calculations now on a global 5 by 5 arcmin grid cell raster (∼ 6 × 9 km^2 in Central Europe). The model combines a global hydrology model and a global water use model (Flörke and Alcamo, 2004; Alcamo et al., 2003; Döll and Siebert, 2002). As our analysis focuses on climate change, only the hydrological component was applied. In order to simulate natural flow conditions, the implemented management of reservoirs and dams was disabled.

The basis of the hydrological component is made up of spatially distributed physiographic characteristics such as land cover, soil properties, topography, permafrost and glaciers, drainage direction, and the location and area of lakes and wetlands. Recently, these datasets have become available as high spatial resolution maps, so that physiographic input parameters and hydrological processes are represented with a higher level of detail (e.g. Farr et al., 2007; Lehner et al., 2008; USGS, 2008). For each individual grid cell, WaterGAP3 calculates daily water balances. The vertical water balance of the land area defines groundwater recharge and surface runoff taking into account canopy, soil and snow water storages. The water balance of freshwater areas considers lakes and wetlands, and is affected by precipitation and evaporation. Both, runoff from land and freshwater areas contribute to the total runoff in each grid cell which is routed along a predefined drainage direction map (DDM5; Lehner et al., 2008) to the next downstream cell. In Europe alone, the simulated river discharge is calibrated at 221 gauging stations against observed annual river flow from the Global Runoff Data Centre (GRDC, 2004).

Besides the higher resolution, several hydrological key processes have been improved in WaterGAP3 with special focus on the model's ability to simulate certain flow characteristics: (1) Snow-related processes such as snowmelt-induced floods are enhanced by a revised snow routine on a sub-grid scale of 1 arcmin (Verzano and Menzel, 2009); (2) flow velocity is calculated dynamically allowing for differentiation between mountainous and lowland rivers (Verzano et al., 2012); (3) river length is represented more realistically by an individual sinuosity factor per grid cell derived from a high-resolution DDM (Lehner et al., 2008); and (4) permafrost distribution is improved using the Frost Number method (Aus der Beek and Teichert, 2008).

In order to drive WaterGAP3 for the baseline, the WATCH-forcing data (WFD; Weedon et al., 2011) were employed as climate input. It consists of a set of daily, 0.5 by 0.5 degree gridded meteorological forcing data, which are, next to others, precipitation, air temperature, and long- and shortwave radiation. The WFD was chosen because it is the reference dataset for the bias-correction of the future GCM projections used in this study. For our study, the gridded meteorological forcing data has been simply disaggregated to 5 arcmin to be used in WaterGAP3. The effect of a changing climate on river flow regimes was taken into account by driving WaterGAP3 with bias-corrected daily GCM projections (precipitation, air temperature, long- and shortwave radiation) as developed in WATCH (Harding et al., 2011). In order to consider the uncertainty in current climate modelling, bias-corrected time series from three different state-of-the art GCMs were applied: (i) ECHAM5/MPI-OM model from the Max-Planck Institute for Meteorology, Germany, (ii) IPSL-CM4 model from the Institute Pierre Simon Laplace, France, and (iii) CNRM-CM3 model from Centre National de Recherches Meteorologiques, France. All three climate projections employed in this study were underpinned by an SRES A2 emission scenario (IPCC, 2007). In the absence of further climate policies, this scenario comprises steadily growing CO_2-emissions which may double by 2050 compared to the year 2000. The SRES A2 scenario was chosen because current CO_2 emissions are close to the upper end of the SRES scenario range (Manning et al., 2010). However, due to the inertia of the climate system, the effect of the IPCC emission scenario will become more obvious in the second half of the 20th century (Meehl et al., 2007). Therefore, we decided to focus only on one emission scenario in our study.

2.2 Indicator assessment

Trends in different flow characteristics provide an indication whether ecological important habitats are available and life-cycle requirements are met in the future (Suen and Herricks, 2009). In order to assess changes in river flow regimes, we applied a methodology by Laize et al. (2010) which is based on the Range of Variability Approach (RVA) using Indicators of Hydrological Alteration (IHA; Richter et al., 1996, 1997). The IHA/RVA has been widely used (Yin et al., 2011), is sensitive to anthropogenic influences (Taylor et al., 2004) and recognises that all aspects of the flow regime are ecological important. It provides 32 different indicators which are organized into five different groups.

Reviewing 171 different hydrologic indicators, Olden and Poff (2003) showed that the IHA capture almost the entire spectrum of all available hydrological indicators, but also duplicate the information for some flow characteristics. Following their framework, a subset of 12 parameters was chosen in our study to describe non-redundant departures from the natural flow regime (Table 1).

In the first step, the 12 parameters were calculated for each year in the 30-yr time series delivering a data record of 30 values per parameter. Second, for each parameter, the 25th, 50th and 75th percentile were calculated from the data record. Third, the final indicators for our study were derived by taking into account the median (i.e. the 50th percentile) as a measure for the average change in magnitude. Additionally, the inter-quartile range (i.e. the difference between the 75th and the 25th percentile) was determined as a measure for the inter-annual variability in the 30-yr time series (Laize et al., 2010). Altogether, considering changes in average magnitude and variability, this approach provides 24 different indicators for our impact analysis which were calculated for the daily time series of all model experiments.

An exception was made in step 2 for the two timing parameters (P23 and P24). Here, the indicators were calculated by specifying the 30 values from the data record as vectors with x- and y-coordinates in a unit circle with a radius of one. For this purpose, the 365 days of the year were adjusted to the 360° (i.e. 2π in radians) of the unit circle. Next, the mean x and y components of all vectors were computed, so that the mean timing of the minimum and maximum flow could be calculated by Eq. (1) and the variability v by Eq. (2). In Eq. (1), α describes the angle on the unit circle which is related to the mean timing whereas 0, π or 2π radians have to be added depending on the quadrant of the mean vector described by the coordinates $\bar{x}$ and $\bar{y}$

$$\alpha = \tan^{-1}\frac{\bar{y}}{\bar{x}} \tag{1}$$

$$v = 1 - \sqrt{\bar{x}^2 + \bar{y}^2} \tag{2}$$

For the setting of flow protection standards, attention has recently turned to percent-of-flow (POF) approaches, where the degree of allowable departure is expressed as percentage change to natural conditions (Richter et al., 2011; Yin et al., 2011). In practice, the threshold point at which ecological health is significantly threatened is difficult to determine. Regarding daily flows, Richter et al. (2011) suggests that for most rivers alterations greater than ±20 % will threaten ecological integrity, while river ecosystem with endangered species or a highly specialized biota require a lower threshold of 10 %. For UK rivers, specifying abstraction thresholds as required by the Water Framework Directive, Acreman et al. (2008) defined maximum abstractions to be in the range of 7.5–35 % of natural flow depending on the ecological sensitivity of the river. Considering threshold values from the literature and the uncertainty of applying a large-scale approach, we assume that the impact on river ecosystems is significant, when the indicator difference is outside a range of ±30 %. An exception was made for the mean timing indicators, where we set the threshold to ±30 days. As natural flow regimes can be modified in various ways, the threshold exceedances were summed presuming that each indicator has the same weight.

