Ecological Indicators 38 (2014) 198–211

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Mapping ecosystem services: The supply and demand of flood regulation services in Europe

Julia Stürck[a,*], Ate Poortinga[b,c], Peter H. Verburg[a]

[a] Institute for Environmental Studies, VU University Amsterdam, De Boelelaan 1087, 1081 HV Amsterdam, The Netherlands
[b] Soil Physics and Land Management Group, Wageningen University, P.O. Box 47, 6700 AA Wageningen, The Netherlands
[c] Water Insight, Postbus 435, 6700 AK Wageningen, The Netherlands

ARTICLE INFO

Article history:
Received 10 June 2013
Received in revised form 9 October 2013
Accepted 6 November 2013

Keywords:
Flood regulation
Europe
Land use
Supply and demand indicators
Modeling
Hydrology

ABSTRACT

Ecosystem services (ES) feature highly distinctive spatial and temporal patterns of distribution, quantity, and flows. The flow of ecosystem goods and services to beneficiaries plays a decisive role in the valuation of ES and the successful implementation of the ES concept in environmental planning. This is particularly relevant to regulating services where demands emerge often spatially separated from supply. However, spatial patterns of both supply and demand are rarely incorporated in ES assessments on continental scales. In this paper, we present an ES modeling approach with low data demand, fit to be employed in scenario analysis and on multiple scales. We analyze flood regulation services at a European scale by explicitly addressing the spatial distribution of ES demand. A flood regulation supply indicator is developed based on scenario runs with a hydrological model in representative river catchments, incorporating detailed information on land, cover, land use and management. Land use sensitive flood damage estimates in the European Union (EU) are employed to develop a spatial indicator for flood regulation demand. Findings are transferred to the EU territory to create a map of the current supply of flood regulation and the potential supply under conditions of natural vegetation. Regions with a high capacity to provide flood regulation are mainly characterized by large patches of natural vegetation or extensive agriculture. The main factor limiting supply on a continental scale is a low water holding capacity of the soil. Flood regulation demand is highest in central Europe, at the foothills of the Alps and upstream of agglomerations. We were able to identify areas with a high potential capacity to provide flood regulation in conjunction with land use modifications. When combined with spatial patterns of current supply and demand, we could identify priority areas for investments in ES flood regulation supply through conservation and land use planning. We found that only in a fraction of the EU river catchments exhibiting a high demand, significant increases in flood regulation supply are achievable by means of land use modifications.

1. Introduction

River floods are the costliest and most frequent natural hazards in Europe (Barredo, 2007; Ciscar et al., 2011; EEA, 2010; Munich Re, 1997). Direct and indirect economic losses originating from river floods are projected to grow due to socio-economic factors and increases in the frequency and magnitude of heavy precipitation events under climate change (Frei et al., 2006; Jongman et al., 2012; te Linde et al., 2011; Kundzewicz et al., 2006). Due to these developments, flood protection is an issue of growing importance. However, structural flood mitigation measures such as dikes are frequently associated with detrimental effects on biodiversity and ecosystem service (ES) provision (e.g., decreased habitat connecitivity due to dikes and dams; Elosegi et al., 2010; Lytle and Poff, 2004; McAllister et al., 2001). Therefore, particularly in the light of The Ecosystem Approach (TEEB, 2010), the interest in cost-benefit estimations of non-structural mitigation measures (e.g., increased water retention in the floodplain) and the assessment of the ecosystem's flood regulation capacity increasingly gained interest over the last years (e.g., Bagstad et al., 2011; Grossmann, 2012; Maes et al., 2011). Flood regulation supply addresses the ecosystem's capacity to lower flood hazards caused by heavy precipitation events by reducing the runoff fraction. As such, flood regulation is an ecosystem service that contributes to human well-being (MA, 2005). The idea that the landscape (i.e., the structure and composition of vegetation and land use) itself features capacities to impact the frequency, magnitude and duration of floods dates back at least as far as to the first century AD (Andréassian, 2004). Systematic experiments to study the effects of landscape elements (e.g., field boundaries or crop types) on floods have been performed since the 19th century (Farrell, 1995). More recently, the use of hydrological models to quantify flood regulation services has

* Corresponding author. Tel.: +31 (0)20 59 89544.
E-mail address: julia.sturck@vu.nl (J. Stürck).

1470-160X/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ecolind.2013.11.010

been introduced (e.g., Eigenbrod et al., 2011; Nedkov and Burkhard, 2012).

The provision of ES is highly dependent on the ecosystem's spatial configuration, e.g., location, shape, and connectivity (Bastian et al., 2012; Turner et al., 2013). Next to the quantification of ES provision, increasingly, the analysis of ES *flows* to beneficiaries gains attention. According to Syrbe and Walz (2012), ES flows connect service provisioning areas (SPA) with service benefitting areas (SBA). In the case of flood regulation services, this flow is of particular interest. The spatial link between flood regulation supply and beneficiaries and the directional flow of the benefit transfer between them is determined by the hydrological system. In the methodological framework of Syrbe and Walz (2012), downstream areas within a river catchment are predominantly characterized as flood regulation benefitting areas, whereas headwaters are characterized as flood regulation supplying areas.

