The future of European floodplain wetlands under a changing climate
Christof Schneider, Martina Flörke, Gertjan Geerling, Harm Duel, Mateusz Grygoruk and Tomasz Okruszko

ABSTRACT
In the future, climate change may severely alter flood patterns over large regional scales. Consequently, besides other anthropogenic factors, climate change represents a potential threat to river ecosystems. The aim of this study is to evaluate the effect of climate change on floodplain inundation for important floodplain wetlands in Europe and to place these results in an ecological context. This work is performed within the Water Scenarios for Europe and Neighbouring States (SCENES) project considering three different climate change projections for the 2050s. The global scale hydrological model WaterGAP is applied to simulate current and future river discharges that are then used to: (i) estimate bankfull flow conditions, (ii) determine three different inundation parameters, and (iii) evaluate the hydrological consequences and their relation to ecology. Results of this study indicate that in snow-affected catchments (e.g. in Central and Eastern Europe) inundation may appear earlier in the year. Duration and volume of inundation are expected to decrease. This will lead to a reduction in habitat for fish, vertebrates, water birds and floodplain-specific vegetation causing a loss in biodiversity, floodplain productivity and fish production. Contradictory results occur in Spain, France, Southern England and the Benelux countries. This reflects the uncertainties of current climate modelling for specific seasons.

Key words | climate change, ecological impacts, floodplain wetlands, floods, partial duration series, WaterGAP

INTRODUCTION
Floodplain wetlands are defined by their recurring inundation caused by flooding of adjacent rivers and often, the health of riverine ecosystems is dependent on the natural pattern of these inundation events (Junk et al. 1989). Hence, changes in flood flows have severe consequences on ecological and biological processes in river ecosystems. They may drain wetlands close to the river, reduce the productivity of river banks, lower the dynamics of delta regions and eradicate communities of organisms in the water (Nilsson et al. 2005). Today, river systems are already regarded as the most threatened ecosystems on the planet (Malmqvist & Rundle 2002) and the loss of biodiversity in riverine ecosystems has proceeded faster over the past 30 years than in terrestrial or marine ecosystems (Jenkins 2003). Besides other anthropogenic factors such as river regulation, channelisation, wetland drainage and water abstractions, climate change may severely alter the natural pattern of inundation over large regional scales in the future. Due to increasing temperatures, evapotranspiration will be raised nearly everywhere causing a reduction in runoff (Frederick & Major 1997). Precipitation patterns are also altering under climate change with regionally and seasonally different developments (IPCC 2007) leading to higher or lower runoff values in the future (Alcamo et al. 2007). In addition, in snow-affected catchments, runoff is influenced by a decreased volume and duration of snow cover in the winter time (Verzano & Menzel 2009). All these effects interact differently at different locations leading to unfavourable changes
in the river flow regimes with large geographical differences in directions and causes.

The hydrological impacts, in turn, can have significant consequences on the quality and functioning of floodplain wetland ecosystems that have evolved under, and become dependent on, regular inundation. Inundation (flooding) steers floodplain aquatic connectivity and the transport of matter and organisms through the system (Junk et al. 1989; Tockner et al. 2000). The floodplain landscape, and hence its connectivity gradient, is formed by interaction between the hydro-morphological regime and changing biota. Along these gradients, called ecotones, environmental factors vary and provide specific habitats for flora and fauna species. The formation of the floodplain landscape as well as the abiotic conditions in floodplain ecotones are highly influenced by the magnitude, timing and duration of inundation (Petts & Amoros 1996; Hughes 1997; Tockner et al. 2000). The magnitude of inundation affects the disturbance generated by a flood by: (i) determining the surface area inundated, (ii) determining the amount of matter and organisms transported, and (iii) influencing the floodplain shape. But reshaping the floodplain by erosion and sedimentation processes is essential for creation of pioneer habitat (Hughes 1997; Petts 2000; Marston et al. 2001; Geerling et al. 2006). Sediment and associated nutrients, transported in the main channel, are deposited in floodplains during floods. The distribution of these sediments and nutrients affect ecological succession and production of various floodplain elements, such as floodplain forests and floodplain lakes (Amoros & Wade 1996; van Geest et al. 2005).

The timing of inundation has an influence on the ecological functioning of floodplains, such as affecting life cycles of biota on various levels of scale. Some examples include: spawning habitat availability for fish species varies greatly at different flood levels, and spawning is mostly confined to a certain time in the year (Van de Wolfshaar et al. 2010). Also settlement of seeds, like poplar or willow, depends on the flood level during seed dispersal. The timing determines if suitable habitat can be colonised and additionally, a subsequent summer floodplain inundation can remove young seedlings and prevent settlement entirely (Merritt et al. 2009). In plant community research, summer floodplain inundations are regarded as more influential than winter inundations, because they determine the zonation of grassland communities, while winter inundations seem to sustain the zonation (van Eck et al. 2004). Also tolerance to inundation of floodplain forest species is lower in the growing season than in winter (Glenz et al. 2006). In the decomposition phase of floodplain life cycles, inundation of floodplains in winter is related to higher decomposition rates of floodplain litter than summer inundations (Langhans & Tockner 2006).

Finally, flood duration accounts for the abiotic soil conditions, the amount of settlement of fine sediments and amount of groundwater contact. The adaptation to flood duration is a selective pressure to floodplain species. For example, Casanova & Brock (2000) state that duration determined the zonation of plant communities. Floodplain forest species survival under flood duration stress varies greatly and determines short-term (extreme) and long-term (chronic influence) community composition (Glenz et al. 2006).