The whole indicator assessment described above was carried out separately for each WaterGAP3 grid cell of the 5 arcmin European raster, from which a subset of 22 915 cells has been selected for our analysis. The criteria of selection was an annual flood of 100 $m^3 s^{-1}$ or higher to represent major rivers and tributaries in Europe. Depending on the number of indicators showing a threshold exceedance, the grid cell was coloured for ease of display and interpretation according to a traffic light coding system (Table 2).

2.3 European climate zones

In order to distinguish the quality of impact in different regions of Europe, an analysis for different climate zones was conducted. The "Map of Climate Areas in Europe" (EUCA15000) divides Europe into 35 different climate areas (Hartwich et al., 2011). For our purposes, the climate areas were aggregated into six classes namely polar, boreal, temperate continental, temperate transitional, temperate oceanic and Mediterranean (Fig. 1). WaterGAP's continental grid cells which were not covered by EUCA15000, such as the Near East, were labelled according to the Köppen-Geiger climate classification (Peel et al., 2007). In doing so, arid regions were assigned to the class "Mediterranean".

In general, the six climate zones applied in this study can by described as follows. In the far north of Europe, the polar zone is prevailing. Its climate is characterised by extreme cold winters with often six sub-zero degree months and cold summers. The boreal climate possesses very cold winters and short cool summers. Precipitation occurs, with increasing distance to the coast, mainly in the warmer summer months. Soil moisture freezes solidly in winter. The boreal climate is followed by the temperate zone which was divided into oceanic, transitional and continental climate. In the continental part, the annual variation in climate is high. While summers are hot and dry, winters are very cold. Precipitation is relatively moderate in summer and occurs predominantly during winter. In contrast, temperate oceanic climate features a narrow annual temperature range as oceans act as a buffer. Summers are warm and winters are mild. Precipitation is high all-season and appears in the form of rain most of the year. The transitional zone stands in between and can be described by warm summers, cold winters and all-season precipitation. Areas of the Mediterranean climate zone are mainly located close to the sea, which acts as a temperature buffer. Consequently, the annual temperature range is relatively small. While summers are hot and dry, winters are mild with temperatures generally above the freezing point. Mediterranean areas receive almost all of their annual rain during the winter time. Snow is a rare event, but can occur in high mountain ranges.

3 Results and discussion

In the following, the impact of climate change on flow regimes in Europe is evaluated for the 2050s, whereas we made use of the ensemble median in our entire study to mitigate uncertainties in current climate modelling. First, changes in climatic driving forces are presented to differentiate the causes of change in each climate zone. Second, areas in Europe are identified where overall flow regime modification is likely to be most severe. Third, it is shown which of the extreme flow characteristics (i.e. high and low flows) will be significantly modified in the different climate zones and finally, potential future flow regime patterns under climate change are described.

3.1 Change in climatic driving forces

Hydrological flow regimes will be modified by climate change in the future through alterations in precipitation, temperature and snowmelt (Fig. 2).

A north-south divide can be found for precipitation in Europe. In general, the north is getting wetter and the already dry south is receiving even less precipitation. In the winter half year (i.e. October to March), only the Mediterranean countries receive less precipitation, while the remaining part of Europe and in particular the north faces higher amounts of precipitation. In the summer half-year (i.e. April to September), reduction in precipitation is getting more severe in the Mediterranean countries, and Eastern Europe is also significantly affected. Temperature is supposed to increase in all parts of Europe, but especially in Eastern Europe and in the far north. As a consequence, runoff will be reduced due to higher evapotranspiration rates (Frederick and Major, 1997). Furthermore, the duration of snow cover decreases with strongest impacts for the Baltic Sea rim countries, but also in mountainous regions (Alps, Dinaric Alps, the Carpathians, Rila Mountains, Icelandic and Scandinavian Mountains). On the west coast of Europe, temperature rise is more moderate. The average values of change for each climate zone are presented in Table 3. Regarding the uncertainty of climate modelling, the climate projections of the three GCMs coincide in the direction of change in most climate zones. Only in the polar and temperate oceanic climate zone, one climate projection points in the opposite direction for winter precipitation.

3.2 Overall flow regime modification

According to the simulated changes in the different climate variables, climate change has the potential to modify flow regimes across Europe significantly in the 2050s (Fig. 3).

Severe impacts can be found in Eastern Europe where the reduction in snowmelt plays a crucial role next to the decline in summer precipitation and the relatively strong increase in temperature. Furthermore, severe impacts are obvious in Southern Europe, which is likely to suffer under reduced precipitation in both, summer and winter half-year. In Western Europe (i.e. in the UK, Ireland, Iceland, BENELUX, Denmark, Galicia and Northern France as well as at the Rhine and Rhone River) and in North-West Scandinavia the impact is lowest. Hydrological alterations caused by changes in precipitation and temperature are moderate in these regions. Our results are in accordance to the study of Laize et al. (2010) who analysed the impact on environmental flows under different future scenarios with monthly flow indicators.

Regarding the impact in different climate zones, the extent of flow regime modification varies (Fig. 4). According to our results, the highest degree of river flow regime alteration can be expected in the Mediterranean and in the temperate continental climate zones. In both zones, approximately 20 % of the analysed grid cells are affected by severe climate change impacts and the number of grid cells with a low impact is marginal. Lowest impacts are found in the temperate oceanic zone. In this climate zone, 17 % of the cells still remain in the low impact class in the future. The temperate oceanic and the polar zones are the only regions without severe impacted cells. Allan et al. (2005) stated that the location of a river basin relative to the ocean may dampen its response to climate change. In our study, generally spoken, impacts increase from west to east (i.e. from oceanic to continental climate) and from north to south (i.e. from polar to Mediterranean climate) in Europe.

3.3 Modification of extreme flow statistics

Besides the degree of flow regime modification, it is also important to consider which flow characteristics are modified in the future as they determine which ecological functions are compromised and thus, which species of flora and fauna are likely to become vulnerable. Climate change impacts on high flow magnitudes (P18) and timing (P24) are shown for the 2050s in Fig. 5. Maximum flows significantly decrease (i.e. by more than 30 %) in Eastern Europe (Belarus, Baltic States, East Russia, Ukraine, Poland and at Rivers influenced by the Carpathians) as well as in parts of Southern Europe (South and East Spain, Middle Italy and Sicily, Greece, the Near East and rivers influenced by the Taurus mountains in Turkey). As a consequence, floodplains will be less inundated in these areas with negative effects on floodplain vegetation and fish (Schneider et al., 2010). The timing of flood peaks is likely to occur earlier in the year in the north-east of Europe and partly, where rivers originated at high mountains (e.g. Alps, Carpathians, Taurus mountains). These changes in high flows can be explained by rising temperatures which cause the 0 °C level to be crossed earlier in the year. In addition, precipitation more often falls as rain instead of snow. Therefore, thaw happens earlier and less water is stored as snow pack leading to advanced and lower snowmelt-induced flood peaks.