While several authors (e.g., van Berkel and Verburg, 2011; Haines-Young et al., 2012; Liquete et al., 2013; Maes et al., 2011), have mapped ecosystem services at the continental scale, mapping the demand *and* supply of ecosystem services has been attempted predominately at the local and regional scale. Burkhard et al. (2012) developed an approach for the spatially explicit analysis of ecosystem service supply, demand and budgets based on land cover properties. This approach has been adopted by Nedkov and Burkhard (2012) for estimating flood regulation budgets in a Bulgarian watershed. Whereas the budget approach is fit to visualize local to regional mismatches in supply and demand, it disregards the effect of service flows by neither taking into account downstream connected SBA nor upstream potential SPA. These, however, are fundamental to reflect the value of flood regulation supply. Syrbe and Walz (2012) analyzed supply and demand patterns of flood regulation in Saxony, specifically accounting for ES flows. It is however difficult to adopt this approach on the European scale due to the high data requirements.

The aim of this study is to provide a spatial analysis of demand and supply of flood regulation at the European level, and hereby identifying areas that have a high potential to mitigate downstream flood risk through land use modifications. The underlying approach is developed to cope with existing data limitations for continental and global studies. Section 2 shortly presents the methodological framework of the paper and reviews the processes determining flood regulation service supply and demand that need to be accounted for. Section 3 presents the approach used to develop a European scale indicator of flood regulation supply as well as an indicator of downstream demand, based on hydrological model experiments and flood damage model estimates. Section 4 presents the spatial variation in these indicators and an assessment of the role of land use and alternative land management to regulate flood risk in European river catchments.

2. Supply and demand of flood regulation

2.1. Framework of this study

In this paper, we develop and apply an approach to quantify the ecosystem service flood regulation. This is achieved by analyzing spatial patterns of indices developed for both the supply of flood regulation and the demand for such services. The underlying methodological framework is presented in Fig. 1. The approach consists of three components: (1) developing a method to quantify both ES flood regulation supply and ES flood regulation demand, (2) applying the resulting indices to land use in Europe, and (3) analyzing the resulting spatial distribution of supply and demand. The following sections provide background to the selected indicators and the processes analyzed.

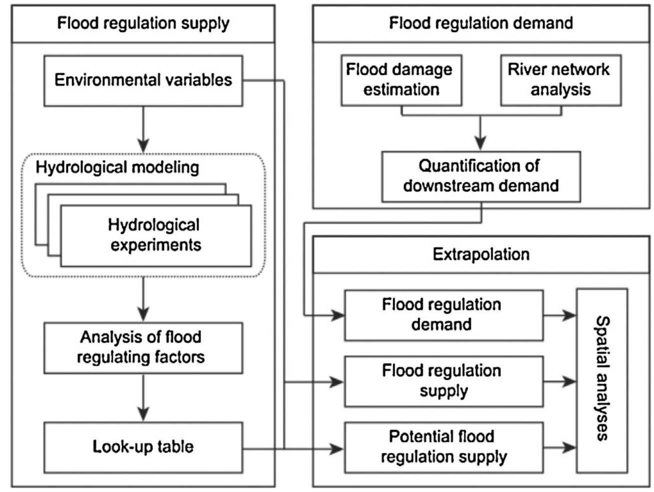

Fig. 1. Overview of the approach.

2.2. Flood regulation supply

The capacity of ecosystems to provide flood regulation by impacting rainfall-runoff responses is dependent on various parameters (Beven and Wood, 1983). In Fig. 1, these factors are referred to as environmental variables. River catchments exhibit different physical characteristics which constitute for highly unique discharge regimes and discharge responses to precipitation (García-Ruiz et al., 2008). However, catchments with resembling geomorphologic characteristics feature significantly similar peak discharge responses to storm rainfall (Morisawa, 1962).

Land cover, land use and land management (hereafter referred to as land use) account for different levels of flood regulation supply by amplifying or moderating river peak flows through surface runoff modulations (Fohrer et al., 2001). Main drivers are land use specific variations in evapotranspiration rates, vegetation–soil interactions and modifications of the surface roughness (e.g., Chen et al., 2007; Leyer et al., 2012). The degree of land use intensity, for instance, can have a strong impact on the land cover's flood regulation capacity, e.g., due to marked differences in crop stand density, the use of heavy land machines, or the presence or absence of forest understories. One relevant proxy for agricultural management is the field size. Field margins such as hedges and walls can impact on runoff protraction, favor infiltration and evaporation and thus potentially lower the runoff fraction contributing to discharge peaks (Levavasseur et al., 2012). In forests, land management can cause spatial and temporal disturbances (e.g., frequent clear-cutting of forest stands) which entails increased overland flow and reduced evapotranspiration. This can be avoided in a close-to-natural management system (Anderson et al., 1976). Therefore, also on a continental scale, it is crucial to include proxies for land use intensity and management in the quantification of ecosystem service provision.

Soil hydraulic properties play a key role in runoff processes and water retention. Infiltration capacity defines the maximum amount of precipitation and overland flow which can be absorbed per time step. The natural infiltration capacity of a soil can be significantly decreased by surface crusting and surface sealing, e.g., in association with built-up area (Haase, 2009). Water holding capacity of the soil (WHC) describes the maximum water quantity soil can potentially contain before it is saturated. WHC varies with soil texture, particle density, soil depth and the fraction of organic matter (e.g., Gupta and Larson, 1979). Runoff characteristics drastically change when the soil is fully saturated and the overland flow rapidly increases (Burt and Butcher, 1985). Therefore, weather conditions