While flooding can cause damages with enormous costs, it is beneficial at natural locations and stimulates important ecosystem services of floodplain wetlands such as detoxification and nutrient removal, biomass and fish production, carbon storage, as well as biodiversity maintenance. In addition, healthy floodplains have recreational and aesthetic value. The aim of this study is an ecologically based assessment of flooding by quantifying the changes in magnitude, timing and duration of overbank flows for major European rivers affected by climate change impacts. For our analysis we used the global scale hydrological model WaterGAP (Water – Global Assessment and Prognosis) to simulate floods on the European scale. In addition, three climate change projections for the 2050s (2040–2069) were selected, calculated by three different GCMs (General Circulation Models): two representing the IPCC SRES (Special Report on Emissions Scenarios) A2 and one the SRES B1 scenario. As a flood indicator we used the ‘bankfull flow approach’ for deriving the inundation parameters. Finally, the expected effects on selected ecological components are qualitatively demonstrated.

This paper is organised as follows. In Methods we describe the selection process of floodplain wetlands for this analysis, the estimation of bankfull flow as an indicator for inundation and the analysis of all overbank flows by different hydrological parameters. Furthermore, the modelling approach of current and future river discharge data by WaterGAP and the selected climate change projections
are described in this section. In Results and Discussion, at first, the impacts of climate change on volume, duration and timing of inundation are presented. Subsequently, the hydrological changes are discussed and their effect on ecology is qualitatively evaluated.

**METHODS**

**Selection of rivers**

The analysis focused on major European rivers that have a high biological potential due to the flooding of adjacent floodplain wetlands. As there is no commonly accepted database of valuable European floodplains, the following procedure has been implemented in order to select the rivers of interest. First, a database of vast (i.e. area greater than 5,000 ha) European wetlands was created and the riparian (river fed) wetlands were extracted for further analysis. Second, spatial analysis of the Corine (Coordination of Information on the Environment) Land Cover (CLC) map (EEA 2004) was performed in order to find the river valleys with specific classes of vegetation assuming that this indicates the potential or the need of flood pulsing.

The database of European wetlands was established in the context of the SCENES project (Water Scenarios for Europe and for Neighbouring States; contract no. GOCE 036822, integrated project in the 6th framework programme) and consists of 102 objects including spatial data and attributes. Thereby, the following data-filtering and preparation procedure was applied:

1. Data about protected wetlands were collected from available European sources (NATURA 2000, Ramsar Convention) and national wetland surveys supported by expert knowledge of wetland specialists in Europe. This database contains more than 4,000 objects.
2. The database was filtered by means of area (i.e. larger than 5,000 ha), which resulted in more than 400 objects.
3. The database was divided into countrywide sets, which were sent to national experts for verification. The main question of the survey was about the ‘real’ extent of the wetland area. Within the database, a protected area is a mix of different habitats and the wetland of interest can cover an insignificant part of the protected territory. Additionally, national experts were asked for further characteristics of the selected objects such as water feeding and wetland type. This part of the procedure resulted in 102 objects.
4. In parallel, a database containing the spatial boundaries of the selected wetlands was created and related to the WGS84 (World Geodetic System 1984) coordinate system. The reviewed database was unified into one comprehensive dataset consisting of tables and ArcGIS software shapefiles (*.shp) associated in topologically correct layers.

A first subset of rivers that fed wetlands during high flows was identified by means of spatial analysis based on the created wetland datasets. Thereby the focus was on hydrological dependent wetlands (so-called riparian wetlands or wetlands of fluviogenic type of hydrological feeding). As the spatial extent of each of the wetland objects was known and precisely mapped in the WGS-84 coordinate system, topological correctness allowed the wetland database to be related to the drainage direction map (DDM5; Lehner et al. 2005) as used in WaterGAP. Subsequently, 44 rivers were selected for the further hydrological analysis.

A second subset of rivers was identified by the analysis of land cover in the river valleys. As a most coherent and prospective data source for the presented study, the CLC dataset was used. During the analysis, the following land use categories were taken into consideration: wetlands, inland marshes, peat bogs, natural grasslands, pastures scrub and herbaceous vegetation associations. If the combined size of such labelled area was greater than 5,000 ha and crossed by a major river of the DDM5 map, then the river was chosen for the further analysis. This phase of the selection resulted in the choice of 30 rivers.

Finally, 74 rivers were taken into consideration, all representing major European rivers responsible for the hydrological feeding of important European wetlands or associated with floodplains still covered with the vegetation resulting from high moisture conditions.

**Bankfull discharge approach and application**

The floodplain analysis performed in this study is based on the concept that in a riverine ecosystem different
flows have different functions. Floodplains are hydrology-dependent ecosystems and in order to maintain their multitude of crucial ecological as well as socio-economic functions, they depend on high flows that lead to inundation. In the analysis of flood dynamics and their ecological impacts, the scientific community has largely adopted magnitude and frequency of bankfull discharge as one of the important concepts (Navratil et al. 2006). Bankfull discharge is the flow at which the channel is full to its capacity (to the top of the banks), where the flow just begins to enter the active floodplain (Leopold et al. 1964). Above this discharge, all in-channel secondary channels and in-channel wetlands are generally hydraulically connected and so it provides important information for the ecological functioning of the river (Navratil et al. 2006).