In Europe, low flows usually occur in late-summer or early-autumn. Due to the decline in mean summer precipitation over large parts of Europe and increasing evapotranspiration rates, further reductions in low flows (P13) can be expected in most regions. Only in Scandinavia elevated low flows can be observed (Fig. 6). For both, low and high flow magnitudes, no significant changes were detected for the UK, Ireland, Iceland, Denmark, The Netherlands and for most rivers in Germany, Switzerland, Northern Italy and Western Austria.

As climate variables are variously affected in the diverse climate zones, different flow characteristics will be modified (Fig. 7). Minimum flow magnitudes (P13) are strongly impacted in the Mediterranean followed by the temperate transitional and continental climate zones where summers also get significantly drier. On the contrary, low flows are less impacted in the Northern climates. Maximum flow magnitudes (P18) are more intensively modified in the temperate continental, temperate transitional and boreal climate zones (i.e. where snowmelt plays a crucial role) but also in the Mediterranean climate zone. In the temperate oceanic and polar climate zones, maximum flow magnitudes are only marginally influenced. Timing of extremes (P23, P24) will be strongly altered in regions where snow cover declines, and hence, especially in the boreal climate zone. This becomes apparent for both, high and low flows.

3.4 Flow regimes in the 2050s in different climate zones

In the following, we present for each climate zone, how "typical" monthly flow regimes may look like in the 2050s under the exclusive effect of climate change. The results may be valid for most rivers in each climate zone, but local variants are possible due to local effects such as high mountain ranges, the storage of water in lakes and wetlands, glacier melt water augmentation, ice jam or anthropogenic modifications. In order to show how robust the results are for each climate zone, the percentage change of monthly discharge is presented by means of Whisker-boxplots which depict the median, the 25th and 75th percentile of all selected grid cells belonging to a climate zone. The ends of the whiskers indicate the minimum and maximum value of the sample excluding outliers. In addition, the effects on the flow regime within a climate zone are explained by a hydrograph of a representative river. These example rivers were chosen by reason of their Central location within the climate zone and their character to reflect the climate-zone-specific flow regime changes as illustrated by the robustness charts. The related hydrographs contain the monthly natural flow regime of the baseline period and the modified flow regime of the 2050s. The latter one is represented by the ensemble median and the uncertainty range caused by the climate projections of the three GCMs.

3.4.1 Polar zone

Owing to the long and extreme cold winter in the polar zone, thaw happens very late in spring causing a massive flood peak centred usually in May or June. After extreme low flows in winter, this flood delivers more than 60 % of the total annual flow within three months (Haines et al., 1988). According to the climate projections, the polar zone faces the highest temperature rise (i.e. 2.9 °C) and an increase in precipitation in both, summer and winter half year. In our study, flows tend to be higher in most months of the year and the higher evapotranspiration is outweighed by higher precipitation amounts (Fig. 8).

Particularly in April, depending on the location of the site, the flow increase can be very high as thaw proceeds faster due to the higher temperatures. Snowmelt induced flood peaks in May and June show different directions of change with slightly more than 50 % of the sites indicating lower discharges. A closer analysis indicated that lower flood peaks are likely to occur mainly in Iceland. On the contrary, peak flows tend to increase in Northern Scandinavia due to the significantly higher projected winter precipitation which causes more snow to be stored in the snow pack leading to higher snowmelt-induced flood peaks. The example of the Altaelva River in Northern Norway describes a typical example for the continental part of the polar zone. Here, peak flows are higher compared to the natural flow regime, but decline faster as a result of the accelerated thaw which can lead to lower flows in early summer despite an increase in rainfall.

3.4.2 Boreal zone

In the boreal zone as well, only little solar energy input is received during the winter time so that snow can accumulate for five to six month, often without interruption by melt events. Again, the prevalent flow pattern is the nival regime where snowmelt and ice break-up causing winter low flows to be rapidly displaced by a spring freshet which usually peaks in May (Woo et al., 2007). In summer, flows are receding due to higher evapotranspiration, but a minor secondary peak can occur in mid-autumn with emerging rainstorms at this time (Haines et al., 1988). In the European boreal zone, the highest winter precipitation increases are projected for the 2050s (i.e. +13.5 %), but also summer precipitation is expected to rise slightly. Accordingly, future winter discharges are higher compared to the natural flow regime, while summer flows are less impacted (Fig. 9).

In the boreal region, the advanced thaw is most significant in comparison to other climate regions (see Fig. 2). Consequently, the highest impact can be found on flows in April as discharge peaks, instead of May, one month earlier in the future. Due to the rising temperatures, rainfall (instead of snow) and occasional melt events occur already in the winter months which elevates winter flows. However, the earlier timing of snowmelt in spring and sporadic melt events in the winter months reduces the snow storage. Hence, spring freshets show lower peaks in the 2050s. During summer (June to September), increased precipitation can be outweighed by a higher evapotranspiration rate. In our study, slightly more than half of the grid cells tend to a lower discharge in summer. These results are in accordance with Woo et al. (2007), who analysed stream flow hydrology in the boreal region on the global scale. Our results indicate that in the European boreal zone, changes will be more severe on the continental eastern part of the boreal zone and less severe in the north-west where rivers arise from high mountain ranges. The hydrograph of the Chirco-Kem River in Karelia (Russia) gives a typical example for the boreal zone. Different studies analysing stream flow trends in Scandinavia (Bergstrom and Carlsson, 1993), European Russia (Georgiyevsky et al., 1995, 1996, 1997), and the Baltic States (Tarend, 1998) indicate that winter, summer and autumn flows are increasing and spring flows are decreasing since the mid-1970s.

In addition to the climate change impacts, many rivers are already heavily regulated by dams in the boreal region, predominantly for the purpose of hydroelectric power generation. However, Renöfält et al. (2010) sees opportunities under climate change for both, a more sustainable production of hydroelectricity and the restoration of river ecosystems. Usually, electricity demand is high in winter where river flows are at a minimum level. Under climate change, especially winter flows are expected to increase and the annual surplus of water in this region could be used to operate dams in a way which makes flow regimes more natural again.

3.4.3 Temperate continental zone

According to the Haines et al. (1998) classification, rivers in the temperate continental zone peak in early or mid-spring. At this time, spring floods could be produced by rainfall alone, but usually they are enhanced by the release of winter precipitation, which was stored as snow during the colder month. In the summertime, flows typically decline until they rise again in late autumn. The ensemble median of the precipitation projections indicates that in the 2050s the high variability in the continental climate zone will be augmented (see Fig. 2). While precipitation increases in winter, the drier summers will be intensified receiving 11.5 % less precipitation, which accounts for the second highest reduction after the Mediterranean climate zone. Furthermore, the second highest value for temperature increase (i.e. 2.6 °C) was found second to the polar zone. The WaterGAP3 simulations in this climate zone show that the highest impact can be expected on summer and autumn flows, but also on peak flows in spring (Fig. 10).