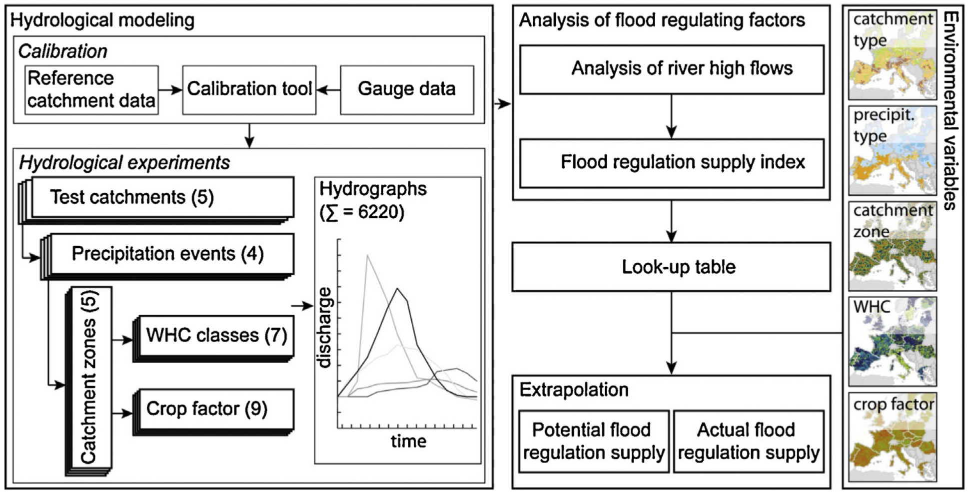

Fig. 2. Quantification scheme for the flood regulation supply indicator.

prior the onset of a precipitation event strongly impact the soil's actual water storage capacity.

The distance of a landscape fragment to the river bed can affect its impact on the contribution of runoff to river discharge (e.g., Saghafian et al., 2002). One reason is the time the runoff requires for reaching the river, which is reduced with increased slope (Valentin et al., 2005). Second, in proximity to the river bed, runoff throughflow accumulates, which, by increasing soil moisture, consequentially decreases actual water storage capacity (Uchida et al., 2006). The combinatorial effect of land use, soil hydraulic properties, and the physical characteristics of a catchment play a key role in determining flood regulation supply.

The onset, duration and magnitude of a flood hazard are highly dependent on precipitation intensity, duration and extent, constituting for different flood types (i.e., rainy-fluvial floods, flash floods, snowmelt-fluvial floods; Barredo, 2007; Nedkov and Burkhard, 2012). The flood regulative effect of the above mentioned environmental variables may, therefore, depend considerably on the underlying precipitation event and prior weather conditions.

2.3. Flood regulation demand

The flood hazard is defined by the extent and depth of inundation. The magnitude of a flood hazard can be expressed in probabilistic recurrence intervals (e.g., a *hundred year flood* has a likelihood of 0.01 to occur each year). The potential damage of a given flood hazard is dependent on the goods and assets exposed, as well as their vulnerability to flooding. The function of flood hazard, exposure and vulnerability of assets is commonly referred to as flood risk (Kron, 2005). Two types of monetary flood damage can be delineated: direct damages, i.e., crop failure and property damages; and indirect damages (i.e., production loss due to power outages). Direct flood damages on large scales are commonly estimated for probabilistic flood events with land use specific depth-damage curves (Lugeri et al., 2010).

Flood damage values give an indication for the need for intensifications in flood protection. However, for quantifying the importance of a specific ecosystem or landscape fragment for flood regulation, we need to change perspective from the point of impact to the source of supply, the landscape fragments forming the SPA. This can be achieved by taking into account all flood damages downstream of a specific location in the river basin which this landscape can possibly impact by its capacity to provide flood regulation. Therefore, we presume that a high demand for natural flood regulation is at hand if damage values are disproportionally large compared to the extent of potential upstream SPA. Thus, in case of high flood regulation demand, particularly the provision in the associated SPA's has to be increased. To be able to refer to downstream demand from a catchment perspective, a straightforward approach is presented in Section 3.2.2.

3. Methodology

3.1. Flood regulation supply assessment

The aim is to provide a spatially explicit indicator of flood regulation supply in Europe. The index is based on the response of hydrographs to environmental variables derived from hydrological experiments carried out with the hydrological model STREAM (Aerts et al., 1999), where the effects of five environmental variables (see Table 1) on discharge volumes following precipitation events are estimated (see Fig. 2). The outcomes of these model experiments are translated into a supply index which is applied to the European extent based on spatial maps of the environmental variables explored in the experiments.

3.1.1. Environmental variables

River catchments are highly diverse. To account for the variation in catchment morphology across Europe, European river catchments (EEA, 2008) are classified into five categories depending on their size, maximum slopes and mean elevation following from a *k*-means cluster analysis (Lloyd, 1982). This approach partitions the observations in a predefined number of *k* clusters depending on the observations' distance to the cluster mean. Resulting catchment type characteristics are summarized in Table 2. River catchments smaller than 2 km^2 have been omitted in this analysis. Maximum cluster differentiation has been achieved by means of a sensitivity analysis on the set of variables and the number of classes included in the *k*-means clustering approach.

Characteristics of intensive rainfall events vary across Europe. To ensure that the resulting index is capturing various possible responses of the environmental variables analyzed, time series of daily precipitation between 1990 and 2000 were analyzed, and the relative quantity of (1) very heavy one day, and (2) very heavy five day precipitation events were counted per grid cell. For both types of precipitation, it was noted whether they occurred in the presence or absence of preceding precipitation in a time period of 15 days prior the onset of the event. The preceding precipitation was included to account for water storage in the soil. This resulted in four modes of rainfall events (see Table 3). Based on the counts of

Table 1
Environmental variables used for the application of the flood regulation supply index.