The determination of bankfull discharge, however, is a complex analysis, and a choice has to be made between different existing methods. In order to estimate bankfull discharge for large-scale modelling purposes, an approach needed to be found that does not require in-situ river characteristics or hydraulic data (such as cross-sectional area) that are not available on a continental grid. Using flood frequency analysis in order to estimate bankfull flow is based on the assumption that on the long-term average, bankfull discharge occurs at a certain time interval (this finding does not imply regularity of occurrence). This assumption is not true for all types of rivers (e.g. bankfull events occur more frequently within the coastal plain as shown by Sweet & Geratz 2003), but still good estimates of bankfull flow can be gained. Leopold et al. (1964) stated that there is a remarkable similarity in the frequency of bankfull stage on a variety of rivers in diverse physiographic settings and sizes. Although some localities may diverge greatly from a specific frequency (Williams 1978; Mosley 1981), a number of studies worldwide have proven a correlation between certain flood return periods and bankfull discharge (Woodyer 1968; Harman et al. 1999; Castro & Jackson 2001). Therefore, in this study a statistical approach on flood frequency analysis has been chosen that was applied on daily discharge data of a 42-year time series (1961–2002) simulated by WaterGAP.

Two methods in flood frequency analysis exist that can be used to estimate bankfull discharge: (i) the Annual Maximum Flood (AMF) approach and (ii) the Partial Duration Series (PDS) approach. Due to its simpler structure, the AMF approach has been often used and a best approximation is obtained by considering a recurrence period of 1.5 years (Dury 1977; Dunne & Leopold 1978). However, a direct comparison has shown that the PDS approach should generally be preferred (Madsen et al. 1997). The PDS approach takes into account all flood peaks above a certain threshold and thus, has several important advantages in contrast to the AMF approach (Begueria 2005). The most important advantage for our analysis is the enhanced resolution for high frequency events (Sweet & Geratz 2003) such as the inundation of floodplains. The return period of bankfull discharge is very close to the smallest value that can be obtained by using annual series (i.e. one year). The PDS approach, however, is able to provide sub-annual recurrence intervals and respects that in some years, rivers can have more than one bankfull flow event. In addition, the PDS approach adapts better to heavy-tailed distributions that are common in hydrological applications (Madsen et al. 1997) and makes better use of simulated hydrographs as it includes more flood peaks (Kite 1977). Thus to be more precise in estimating bankfull discharge, we made use of the PDS approach whereas a return period of 0.92 years was applied as suggested by Dunne & Leopold (1978). In Europe, the PDS approach was applied by Petit & Paquet (1997) to determine the return period of bankfull discharge of 33 gravel-bed rivers in Belgium. For these rivers, an average return period of 1.2 years was found.

PDS approach

The PDS approach is based on the selection of flood peaks above a fixed threshold and comprises the assumptions that these are mutually independent, exponentially distributed and their number per time period follows a Poisson distribution (Langbein 1949; Shane & Lynn 1964; Todorovic & Zelenhasic 1970; Davison & Smith 1990). Hence, the choice of an appropriate threshold is the crucial part of the PDS approach that, however, represents one of the most difficult issues in its appliance (Nguyen 2002). In general, a threshold that is too low makes the threshold exceedances too close in time and thus, introduces serial dependence. On the other hand, a threshold that is too high, leads to an important loss in information of the hydrograph.
In the scientific literature, different systematic methods for the choice of threshold have been proposed and applied whereas the determination of the optimal threshold selection still requires more research (Adamowski et al. 1998; Deidda & Puliga 2009). Many researchers suggested methodologies that are based on the mean number of threshold exceedances per year. Most frequently a value between one and five has been cited (Choulakian et al. 1990; Begueria 2005). However, Lang et al. (1999) stated that no unique specific value exists for precise modelling and hence, an increasing threshold censoring procedure is recommended that is based on mathematical tests. One of these tests is the dispersion index (DI) that was proposed by Cunnane (1979). The DI is used to verify the adequacy of the Poisson assumption and is defined as the ratio of the average number of threshold exceedances per year to its variance. If the threshold exceedances follow a Poisson process, then the DI should be close to 1. Consequently, the DI was used in our study to find the most suitable threshold within a range of 1–5 threshold exceedances per year. The values applied for threshold setting were: 1/0.1/2/1.6/2/2.5/3/3.5/4.5/5. Ashkar & Rousseau (1986) showed that if a specific threshold has been found that follows a Poisson process, then any higher threshold produces independent flood peaks. Thus, we started with the lowest threshold of our range (i.e. 5) and raised it step-by-step until the DI was close to 1 (i.e. the DI must be within the limits of a confidence interval around 1 that was calculated by testing against a chi-squared distribution with a significance level of 0.05). In addition, the assumption of independence was relaxed by applying a declustering scheme. As hydrological events occur grouped in clusters (i.e. multiple peaks correspond to the same flood event), only the single highest flood peak within a cluster was included in the PDS. Thereby, one flood event is characterised by an up-crossing of the threshold level and the subsequent down-crossing.

The gained flood peaks were then arranged in order of magnitude and fitted to a Generalised Pareto distribution (GPD), which is a special case of both exponential and Wakeby distribution. The GPD was introduced by Pickands (1975). Since then, it has often been used in hydrology, especially for the distribution of independent exceedances over a certain threshold (Hosking & Wallis 1987; Davison & Smith 1990; Wang 1991; Rosbjerg et al. 1992) because of its inherent properties. Finally, estimating the inherent parameters of the GPD enabled the calculation of bankfull discharge by applying a recurrence period of 0.92 years.