Due to the reduced summer precipitation, flows tend to be significantly lower between April and November providing exceptional low flows. Like in the boreal zone, thaw peaks are reduced and occur earlier in the year due to the discussed changes in snowmelt which will have a significant impact in this region with very cold winter month. The example of the Dniestr River shows that both, maximum and minimum flows are reduced. Regarding the boxplots which represent the entire region, the widest ranges of change were found in comparison to other climate zones. The reason is that the continental climate zone is the biggest area in our study containing important mountain ranges such as Alps, Pyreneans and Carpathians and ranging from south Sweden to Turkey causing local extremes or divergencies. However, the direction of change is very robust from April to September. Winter flows tend to be increased in the 2050s, but can also be reduced depending on the location. For the Black Sea region, Flörke et al. (2012) found that cross-sectoral conflicts may arise in the future due to increasing water withdrawals for irrigation and electricity production purposes. In addition to the climate change impact, this would further reduce flows intensifying the impact on the river flow regimes in this region.

3.4.4 Temperate transitional zone

Flow regime patterns in the temperate transitional zone are quite similar to flow regimes in the continental part of Europe, but more uniform. High flows ascend slower and earlier in spring. Low flows are less distinct. The simulated climate conditions for this region project a relatively high temperature increase by 2.5 °C until the 2050s. No significant change in summer precipitation is detected in all three climate projections, but winter precipitation is expected to increase by 9.5 % in the ensemble median. Our simulated hydrographs in this region show a strong impact on autumn flows in the 2050s (Fig. 11), exemplarily depicted at the Oder river.

Relatively robust, the results indicate lower flows between April and November due to higher evapotranspiration, especially pronounced during the three autumn months. Peak flows usually occurring in March or April are slightly lower and can be advanced. In the winter months our results are less robust showing a wider range of change with no clear tendency. However, the increased winter precipitation, transition of snowfall to rain, and so-called “rain on snow events” can cause that rainfall triggers immediate runoff peaks making winter flows more variable in this region. Such a trend from snowmelt runoff regimes to winter rainy regimes has already been observed at some locations (Allan et al., 2005).

3.4.5 Temperate oceanic zone

In the moist temperate oceanic zone with fairly even precipitation throughout the year, flow regimes are more uniform. Usually, they possess a broad winter peak (in Scotland, a broad autumn peak) and lower flows in summer due to evapotranspiration losses (Haines et al., 1988). The lowest value for temperature rise (i.e. 2.0 °C) was found for this region adjoining the Atlantic coast and precipitation changes are moderate. While winter precipitation increases only slightly, summer precipitation is decreasing by 8.0 % in the ensemble median.

Therefore, river flow regimes of the 2050s are less affected by climate change (Fig. 12). Nevertheless, flows in the summer half-year tend to be reduced in the 2050s with highest alterations in September and October. Only in December and January, most locations of the climate zone show a minor increase in discharge. The example hydrograph of the Thames river near Teddington illustrates almost natural flow conditions in the future which could be maintained in the temperate oceanic zone and especially in the UK. Trend analyses of river flow regimes in the UK show no clear climate-driven statistical trends for both, high (Robson et al., 1998) and low flows (Hisdal et al., 2001). In Ireland and Scotland, in the last forty years increasing runoff values were discovered by Hannaford et al. (2007).

3.4.6 Mediterranean zone

River flow regimes in the Mediterranean climate zone are highly variable (Oueslati et al., 2010). While precipitation mainly occurs in the winter half-year, extensive low or even zero flow patterns can appear during the dry summer months which can lead to isolated pools along the river (Argyroudi et al., 2009) and transitions from lotic to lentic waters (Morais et al., 2004). Hydrological simulations for the Mediterranean climate zone are characterised by a reduction in precipitation in both, winter and summer half-year. Especially in summer, precipitation decreases by 24.2 % which accounts for the highest decline found in our study. Accordingly, our river flow regime simulations for the 2050s indicate that river discharge is likely to be lower during the entire year, but particularly in spring and autumn (Fig. 13).

While changes in river flow show very robust results for the whole region between April and September, the range of change is very broad from November to March. One reason for this is the impact of different mountains ranges in Southern Europe (e.g. Turkish mountains elevate up to 3900 m), so that runoff can be influenced at some locations by snow. The hydrograph of the Guadalquivir river near Sevilla shows that flow reduction is severe throughout the year. However, the broad variety of uncertainty in winter river discharge (January to March) is remarkable and indicates the different GCM calculation of future precipitation. According to the WaterGAP3 simulations, river flows in the Mediterranean are likely to be even more intermittent in the future with an increasing number of zero flow events creating isolated pools. Moreover, in a holistic context, this situation caused by climate change will be exacerbated as large amounts of water are withdrawn in this region for irrigation purposes (Schaldach et al., 2012). Consequently, especially here, intelligent dam management according to the Block Building Methodology (BBM; Tharme and King, 1998) or the Basic Flow Methodology (BFM; Palau and Alcazar, 2012) will be required to provide at least certain flow elements that are ecological important.

4 Conclusions

This study aimed at evaluating the future impact of climate change on river flow regimes in Europe and identifying the dynamics separately for each climate zone. Therefore, natural and future modified flow regimes were modelled by the global hydrology model

WaterGAP3 taking into account climate projections of three different GCMs. Subsequently, alterations in various flow characteristics were assessed applying the Indicators of Hydrological Alteration.

Our results show that besides other anthropogenic factors, climate change may severely alter natural patterns of flow over large regional scales. Regarding the total degree of flow regime modification, a north-south (i.e. from colder to warmer climate) and a west-east gradient (i.e. from oceanic to continental climate) became obvious. Accordingly, strongest impacts on European river flow regimes in the 2050s were found for the Mediterranean and the temperate continental climate zones. The smallest impacts, in turn, can be expected for the oceanic climate zone. Here, projections for both, temperature and precipitation, indicate only moderate changes.

Changes in temperature, precipitation and snowmelt interact differently at different climate zones causing diverse flow characteristics to be altered. In the boreal climate zone, WaterGAP3 calculations indicated that snow cover duration is significantly reduced. In accordance with that, the timing of both, high and low flows, was predominantly modified in our simulations in the boreal region of Europe.

In snow climates with warmer summers (i.e. in the temperate transitional, temperate continental and the boreal climate zone), high flows leading to ecological important floodplain inundation are most likely to be significantly reduced. Due to rising temperatures, the impact of thaw is debased leading to lower snowmelt-induced flood peaks in spring. On the contrary, in the continental part of the polar zone, flood peaks tend to be increased due to significantly higher projected winter precipitation and faster proceeding snowmelt in spring.

In most regions, climate change represents an additional threat to other anthropogenic factors. In particular in the dry Mediterranean climate zone where flows are likely to be lower in all months of the year in the 2050s exacerbating the impacts of high water abstraction for irrigation purposes in this region. But also in the continental climate zone, where high amounts of water are withdrawn for electricity production and irrigation, climate change is likely to further reduce river flows significantly from spring until autumn. Summer precipitation is expected to decrease over large parts in Europe, but especially in Southern and Eastern Europe.