Environmental variable	Inputs	Resolution	Sources
Catchment types	River catchment map		EEA (2008)
	DEM HYDRO1k	~1 km	USGS (2007)
Catchment zones	DEM HYDRO1k	~1 km	USGS (2007)
Precipitation types	Daily precipitation (1990–2000)	~27 km	Haylock et al. (2008)
Crop factor	CORINE land cover 2000	~100 m	EEA (2011)
	Agricultural intensity	~1 km	Temme and Verburg (2011)
	Agricultural field size	~1 km	Kuemmerle et al. (2012)
	Growing stock and forest biomass	~500 m	Gallaun et al. (2010)
	Forest management	~1 km	Hengeveld et al. (2012)
	Tree species	~1 km	Brus et al. (2012)
WHC	WHC classes	~1 km	FAO (2009)

Table 2
Catchment type characteristics and selected test catchments.

Catchment type characteristics				Test catchment characteristics				
Type	Size (km^2)	Elevation (m)	Slope (°)	Size (km^2)	Elevation (m)	Slope (°)	River, country	Gauge station[a]
Lowland	148 ± 413	51 ± 23	2.2 ± 0.7	862	60	0.3	Aurajoki, FI	Halinen
Large plains	4821 ± 1557	232 ± 88	2.6 ± 1.7	4158	312	3.9	Meuse, FR	Stenay
Small hills	264 ± 470	308 ± 154	7.8 ± 3.6	1115	248	6.5	Lune, UK	Caton
Large hills	2205 ± 3358	576 ± 269	9.6 ± 5.1	6451	444	5.7	Jizera, CZ	Turice
Mountains	1441 ± 1368	1116 ± 483	17.2 ± 7.6	720	1428	20.1	Ara, ES	Boltaqa

[a] *Source*: GRDC.

Table 3
Characteristics of precipitation types as environmental variable and as input in hydrological experiments.

Precipitation type		Environmental variable		Hydrological experiments	
Duration	Antecedent soil moisture	Minimum quantity of event (mm)	Antecedent precipitation in prior 15 days (mm d^{-1})	Quantity of event (mm d^{-1})	Antecedent precipitation in prior 5 days (mm d^{-1})
One day	Wet	20	≥1	20	2
One day	Dry	20	<1	20	0
Five days	Wet	100	≥1	10	2
Five days	Dry	100	<1	10	0

these events in each grid cell, the most frequent precipitation type was identified for each catchment.

To be able to account for the position within a catchment as a determinant of the influence of land use effects on flood regulation, the river catchments are divided into five equally sized zones, depending on their respective elevation and a slope factor. The slope factor reflects the duration of the slow flow. The zones reflect the steepness and the proximity of each location to the river network, subdividing a river catchment in upstream and downstream areas (see Fig. 5(right) for an example and Fig. A.5 (supplementary material) for the zonation of the entire study area).

Supplementary to land cover, we also included land use and land management information in the assessment. For agricultural land uses, it was assumed that field size and land use intensity modify the vegetation parameter. For forests, differences in dominant species (e.g., coniferous, mixed or broadleaved; deciduous or evergreen species), above-ground biomass, and a proxy for the naturalness of the forest management were included to account for the heterogeneity of forest land cover across Europe. The data sets used to derive these characteristics are shown in Table 1. *Crop factors* are parameters in hydrological modeling used to determine the actual evapotranspiration from the potential evapotranspiration dependent on land use and management characteristics. Crop factors were assigned to land cover types based on crop factors described or employed in hydrological models by Breuer et al. (2003), van Deursen and Kwadijk (1993), Fohrer et al. (2001), Hargreaves (1974), van Seters and Price (2001), and Tomar and O'Toole (1980). To supplement this information, the land use crop factor was adjusted to account for the effects of land management and land use intensity of arable land and forest. For agricultural land use types, the crop factor was decreased with increasing field size (following Levavasseur et al., 2012) and with increasing land use intensity (based on Fiener et al., 2011). For forest, the crop factors were increased depending on the naturalness of the management (Planinšek et al., 2011; Gomi et al., 2008), the biomass per hectare, and for evergreen species (Peel et al., 2001). Crop factors for all land use types used in this study and their variability in dependence on land management and intensity are shown in Fig. 3.

To reflect the impact of soil hydraulic properties on water storage and retention, a European map representing WHC was retrieved from FAO (2009). It includes seven classes ranging from 0 to 150 mm.

3.1.2. *Hydrological modeling*

STREAM (Spatial Tools for River basins and Environment and Analysis of Management options) is a GIS based spatially distributed rainfall runoff model optimized for the analysis of the hydrological impact of land use and climate changes in large river basins (Aerts et al., 1999). The water balance is calculated per grid cell based on the Thornthwaite and Mather (1957) equation. In this study, STREAM v1.1.3.1 was used. The hydrological experiments are based on three steps. (1) *Select and process reference catchment data*. For each catchment type included in this study, a representative European catchment was selected based on its proximity to the