The procedure to determine bankfull discharge includes the modelling of a 42-years time series on a daily resolution, threshold setting, declustering and distribution fitting. All was done individually for each relevant WaterGAP grid cell (5 × 5 arc minutes) in Europe. However, our continental-scale approach is connected with a number of uncertainties such as the setting of an appropriate threshold, the ambiguity of bankfull stage and the assumption of a specific return period that characterises bankfull discharge for all types of rivers.

Parameter of interest

In general, all components of a natural flow regime have a certain ecological significance. Low, medium and high flows create and maintain different habitat features, and aquatic species have evolved life history strategies primarily in direct response to them (Bunn & Arthington 2002). As it is important for this study to know about the flow events associated with overtopping of the banks and inundation of the floodplain, any flow greater than bankfull flow is considered a critical flow to investigate. But besides the magnitude of these overbank flows, it is also important to analyse how long they last and at what time of the year they occur. Flood magnitude and volume account for the extent of inundation whereas the duration of inundation determines whether a particular life-cycle phase of aquatic species can be completed. The timing of inundation assesses if life-cycle requirements are met, because key life-cycle phases are linked to the timing of annual extremes.

In this study, these parameters were regarded as crucial for describing hydrological alterations and are defined as follows (see also Figure 1):

- Flood volume for inundation (i.e. the cumulative amount of water above bankfull flow).
- Duration of overbank flows (i.e. the number of days flow exceeds bankfull flow).
- Timing of inundation (i.e. the month of the year with the highest flood volume).
Modelling of current and future daily time series

To compute the impact of climate change and other important driving forces on future water resources, the WaterGAP model (Water – Global Assessment and Prognosis) (Alcamo et al. 2003; Döll et al. 2003) was used. The model version applied in this study, WaterGAP3, herein referred as WaterGAP, computes both water availability and water uses on a 5 × 5 arc minutes grid (longitude and latitude), covering the whole of Europe. WaterGAP consists of two main components: a Global Hydrology Model to simulate the terrestrial water cycle and a Global Water Use Model (Flörke & Alcamo 2005) to estimate water withdrawals and water consumption of five different water use sectors. As this study focuses on the impact of climate change on hydrological alterations of river discharges, the influence of water uses has not been taken into account. Thus, only the hydrological model of WaterGAP is described in more detail.

The aim of the Global Hydrology Model is to simulate the characteristic macro-scale behaviour of the terrestrial water cycle in order to estimate water availability. Herein, water availability is defined as the total river discharge, which is the sum of surface runoff and groundwater recharge. The upstream/downstream relationship among the grid cells is defined by a global drainage direction map (DDM5), which indicates the drainage direction of surface water (Döll & Lehner 2002). Additionally, the flow length per grid cell is enhanced by applying an individual meandering factor for each grid cell derived from a high-resolution DDM (Lehner et al. 2008). In a standard model run, river discharges are simulated in 19,254 river basins in Europe. The effect of changing climate on runoff is taken into account via the impacts of temperature and precipitation on the vertical water balance.

Next to others, the main improvements of the model were done with special focus on the models ability to simulate floods. First, the storage of precipitation as snow is a crucial process within the hydrological cycle, as snow melt in spring induces increased river discharges and even floods in snow-affected watersheds. Second, with the calculation of dynamical flow velocities the differentiation between mountainous rivers with steep river bed slopes and rivers in lower altitude regions is possible. Therefore the inclusion of snow-related processes, with snow melt calculated by a simple degree-day algorithm on sub-grid scale (Verzano & Menzel 2009) and the consideration of dynamical flow velocity (Verzano et al. 2005) were implemented in the model code.

The parameters of interest indicating hydrological alterations in major European floodplain wetlands have been derived from the 30-year time series of gridded daily river discharge results calculated by WaterGAP for the reference period (1961–1990) and for three GCM-scenario combinations representing the 2050s (2040–2069). Thus time series were modelled for selected European floodplain wetlands taking into account a daily resolution.

Climate change scenarios

The baseline climate input including monthly information on precipitation, temperature and others covers the timeframe 1961–1990. For the model simulations we used a combination of the datasets CRU TS 2.1 (Mitchell & Jones 2003) and CRU TS 1.2 (Mitchell et al. 2004). Although the CRU TS 1.2 dataset has a higher spatial resolution (10 arc minutes) it covers only the predominant part of Europe. In order to get information for grid cells that were not covered, the CRU TS 2.1 dataset with a spatial resolution of 30 arc minutes was applied. Then both datasets were simply downscaled to a 5 arc minutes grid. Both CRU datasets, TS 2.1 and TS 1.2, provide monthly values for precipitation, temperature, cloud cover and the number of wet days per month. However, the WaterGAP model simulates river discharges on a daily time
step. Therefore, the monthly climate input had to be downscaled from monthly to daily values. In this context, temperature and cloudiness were downscaled with a cubic-spline-function between the monthly averages, which were assigned to the middle of each month. Precipitation was first distributed equally over the number of wet days per month and then distributed between the wet days within a month. The latter calculation was mathematically realised by using a two-state, first-order Markov Chain, for which the parameters were chosen according to Geng et al. (1986).

Both, downscaling of temporal and spatial data are associated with uncertainties as local sub-grid features and dynamics are neglected. However, Prudhomme & Davies (2009) showed that these uncertainties are generally lower than uncertainties caused by using different GCMs. In the scope of this paper, only one downscaling method was used.