At least in the boreal zone, climate change could provide opportunities to re-establish a more natural flow regime. Many rivers are modified in Scandinavia by dam operations to support hydropower demands, but competition between different water use sectors is marginal. As precipitation is expected to increase in both, winter and summer half-year, the surplus of water could be used to operate dams in a way which benefits river ecosystems.

The consequences of flow regime change are manifold. Related water quantity and water quality issues can provoke socio-economic and environmental problems. Especially river ecosystem health and provision of ecosystem services are threatened as further modifications of natural flow patterns will make species more vulnerable to extinction. Freshwater ecosystems might somehow adapt to the new conditions and probably find a new equilibrium. However, we want to emphasize that this will be accompanied by a loss in biodiversity causing that especially endangered and specialised species will become extinct, and be replaced by invasive species. At some point, thresholds could be crossed with unforeseeable consequences for mankind (Jenkins, 2003). Our results show that the need for environmental flow actions is further increasing under climate change, and various effects of climate change need to be considered. To reduce further stress on river ecosystems, adaptive environmental flow management, intelligent dam operation providing ecological important elements of the flow regime (e.g. by the Block Building Methodology), and provision of high flows for floodplain wetland inundation are required.

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Table 1. Hydrologic parameters of the IHA used in this study.

ID	Parameter	Unit	Group
P1	January mean flow	$m^3 s^{-1}$	Group 1: Magnitude of monthly water conditions
P4	April mean flow	$m^3 s^{-1}$	
P7	July mean flow	$m^3 s^{-1}$	
P10	October mean flow	$m^3 s^{-1}$	
P13	1-day minimum flow	$m^3 s^{-1}$	Group 2: Magnitude of extreme water conditions
P18	1-day maximum flow	$m^3 s^{-1}$	
P23	Julian date of 1-day minimum	Day	Group 3: Timing of extreme water conditions
P24	Julian date of 1-day maximum	Day	
P25	Number of high pulses	Number	Group 4: Frequency and duration of high and low pulses
P26	Number of low pulses	Number	
P29	Number of flow rises	Number	Group 5: Rate and frequency of water condition changes
P31	Mean rise rate	$m^3 s^{-1}$	

Table 2. Impact coding system.

Threshold exceedances	Ecological impact	Colour code
0–5	Low	Green
6–9	Medium	Yellow
10–12	High	Orange
13–24	Severe	Red

Table 3. Mean change in climate variables for the different climate zones of Europe derived from the ensemble median. The brackets contain the range of the three climate projections.

Climate zone	Precipitation winter (%)	Precipitation summer (%)	Temperature annual (˚C)
Polar	+10.2 (−5.1 to +20.0)	+10.9 (+3.8 to +19.2)	+2.9 (1.7 to 3.7)
Boreal	+13.4 (+1.5 to +18.4)	+4.9 (+2.4 to +11.6)	+2.3 (1.7 to 3.6)
Temperate continental	+5.4 (+1.5 to +10.2)	−11.9 (−11.3 to −15.7)	+2.6 (1.8 to 2.7)
Temperate transitional	+9.6 (+2.2 to +22.8)	+0.6 (+0.3 to +3.7)	+2.5 (1.6 to 2.8)
Temperate oceanic	+5.6 (−2.0 to +12.8)	−8.0 (−6.5 to −10.9)	+2.0 (1.4 to 2.2)
Mediterranean	−9.5 (−5.3 to −19.0)	−24.2 (−17.2 to −29.9)	+2.3 (2.1 to 2.5)

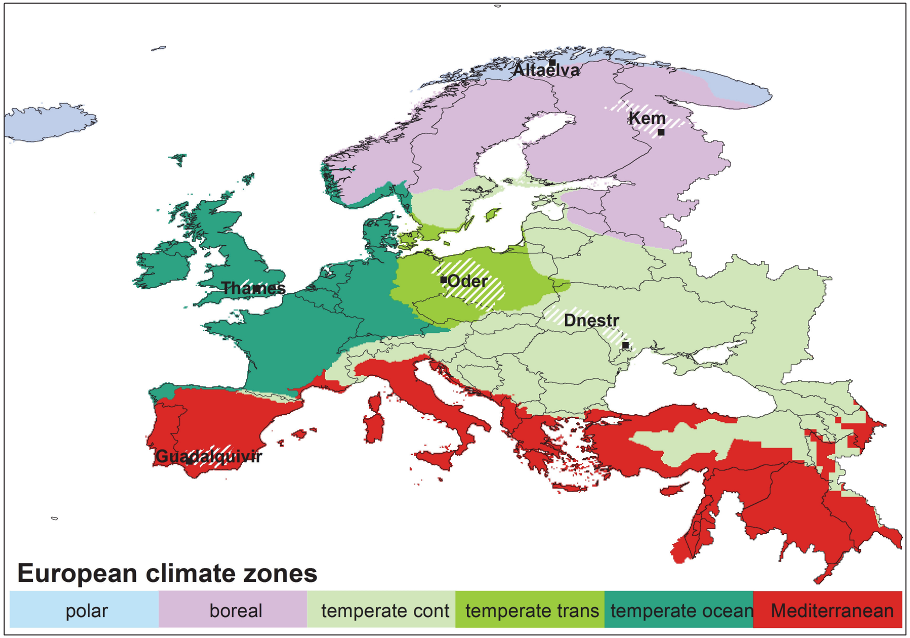

Fig. 1. European climate zones based on information provided by EUCA15000. The six highlighted basins are presented as typical examples in the Results and Discussion chapter.