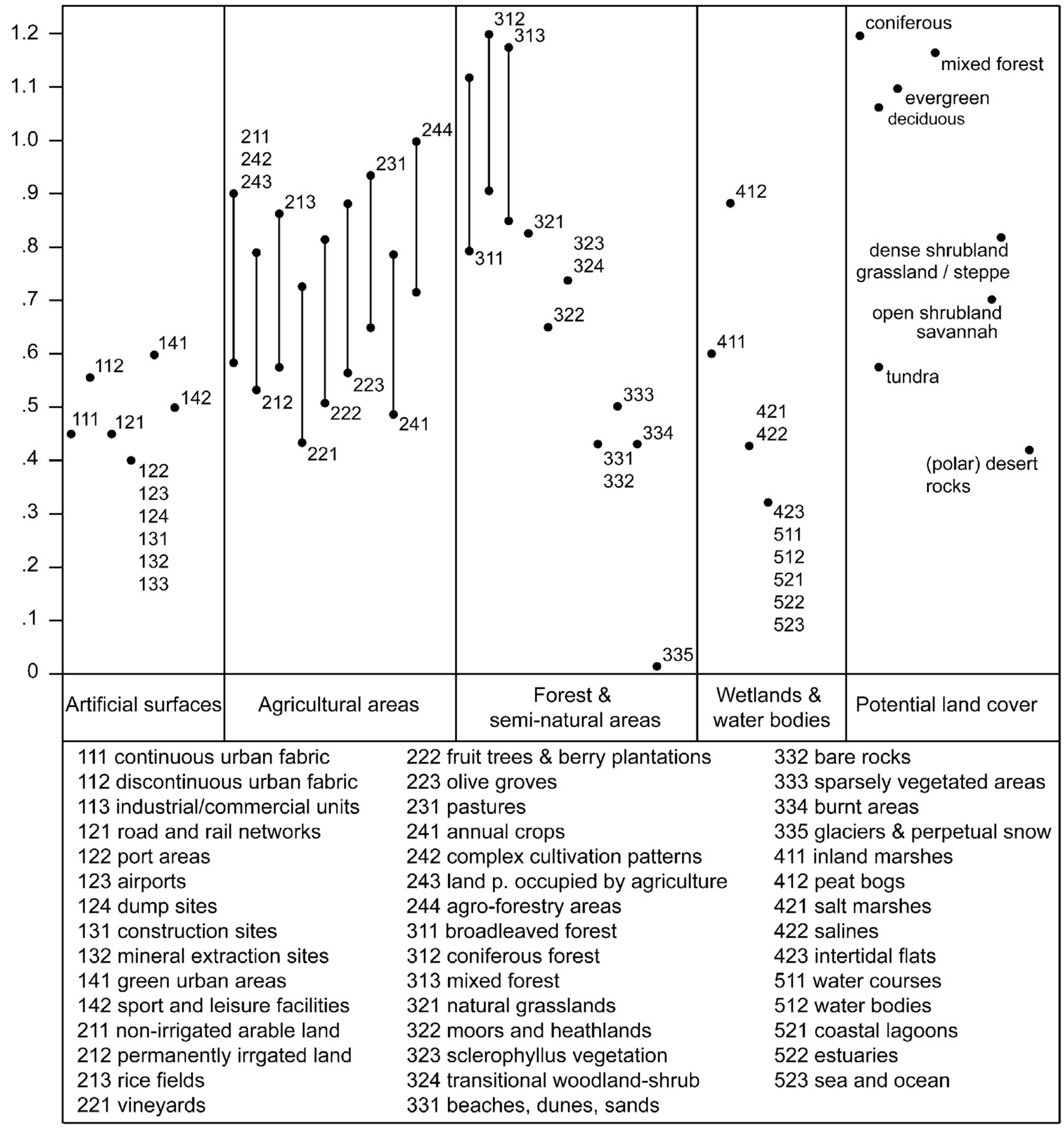

Fig. 3. Crop factor estimates per CORINE land cover class. The crop factor varies in agricultural and forest land cover classes in dependence of land use management and intensity. In the right column, crop factors for potential land cover classes after Ramankutty and Foley (1999) are shown.

cluster mean, the presence of sufficient gauge data, and the absence of karst and large built-up areas in the catchment. The selected test catchments are presented in Table 2. (2) *Calibration of the hydrological model for the test catchments*. The STREAM model has been calibrated for the selected test catchments using monthly discharge data observed at a gauge station at the catchment outlet provided by the Global Runoff Data Centre (GRDC) and the calibration tool PEST (Watermark Numerical Computing, 2005) implemented in STREAM. For the calibration of the test catchments, monthly temperature and precipitation fields of 0.5° (retrieved from CRU TS 3.10 and CRU TS 3.10.01, respectively; Mitchell and Jones, 2005) were statistically downscaled to 1 km^2 using monthly, high resolution (1 km^2) climatologies (Hijmans et al., 2005). (3) *Hydrological experiments to estimate flood regulation capacity*. For the calibrated models of the test catchments, hydrological experiments were run. In the experiments, the chosen environmental variables were varied to capture the variation of their conditions across Europe. Each run was initialized with observed daily climate data (Haylock et al., 2008). According to the precipitation types described above, four design events were tested in the STREAM experiments (see Table 3) in each test catchment. For all experimental runs, nine crop factors (0.4, 0.5,. . ., 1.2) and seven WHC classes have been iteratively adjusted in one catchment zone, while the remaining four zones were set to the lowest values of both variables. For each simulation, the discharge record at the catchment outlet was retrieved. A reference scenario for each precipitation event and test catchment was simulated in which WHC and crop factors are set to lowest value throughout the catchment. In total, for all variable combinations, 6220 simulation experiments were made and the discharge records analyzed.

3.1.3. Analysis of flood regulating factors and extrapolation

To quantify the effect of environmental factors on river discharge after precipitation events, an approach to relate the variable changes of land use and soil distribution to discharge quantities was developed. Therefore, river discharge quantities at the catchment outlet following the designed precipitation events were analyzed for each experiment. The flood regulation supply