The impact of climate change on water resources is expected to be stronger in 2050 compared with 2025. For this reason, we have drawn our attention only to the 2050s time period. To take into account the uncertainty of climate modelling, two SRES emission scenarios from three different GCMs were analysed. Within the SCENES project, the following model and scenario combinations were selected:

1. The IPSL-CM4 model from the Institute Pierre Simon Laplace, France representing an A2 scenario (IPCM4-A2). This GCM-scenario combination indicates high temperature increase and low precipitation increase or decrease in Europe (warm and dry);
2. The MICRO3.2 model from the Center for Climate System Research, University of Tokyo, Japan representing an A2 scenario (MIMR-A2). In accordance with the IPCM4 model, the Multifrequency Imaging Microwave Radiometer model projects a high temperature increase over Europe, but in combination with a high precipitation increase or low decrease (warm & wet);
3. The ECHAM5/MPI-OM model from the Max-Planck Institute for Meteorology, Germany representing a B1 scenario (MPEH5-B1). In contrast to the A2 scenario, the B1 scenario predicts a small temperature increase and an average precipitation change (moderate). These models were chosen to compute climate projections under changed levels of greenhouse gas emissions as specified for the SRES A2 and B1 scenarios for the 2050s represented by a time series covering the years 2040–2069. The original GCM outputs have a spatial resolution of $1.875^\circ \times 1.875^\circ$ (T63, longitudinal and latitudinal) and have been downscaled to the 5 arc minutes grid cells by applying a simple bilinear interpolation approach. Here, monthly temperature (T) and precipitation (P) results were used from the selected GCMs described above. The number of rain days per month and the cloudiness were taken from the reference period (1961–1990), and then the climate values were downscaled to daily climate as described in the section above. Hence, a possible increase of climate variability at the daily scale was not taken into account. This simple approximation of pseudo-daily future climate input was initially implemented in WaterGAP for studies of climate change impacts on long-term average discharge and may affect the simulated magnitude of high flows. The future climate input was scaled in consideration of the difference between observed and simulated climate of the reference period (Henrichs & Kaspar 2001; Lehner et al. 2006). For temperature, the observed CRU time series were scaled by adding the respective difference between the future and present-day temperature values from the GCM. For precipitation, observed precipitation time series were scaled by multiplication with the respective ratio between future and present-day precipitation. An exception to this rule occurs when present-day precipitation is close to zero (<1 mm); in this case the respective value was added. Following this method, monthly values for 50-year climate time series were constructed for the 2050s. This scaling approach is frequently applied to force global scale hydrological models for climate change studies.

**RESULTS AND DISCUSSION**

Although high flows leading to floodplain inundation can occur the whole year, usually, they accumulate within a specific season or month of the year. Therefore, our results strongly depend on seasonal climatic conditions. Within this study we assumed that the more uniform the results for a river and the larger a regional pattern, the higher the significance of changes in future floodplain inundation.

**Change in flood volume**

Flood volume determines the extent of inundation. The three different climate change realisations generally imply a
change in flood volume for almost all regions of Europe (Figure 2). In Central and Eastern Europe, all three climate projections show agreement in flood volume causing floodplain inundation, which is likely to be reduced in the 2050s. Thereby, the climate impacts are stronger under the IPCM4-A2 and MIMR-A2 projections compared with the MPEH5-B1 scenario realisation. Likewise, there is agreement in Ireland, Scotland and Western England. In this area more water will be available for floodplain inundation in the future.

An area of high uncertainty indicated by contradictory results in our analysis occurs in France, Spain and the Benelux countries, as well as on the River Thames and Derwent. Depending on the climate change data used, flood volume is reduced (IPCM4-A2) or increased (MIMR-A2) in the future. However, in these regions, agreement can be found in mountainous areas where rivers originate at high altitude. A reduced flood volume is predicted under all three climate change projections for river reaches at the Sisterna Iberico (Turia), the Pyrenees (Cinca and Garonne), Massif Central (Dordogne, Loire and Lot), the Alps (Rhone, Rhine, Enns, Mura, Drava, Isar, Inn, and Po), and likewise at the Dinaric Alps (Neretva) and Rila mountains (Maritza). The reduced flood peak is then carried forward along the rivers, at least for some distance.

Change in duration of overbank flows

The sensitivity of floodplains is often based on the duration of floodplain inundation. For the parameter duration a quite similar picture is drawn as for the flood volume (Figure 3).
In Central and Eastern Europe as well as in mountainous areas the duration of overbank flows is reduced, while in Ireland, Scotland and Western England duration of overbank flows is increased. The results based on MPEH5-B1 climate predict for most rivers only minor changes. Again, in France, Northern Spain and the Benelux countries as well as on the River Thames, no agreement can be found under the three GCM-scenario realisations. In contrast to the flood volume, there is also no agreement for the rivers Elbe, Havel, Warta and Narew, as well as for parts of the Oder and Dnieper.

**Change in timing of floodplain inundation**

The timing of floodplain inundation is important as access to and availability of floodplain habitats must coincide with life-cycle requirements of flood dependent local flora and fauna. Figure 4 depicts the month of the year with the highest flood volume in the baseline period, i.e. the time of the year where usually floodplain inundation occurs. According to this finding, in Western and Southern Europe, floodplain inundation accumulates in the winter time (blue grid cells) while in Central, Eastern and Northern Europe inundation usually occurs in spring (green grid cells). The North of Fennoscandia and mountainous areas stand out with the highest flood volume occurring mostly in June.

In the 2050s, there will be a shift in timing of floodplain inundation on many rivers in Europe, especially under the IPCM4-A2 and MIMR-A2 climate change projections (Figure 5). In Eastern and Northern Europe, floodplain inundation is expected to occur earlier than under baseline conditions (i.e. at least one month). In Southern and Central Europe, timing of floodplain inundation is likely to be earlier.
for many rivers, but there are also some rivers, especially in northern Italy, where timing can also be later within the year.