HESSD
9, 9193–9238, 2012

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

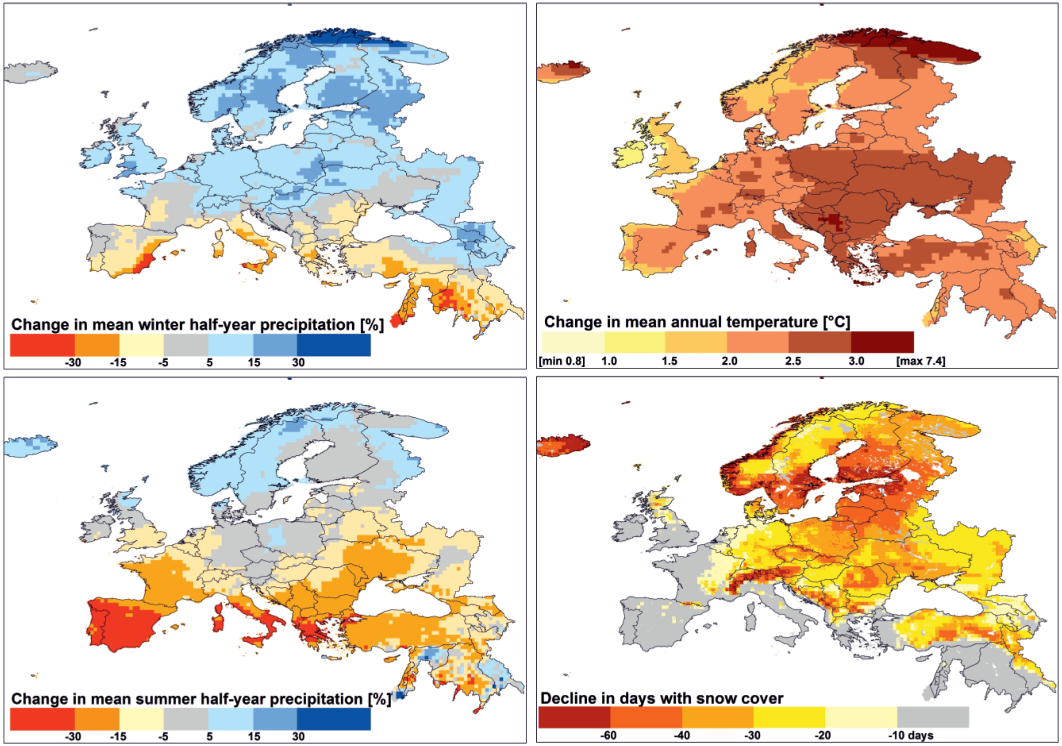

Fig. 2. Climatic changes in the 2050s featuring changes from the baseline in mean precipitation of winter and summer half-year (left panels), and mean annual temperature and snowmelt (right panels). Maps represent the ensemble median of the three climate projections.

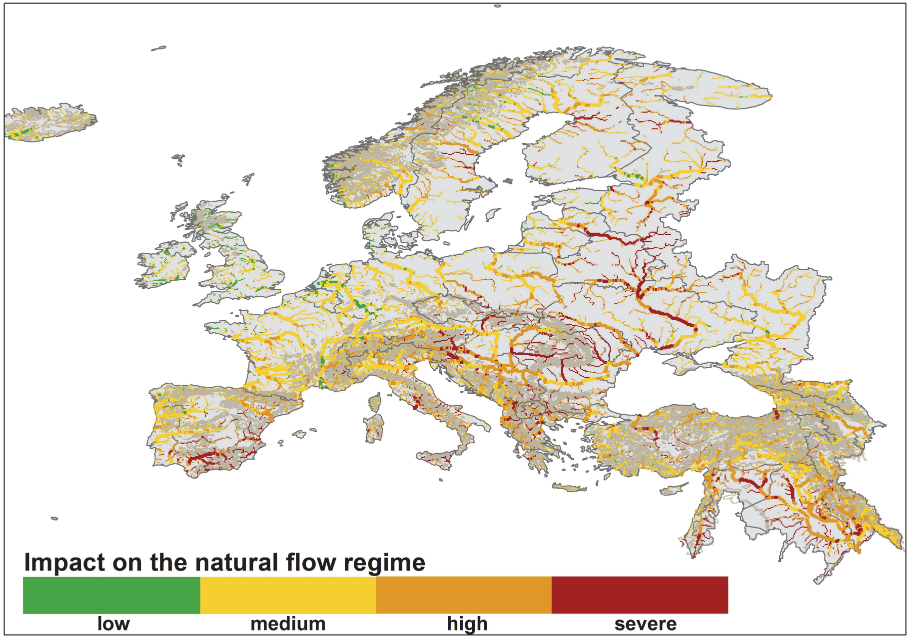

Fig. 3. Climate change impact on the natural flow regime in the 2050s under the A2 emission scenario considering 24 selected indicators and the ensemble median of the three climate projections.

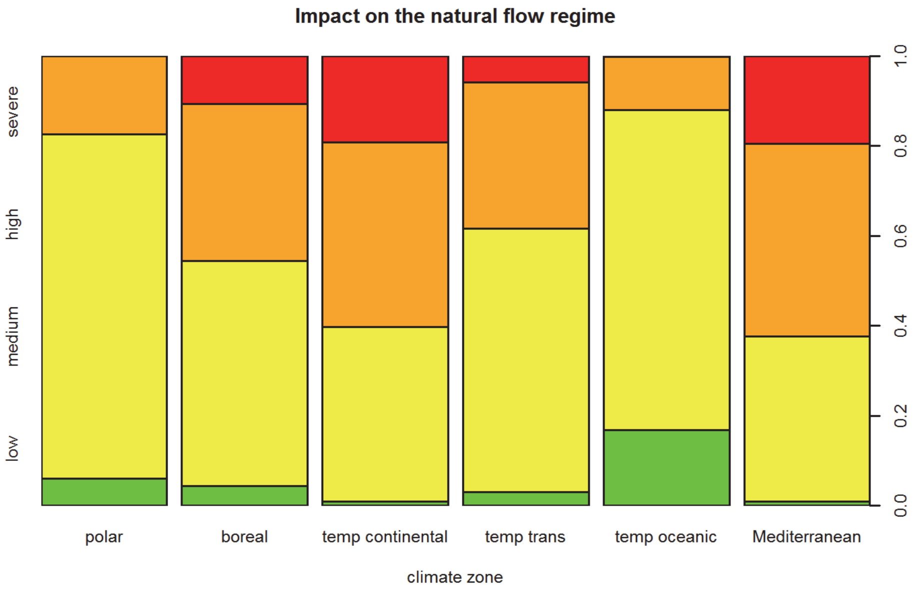

Fig. 4. Impact of climate change on natural flow regimes in different climate zones in the 2050s, represented by the proportion of grid cells showing low, medium, high or severe impact.

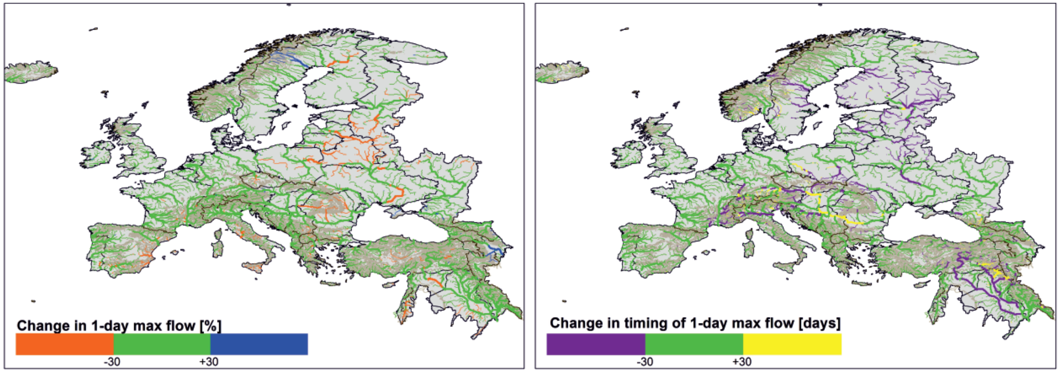

Fig. 5. Change of high flow magnitude and timing as a result of climate change in the 2050s.