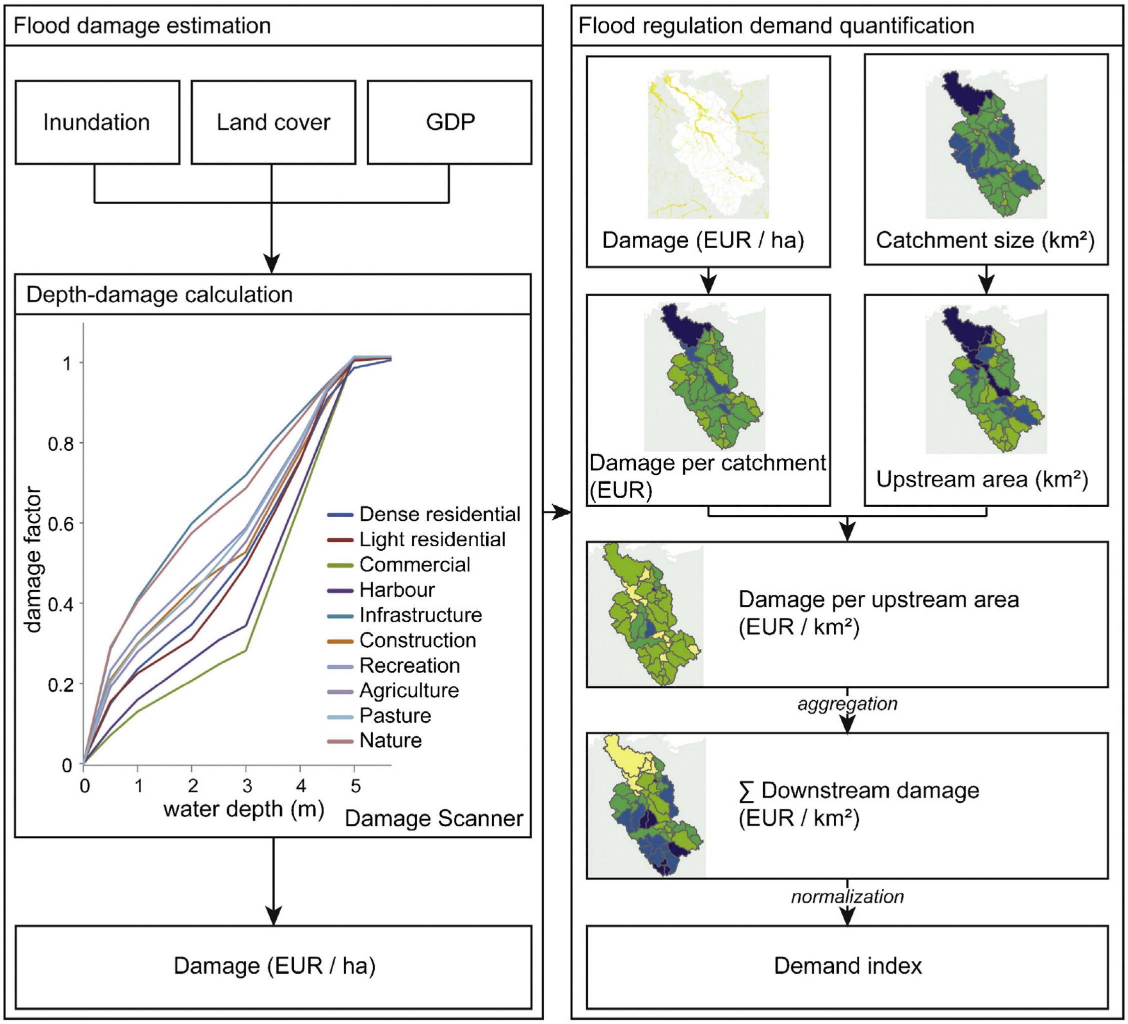

Fig. 4. Quantification scheme for flood regulation demand. Flood damages are based on the Damage Scanner model (left). Flood regulation demand on the catchment level is quantified based on flood damages for 1/50 floods and the extent of service providing area upstream.

indicator is derived from normalizing the total river discharge within five days after the precipitation event by scaling the results from the precipitation experiments between 0 and 1 across the different catchment types, resulting in a dimensionless factor. This is given in Eq. (1), where the flood regulation supply indicator IFS for test run i in dependence of the discharge volume d and maximum discharge $D_{\max}$ and minimum discharge $D_{\min}$ per test catchment is given:

$$\mathrm{IFS}_i = \frac{d_i - D_{\min}}{D_{\max} - D_{\min}} \tag{1}$$

The values retrieved were entered into a look-up table which distinguishes the catchment type, precipitation type, catchment zone, crop factor and WHC class. The look-up table was then applied to the environmental variable maps at European scale described above to create a European level map of the flood regulation supply indicator. For crop factors not included in the look-up table, the index was linearly interpolated between the simulated values.

3.2. Flood regulation demand assessment

A demand indicator for flood regulation is calculated by relating flood damages to areas that potentially can provide flood regulation. Flood damage values were aggregated to the catchment level and a demand index is calculated by relating the downstream damages to the extent of the upstream area that can potentially provide flood regulation. Therefore, the demand index depends on the flood damage values downstream and the location of the tributary within the river network (see Fig. 4). The demand index allows comparing the catchments included in this study in terms of demand for the regulating services provided. Furthermore, it facilitates the identification of priority areas for flood regulation enhancements.

3.2.1. Flood damage estimation

Flood damages are calculated using the Damage Scanner model (DSM). The DSM (Bubeck et al., 2011), originally developed for the Netherlands, derives the potential flood damage associated with a distinct flood risk based on the inundation depth by employing land use specific depth-damage functions. Inundation data representing 1/50 year flood hazards for European river catchments originates from the LISFLOOD model (van der Knijff et al., 2010). The chosen return period is common in studies addressing the sensitivity of flood damage to land use change (e.g., Reynard et al., 2001; Schilling et al., 2013). The analysis of more extreme flood hazards was omitted in this study because it was shown that their magnitude is less affected by land use (change) (Kramer et al., 1997). River basins with an upstream area smaller than 500 km^2 have been omitted in LISFLOOD. DSM depth-damage functions are representing the relative progression of damages to 100% of value loss dependent