**Assessment of the hydrological changes**

The impact of climate change on floodplain inundation is induced on the one hand by increasing temperatures and on the other hand by spatial and temporal changes in precipitation patterns. Northern and Eastern Europe are characterised by cold or continental climate with strong winters often permanently below 0°C. Floodplain inundation in this area often occurs as a consequence of snow melt in spring falling together with strong precipitation events during this time (see also Figure 4). Due to increasing temperatures under climate change, extent and duration of snow cover are significantly reduced in this area in the 2050s. In the Northern Hemisphere, a reduction of approximately 10% in snow cover has been observed since 1966 (IPCC 2001) and Arnell (1999) showed that in the 2050s, snow cover will be considerably decreased over large parts of Central and Eastern Europe by the end of the winter. In addition, precipitation falls more often as rain instead of snow, leading directly to runoff in the winter time. Hence, in Central and Eastern Europe, discharges are likely to be increased in the winter, but the resulting snow melt induced flood peak in spring is expected to be decreased in the 2050s as less water is stored in the snow pack. This development in snow-affected river basins was demonstrated on an example in Belarus by Arnell (1999) and is exemplified here for the Narew River in Figure 6.

The reduced flood volume for inundation and the reduced duration of overbank flows as identified in our study for rivers in Central and Eastern Europe can be explained by the major role of snow melt in this region. Here, in the snow-affected river basins, the three scenarios show high agreement. An analysis of flood hazards was also conducted by Dankers & Feyen (2008). They also found a considerably decrease in flood hazards in the northeast of Europe. While in their study, this situation applies for the Baltic States, Finland and Northern Russia, in our study reduced flood volumes were already found in Poland and Eastern Germany. These differences could be explained by a much higher return period (i.e. 100 years) and the choice of a different GCM input. Dankers & Feyen (2008) expected in their analysis an increase in flood hazards in France and Northern Italy. This development corresponds to our analysis at least in two scenarios (MIMR-A2 and MPEH5-B1).

The duration of overbank flows shows a similar development to the flood volume. But considering MIMR-A2 climate, the duration of overbank flows shows an increase for a few rivers in Central and Eastern Europe (the Elbe,
Havel, Warta and Narew, as well as parts of the Oder and Dnieper). However, this change can be explained by the increased runoff in the winter, which causes some minor discharge peaks above bankfull flow for this climate projection, but does not lead to widespread inundation of the associated floodplains. As the 0 °C level is crossed earlier in the year, snowmelt is induced earlier in the year, too. Therefore, floodplain inundation is likely to occur earlier within the year in the 2050s. The same effect on flood patterns applies to rivers originating in mountainous areas (e.g. Alps, Massif Central, and Pyrenees) where snow melt influences the different indicators for some river distance. The shift in flood patterns to earlier seasons in the year in European mountain regions could also be shown by Dankers & Feyen (2008).

Figure 5 | Change in timing of floodplain inundation in the 2050s compared with the baseline (1961–90) under different future GCM-scenario combinations (IPCM-A2, MIMR-A2 and MPEH5-B1). Agreement between these scenarios is shown in the map on the bottom right. Here, grid cells are labelled as ‘no shift’, when the highest flood volume occurs under all three scenarios in the same month as in the baseline. Grid cells are labelled as ‘earlier’ or ‘later’, when the shift has the same direction under all three scenarios and is at least one month in one scenario.

Figure 6 | Two-year example of the Narew River in Poland simulated by WaterGAP showing changing discharges in the 2050s under the three applied scenarios compared with the baseline period (blue hydrograph).
Western and Southern Europe are characterised by maritime climate with milder winters where snow melt does not play a crucial role in the formation of high flows. Here, floodplain inundation is often caused by winter rains at a time of the year where evapotranspiration is low. Hence, in this area, future predictions of floodplain inundation strongly depend on the GCMs’ precipitation patterns rather than temperature. However for France, Spain, Southern England and the Benelux countries, the three different climate projections applied in our study predict contradictory results for precipitation in winter (Figure 7), the time where usually overbank flows occur in these regions.

Under the IPCM4-A2 climate projection, less winter precipitation in France, Spain, South England and the Benelux countries leads to a reduction in floodplain inundation, while under the MIMR-A2 climate higher winter precipitation causes an increase in floodplain inundation. The MPEH5-B1 climate shows moderate changes in winter precipitation with higher winter precipitation in parts of France, Benelux and Southern England, but less winter precipitation in Spain, parts of Turkey and the Middle East. Consequently, for the selected rivers in France, Spain, Southern England and the Benelux countries, our analysis provides contradictory results that reflect the uncertainties of current climate model calculations.

In this study, the scaling approach was chosen to calculate future projections of temperature and precipitation to force WaterGAP (see Methods). This approach was applied to CRU climate data that provide a significantly higher spatial resolution (0.167°) in contrast to time series calculated by GCMs (1.875°). Therefore, snow-induced flood peaks were represented significantly better, especially in the comparable small mountains of Europe. On the other side, the appliance of time series calculated by GCMs would directly respect the enhanced future climate variability, which is again supposed to increase flooding in the future in many areas (IPCC 2007; Kundzewicz et al. 2007). For future analysis, uncertainties due to spatial downscaling could be reduced by applying Regional Climate Model (RCM) output to force WaterGAP. State-of-the-art RCMs possess a spatial extent between 12 and 50 km over Europe (Christensen & Christensen 2007). Uncertainties due to temporal downscaling could be minimised by using lately established climate data based on daily time steps (Weedon et al. 2010).