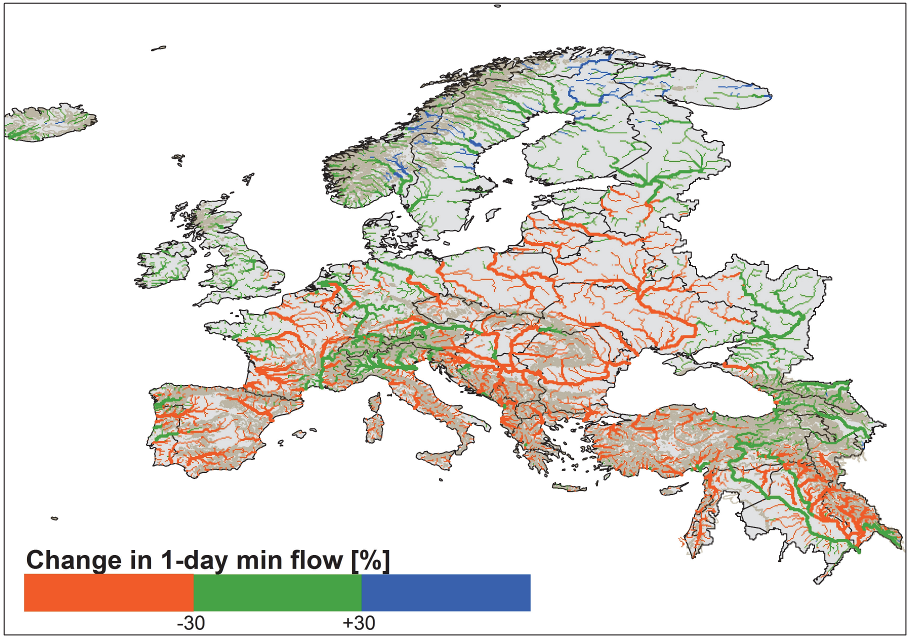

Fig. 6. Change in low flow magnitudes caused by climate change in the 2050s.

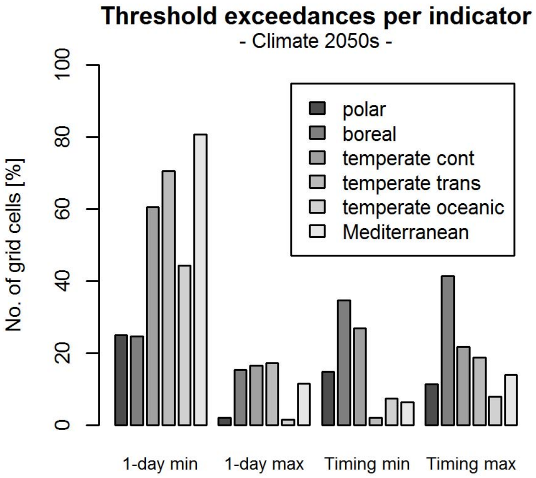

Fig. 7. Percentage of grid cells which are significantly affected by climate change according to climate zones in Europe. Magnitude and timing of low and high flows are distinguished.

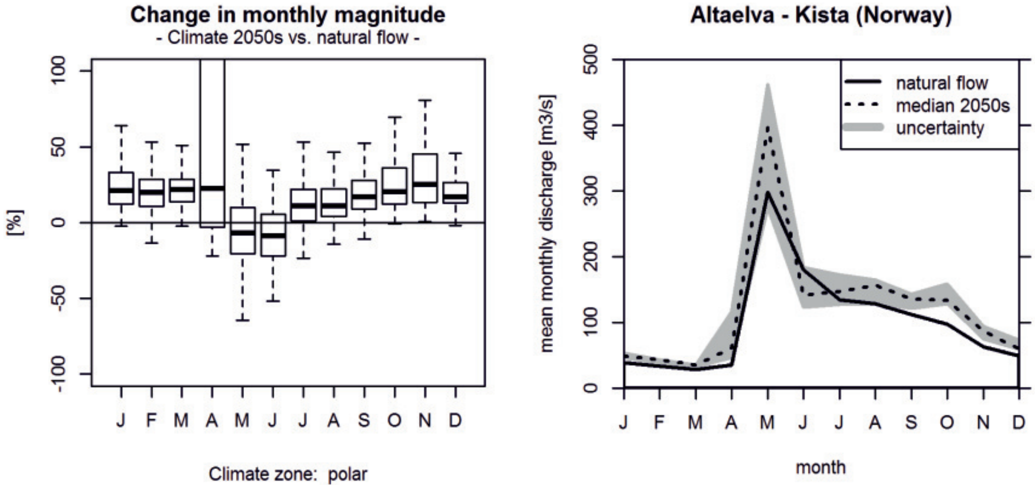

Fig. 8. Direction of change in the 2050s plotted for all grid cells of the polar climate zone (left panel) and the Altaelva river near Kista (right panel).

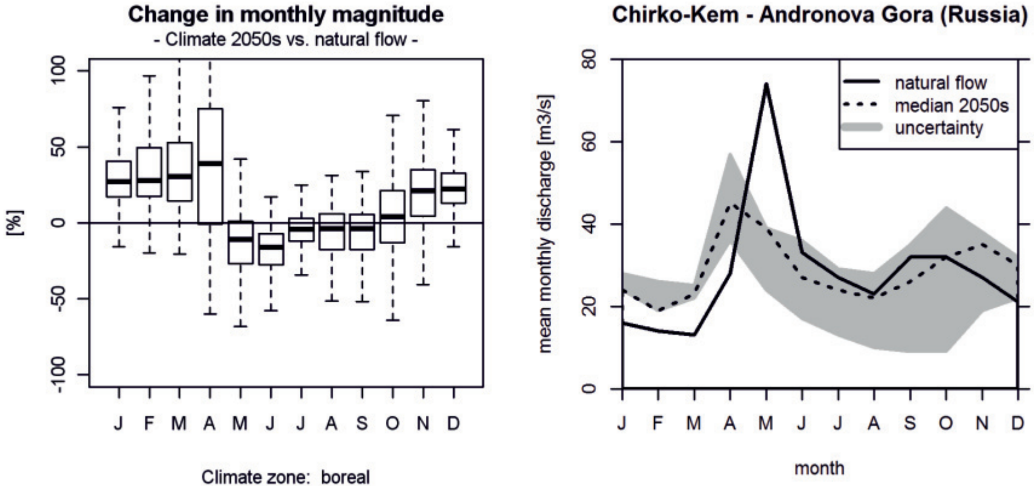

Fig. 9. Direction of change in the 2050s plotted for all grid cells of the boreal climate zone (left panel) and the Kem river near Andronova Gora (right panel).