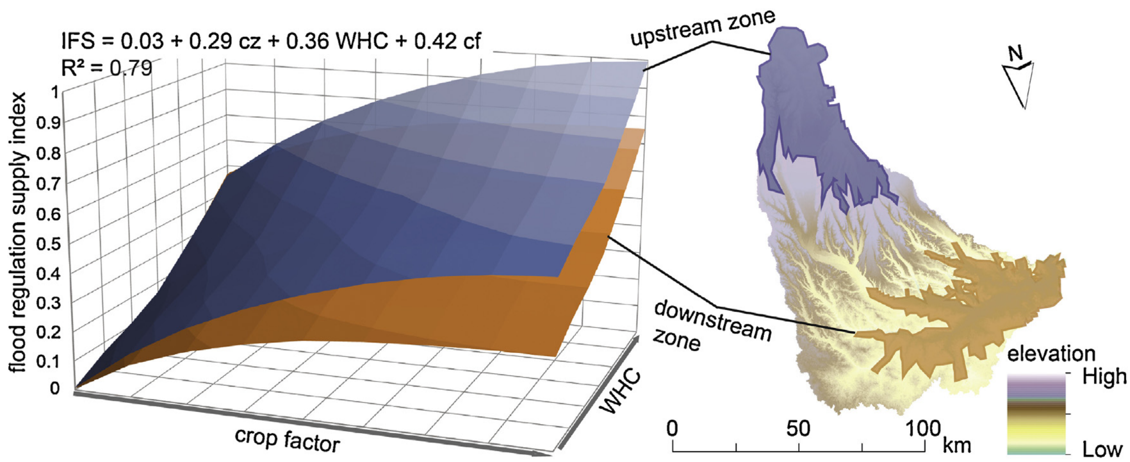

Fig. 5. Visualization of the partial look-up table for catchment type *large hills*, showing the sensitivity of the flood regulation supply index IFS to the relative position of a grid cell (catchment zone *cz*), the water holding capacity *WHC* and the crop factor *cf* in a catchment for a one day precipitation event without antecedent rainfall. Blue (orange) plane refers to the most upstream (downstream) zone of the river catchment and the associated supply index. An example for the zonation of the river catchments is given on the right (only most upstream and downstream zones are shown). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

on inundation depth. Maximum damages for most land use categories are reached at inundations of five meters. Damage values in DSM are based on Dutch economic values. In order to correct for economic disparities across the European territory, the maximum damage values included in DSM were scaled with the gross domestic product (GDP) for the reference year 2009 on NUTS2 level (Eurostat, 2012). Inherent to this approach, only direct damages are accounted for in this study to describe flood regulation demand.

3.2.2. Flood regulation demand quantification

Based on the inventory of potential flood damage values, an index is created that attributes the demand for flood regulation to the upstream catchments. To create such an index, the level of flood regulation demand per upstream area was calculated. In a first step, the DSM based flood damages for 1/50 flood hazards are aggregated to the catchment level. Second, the entire upstream area is calculated per catchment. In a third step, the ratio of catchment-scale damages and upstream area is calculated as a proxy for the flood regulation need. This ratio was calculated for each catchment within all river basins included in the study. However, to be able to relate ES supply of a catchment to the demand, the aggregated downstream need is relevant. Therefore, to establish the demand index, these ratios were aggregated for all downstream catchments relative to each catchment. The demand index is thus based on the aggregated damage within and downstream of each catchment, in relation to the available area potentially providing the service. The aggregated ratios were normalized to a scale ranging from 0 to 1 based on a min–max normalization to obtain the demand index. The different inputs and steps of this approach are exemplarily shown for the Elbe catchment in Fig. 4.

3.3. Spatial analyses of flood regulation supply and demand

The flood regulation supply index is calculated for the current land use as well as for a potential land cover scenario to analyze the potential effect of modified land use on flood regulation supply. Potential land cover has been determined by assigning crop factors to land cover of potential European biomes based on Ramankutty and Foley (1999); see also Fig. 3. In this case, land use and land management information has been set to the state most closely resembling the natural vegetation in terms of flood regulation supply capacity. The disparities between the index based on current land use and the index based on potential vegetation is a proxy for the potential to increase flood regulation by means of land use modifications. Water bodies have been excluded from the analysis.

In order to be able to compare the spatial distribution of the supply index to the distribution of the demand index, the flood regulation supply was aggregated to catchment scale and spatial overlaps between demand and supply were analyzed. The indices presented are not apt to make quantitative statements on the extent to which the supply meets the demand (given the different units and normalization). However, comparing the distribution of catchments with high supply and/or high demand can show whether a catchments' flood regulation supply is in balance with the downstream demand. In combination with the map of potential flood regulation supply, one can address whether land use modifications hold the potential to increase the flood regulation supply within a catchment (see Figs. 5(left) and 6), and show where land use change can potentially increase flood regulation most effectively.

4. Results

4.1. Flood regulation supply

The effects of environmental variables on river discharge volumes succeeding modeled precipitation events were analyzed. For each combination of environmental variables, the normalized discharge volumes were compared per type of precipitation event. This analysis provides a measure of the relative flood regulation of land use and soil on river high flows, while accounting for the position within the river catchment. In all test catchments, the impact of the environmental variables on discharge quantities is significant (see Table A.1). Fig. 5(left) shows a section of the resulting look-up table, depicting the relative flood regulation in dependence of land use, water holding capacity, and the location within the catchment, exemplarily for the most upstream and most downstream catchment zone (Fig. 5(right)). It is apparent that the magnitude of flood regulation depends on land use, but differs by the relative position within the catchment. To clarify this relationship, a linear regression has been performed after standardizing the variables land use, WHC and catchment zone. The equation shown in Fig. 5 reflects the relative impact of each variable on the flood regulation supply index IFS for the catchment type large hills under a one day precipitation scenario without antecedent rainfall.