Ecological impacts

Here, the results regarding changes in volume, duration and timing of inundations are placed in an ecological context, focusing on the effects on two major floodplain vegetation types and fish. To assess the effect of climate change on floodplain vegetation, a literature survey was carried out. The challenge is to fit the knowledge available to the applied model scale and outputs.

Floodplain vegetation

As shown above climate change has an impact on the hydro-morphological regime of rivers and wetlands, and as such can influence the spatial arrangement of floodplain vegetation. In particular the vegetation communities that reach their climax stage after long development cycles and depend on specific hydro-morphological regimes are sensitive to climate change. Those include the hardwood floodplain forests and the dry river grasslands that also inhabit the so-called river corridor species or ‘Stromtalpflanzen’ (Burkhart 2001;
van Looy & Meire 2009). Drier river grasslands and riparian mixed forest habitat is already marginalised through direct anthropogenic impacts such as deforestation and the cut-off of the lower dynamic floodplain area from the river by embankments. Expert judgement based on the literature reviewed gives the following climate related factors and ranges, which are needed to sustain hardwood forests and dry floodplain grasslands (see Table 1).

Exact dry grassland and hardwood forest community composition varies across Europe depending on eco-region and adaptation to existing flood regimes and local management.

Management such as grazing, mowing or cutting, and flood regime both influence vegetation composition (Gerard et al. 2008). Therefore, to assess effects of climate change on the European scale, the relative shift of parameters is the most important factor. Important to distinguish are the acute sensitivity of individuals and the sensitivity of populations or communities to chronic hydrologic alteration (Merritt et al. 2009). The latter is important to sustain the dry grasslands and floodplain forests on the long term (Geerling et al. 2006).

Changes in flood magnitude as found under most climate projections seem to point toward a reduction of flood

<table>
<thead>
<tr>
<th>Climatic factor</th>
<th>Alluvial hardwood forest</th>
<th>Alluvial ‘dry river meadows’</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Magnitude</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extreme flood</td>
<td>At least every 10–20 years to block succession to pure terrestrial forest.</td>
<td>Winter floods maintain habitat gradients shaped by summer floods.</td>
</tr>
<tr>
<td>Sedimentation</td>
<td>Fundamental for succession towards less frequent inundated area.</td>
<td>Increased input from sediment rich in nutrients will deteriorate habitat conditions.</td>
</tr>
<tr>
<td>Bankfull</td>
<td>125% bankfull can be important to create new pioneer sites along meandering rivers to colonize by succession precursors for hardwood forest development (Richter &amp; Richter 2000).</td>
<td>125% bankfull can be important to create new pioneer sites along meandering rivers to colonize (Richter &amp; Richter 2000). New pioneer sites are important for dispersal and recruitment for river corridor species (van Looy &amp; Meire 2009).</td>
</tr>
<tr>
<td><strong>Duration</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inundation (days/year)</td>
<td>&lt;40 days/yr</td>
<td>2–20 (max) days/yr</td>
</tr>
<tr>
<td>Duration of flood event</td>
<td>Direct vital range: not longer than 60% of growing season and not two seasons in a row (no recovery; Glenz et al. 2006). Recruitment: no recruitment when flooded more than 30–40% of growing season (Glenz et al. 2006).</td>
<td>Less than 1 week in growing season.</td>
</tr>
<tr>
<td><strong>Timing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Summer flooding</td>
<td>Chronic increase in inundating in summer can influence the species composition of existing sites.</td>
<td>Very sensitive to inundations in summer. Floodplain inundations in summer influence habitat zonation, (van Eck et al. 2004). An increase of inundations in summer will lead to decrease of habitat suitability.</td>
</tr>
<tr>
<td>Summer drought</td>
<td>Can tolerate summer drought (Glenz et al. 2006).</td>
<td>River corridor species (Stromtalpflanzen) seem to have the advantage on being able to withstand flooding, while also being able to cope with dry circumstances due to high drainage capacity of the elevated floodplain parts they occupy. Changes in either of these parameters will influence distribution negatively (Burkhart 2001).</td>
</tr>
</tbody>
</table>

Table 1 | Climatic factors and their responses for floodplain forests and dry river meadows. The vegetation types focused on are in the Natura 2000 habitat list (CEC 1992): (91E0) Alluvial forests with Alnus glutinosa and Fraxinus excelsior (Alno-Padion, Alnion incanae, Salicion albae); (91F0) Riparian mixed forests of Quercus robur, Ulmus laevis and Ulmus minor, Fraxinus excelsior or Fraxinus angustifolia, along the great rivers (Ulmenion minoris); (6120) Dry river grasslands of calcareous soils. In The Netherlands these are of the Medicago-avenetum pubescens type (van Looy & Meire 2009) also including the Stromtalpflanzen (Burkhart 2001). Growing season is defined as May–September.
volumes (Figure 2). Consequently, the floodplain area can decrease and formerly inundated floodplain forests and dry grasslands will be colonised by more terrestrial species or invaders (Predick & Turner 2008). This situation will directly lead to a decline of habitat area for these vegetation types. Secondly, a decrease of flood volume can lead to morphologically less active systems, especially in the upland areas. However, this change can lead to an initial increase in softwood forest establishment as deduced from Marston et al. (2001). The loss of floodplain dynamics will eventually lead to a loss of floodplain diversity, also for dry grasslands.