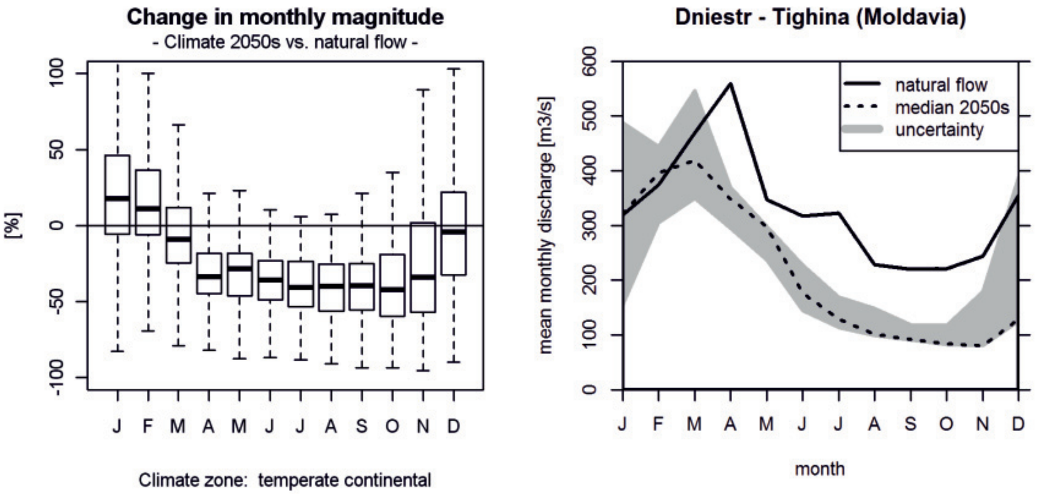

Fig. 10. Direction of change in the 2050s plotted for all grid cells of the temperate continental climate zone (left panel) and the Dniestr river near Tighina (right panel).

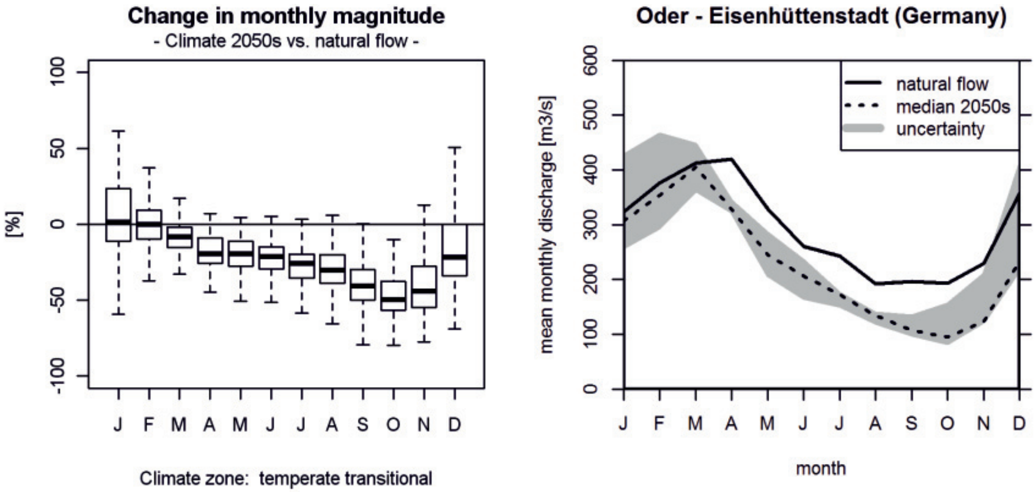

Fig. 11. Direction of change in the 2050s plotted for all grid cells of the temperate transitional climate zone (left panel) and the Oder river near Eisenhüttenstadt (right panel).

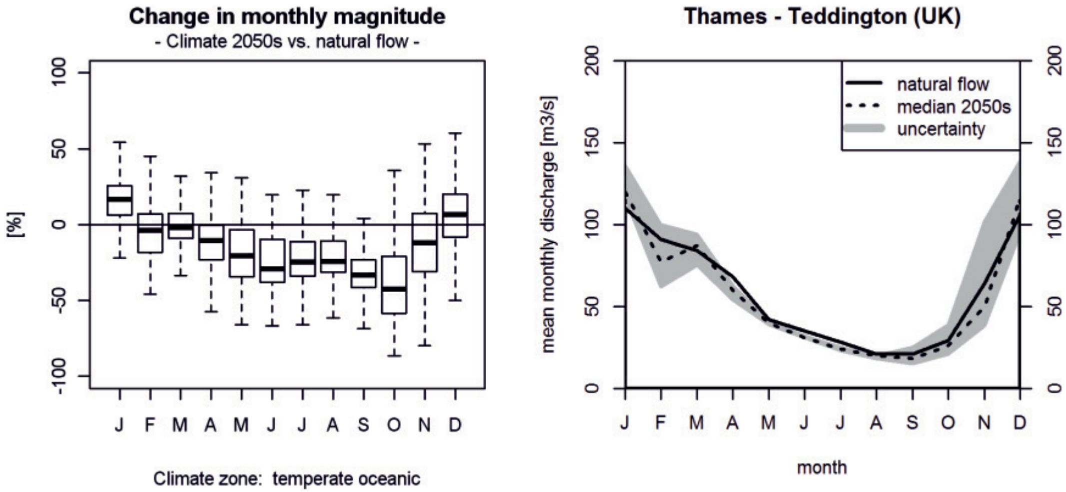

Fig. 12. Direction of change in the 2050s plotted for all grid cells of the temperate oceanic climate zone (left panel) and the Thames river near Teddington (right panel).

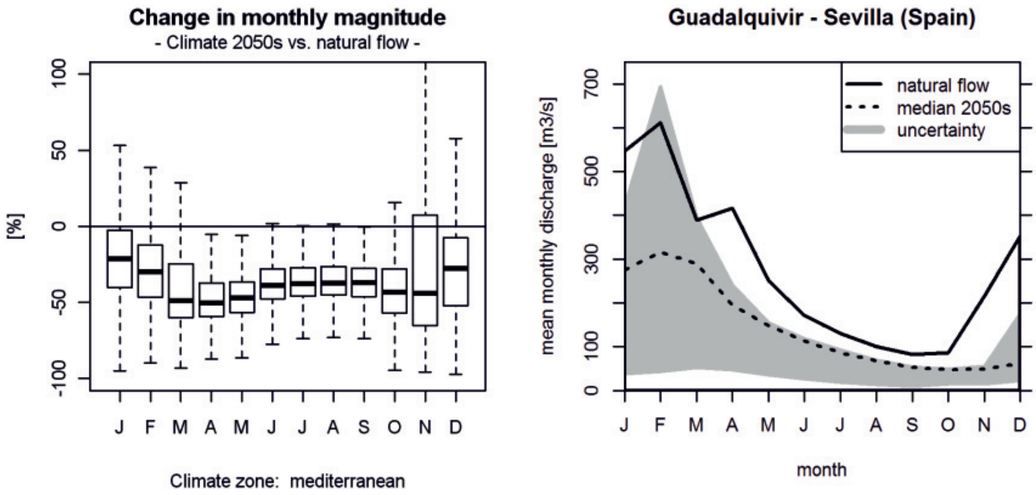

Fig. 13. Direction of change in the 2050s plotted for all grid cells of the Mediterranean climate zone (left panel) and the Guadalquivir river near Sevilla (right panel).