An increase in flood volume will increase floodplain area. A gradual change will affect current locations of dry grassland and hardwood stands as they are inundated more frequently or with longer durations. However, available habitat may shift towards formerly dry areas. Secondly, the affected rivers can become more morphologically active and can rejuvenate existing habitats.

Duration of overbank flows is decreasing for most rivers with agreement of all three climate projections (Figure 3). Change is up to five days per year or more. Overall consequences are similar as to reduction in flood magnitude, a decrease of habitat availability. However, as other more frequently inundated areas become suitable, i.e. less inundated, habitat for dry grassland and floodplain forest may shift towards these.

The results show that the timing of flood peaks may shift, in most agreement the floods appear earlier in the season. Most influential is timing for reproduction, or seed dispersal for genera like willow (Salix spp.) or Poplar (Populus spp.). These genera time their seed release in such a way that competition between different species of Salix spp. and Populus spp. are minimised. Floods affect the habitat availability, and change in flood timing can decrease the available habitat for some of these species. Additionally, vegetation reacts also to spring temperature changes and timing of these may also change due to climate change. This change can either mitigate or enhance the consequences of changes in flood timing. Recent studies support the notion that floods during the growing season may be particularly important from the ecological point of view by affecting plant distribution and survival. In contrast, the effect of winter flood timing on vegetation is not easily determined and regarded less influential (van Eck et al. 2004). A differentiation between summer and winter floods was not carried out in this study, but could lead to improvements in future ecological impact assessments.

**Fauna (fish)**

A reduction in flood magnitude influences the connectivity of the landscape, notably for aquatic habitats (Petts & Amoros 1996). In combination with the expected reduction of flood duration, there will be less habitat available for aquatic species. Fish production will probably decrease when flood volume decreases as can be deduced from Lindholm et al. (2007) for tropical systems. Additionally the expected change of flood timing towards earlier spring can make habitats unreachable. A decrease in morpho-dynamics for upper reaches can lead to a less diverse riverine landscape with lower availability of aquatic habitat.

**CONCLUSION**

River ecosystems including floodplain wetlands belong to the most threatened ecosystems on the planet with a proceeding loss in biodiversity. Regarding the health of these ecosystems, flows above bankfull flow play a crucial role as ecological and biological processes change when the river is linked to the associated floodplain. However, floodplain inundation is often disturbed by anthropogenic factors such as river regulation, channelization, wetland drainage and water abstractions. Climate change is altering volume, duration and timing of future floodplain inundation events, and therefore constitutes an additional threat to river ecosystems.

Results of this study indicate that climate change affects floodplain inundations over large regional scales in Europe in the 2050s. In snow-affected catchments (i.e. in Central, Eastern and Northern Europe as well as in mountainous areas) duration and volume of inundation are expected to decrease and inundation may appear earlier in the year. Here, inundation usually occurs in spring when snow melt falls together with strong precipitation. Due to an increased temperature, the proportion of precipitation falling as snow is reduced as well as extent and duration of snow cover. This change leads to earlier snow melt within the year and...
considerably reduced snow melt induced flood peaks. According to this finding on the selected floodplains in Central, Eastern and Northern Europe, the extent of floodplain habitat is reduced in the 2050s compared with current conditions. Consequently, floodplain forests and dry grasslands are expected to be colonised by more terrestrial species or invaders. As habitats for spawning, nursery, foraging and escaping from predation are narrowed, fish can be negatively affected. All in all, important ecosystem services such as biodiversity maintenance, nutrient removal, detoxification, carbon storage, floodplain productivity and fish production are likely to decrease on the selected floodplain wetlands in Eastern and Northern Europe. Hence, to avoid economic losses and to assure a natural pattern of floodplain inundation, it is important to consider the impact of climate change in the planning of future adaptation measures.

In warmer regions, inundation strongly depends on the simulated precipitation patterns. Here, the choice of the climate projection has a bigger influence on the hydrological results compared with areas where snow melt-induced flood peaks occur. In our analysis, precipitation patterns modelled by three different GCMs representing two different emission scenarios lead to contradictory results for future changes in volume, duration and timing of floodplain inundation. This finding reflects the uncertainties of current climate modelling for specific seasons and therefore, no consistent conclusions could be drawn for rivers in Spain, France, Southern England and the Benelux countries.

The simulation of flood scenarios and hence bankfull flow events could be improved by the usage of daily climate data to force WaterGAP. Instead of applying the ‘scaling approach’ to get a higher spatial resolution climate input according to measured data, time series as calculated by RCMs, but bias-corrected, could be used to consider changes in future climate variability. One aim in riparian ecology is to build a general framework for predictions of, for example, vegetation response to altering inundation conditions. In this study, the ecological impact analysis has been performed in an indicative and qualitative manner. For our future work, we will improve ecological consequences for fish and fauna by distinguishing upland and lowland rivers as well as incorporating a more systematic approach by considering functional classifications of species that respond in similar ways to components of hydrological regimes.

**ACKNOWLEDGEMENTS**

The financial support from the EU’s Research Framework Programme (FP6) under contract no. 036822 (SCENES) is gratefully acknowledged. The authors express their appreciation to Professor Mike Acreman from the Centre for Ecology and Hydrology in Wallingford for fruitful discussions.

**REFERENCES**


Frederick, K. D. & Major, D. C. 1997 Climate change and water resources. Clim. Change 37, 7–23.


Langhans, S. D. & Tockner, K. 2006 The role of timing, duration, and frequency of inundation in controlling leaf litter decomposition in a river-floodplain ecosystem (Tagliamento, northeastern Italy). Oecologia 147, 501–509.


First received 21 April 2010; accepted in revised form 28 February 2011