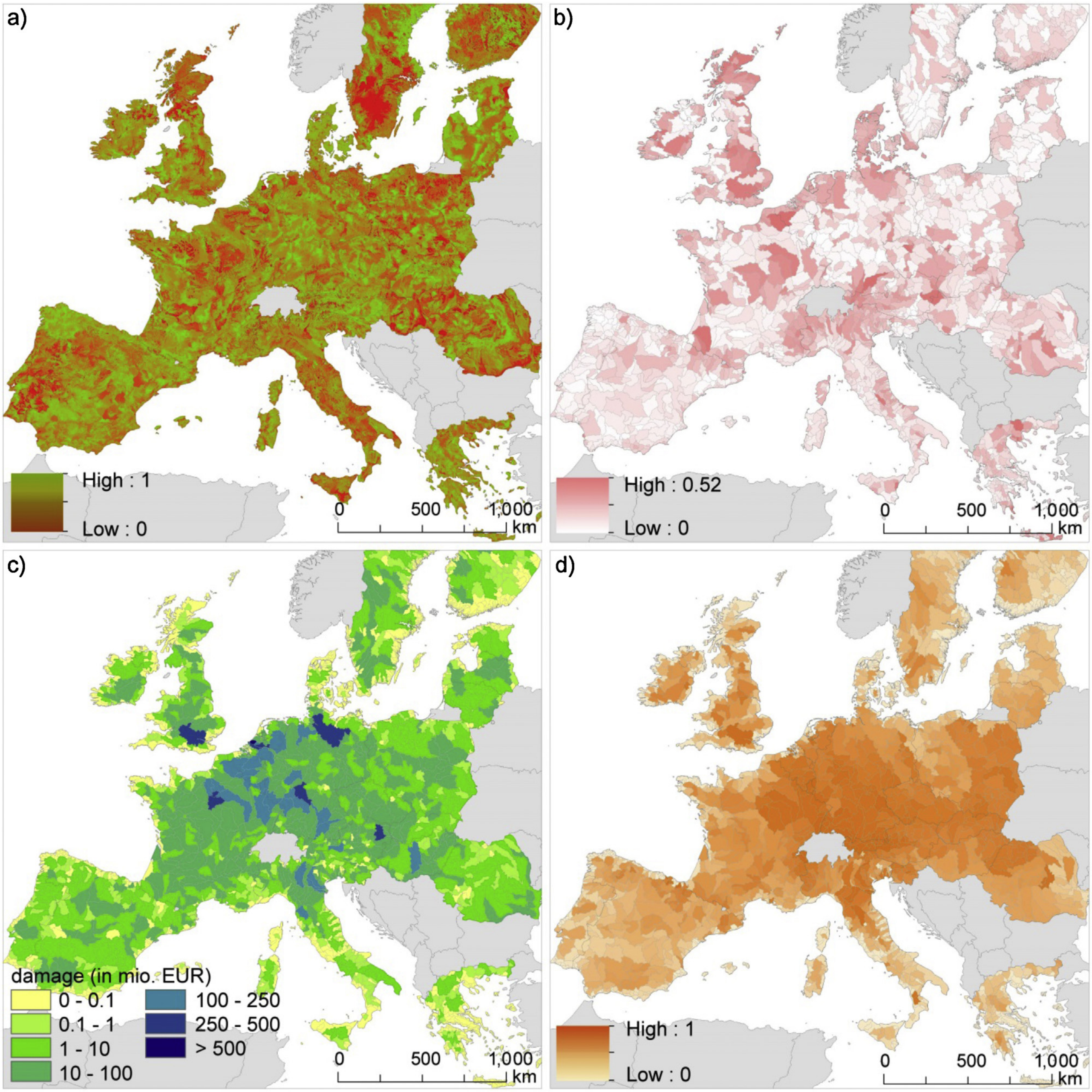

Fig. 6. (a) Flood regulation supply indicator in Europe. (b) Potential increases in flood regulation supply based on potential vegetation, aggregated to the catchment level. (c) Flood damages aggregated to the catchment level. (d) Demand indicator for flood regulation in Europe, aggregated to the catchment level. Flood regulation supply and demand are represented with dimensionless indicators ranging from 0 to 1.

According to the catchment types defined in Section 3, the look-up table results were interpolated and applied to the European countries included in this study. The results are shown in Fig. 6a. On a European scale, the supply index reflects very well the land use and soil distributions in Europe. High levels of ES flood regulation supply are detected, e.g., in Ireland, North-Western Spain, the Pyrenees, Eastern Sweden, and the Carpathians. Low capacities for supply are found in large parts of Southern Sweden, Scotland and the Apennines. Regions which provide high capacities for flood regulation supply are mainly characterized by large patches of natural vegetation or extensive agriculture. On the other hand, the main restriction for high supply on a continental scale is the available water holding capacity (e.g., low in Scotland), which impact cannot be completely offset by high crop factors (see also Fig. 5(left)).

4.2. Flood regulation demand

Fig. 6c shows flood damages aggregated to the catchment scale. High flood damages occur in economic centers and urban agglomerations, i.e., London, Paris, Vienna, Northern Italy, and large parts of Belgium, The Netherlands, and Germany. Lowest damage values are found in Spain, Finland, and Southern Italy. These low damages are mostly associated with landscapes dominated by agricultural use or large areas of natural vegetation. The flood regulation demand describes the calculated accumulated flood damage downstream of each river catchment relative to the extent of

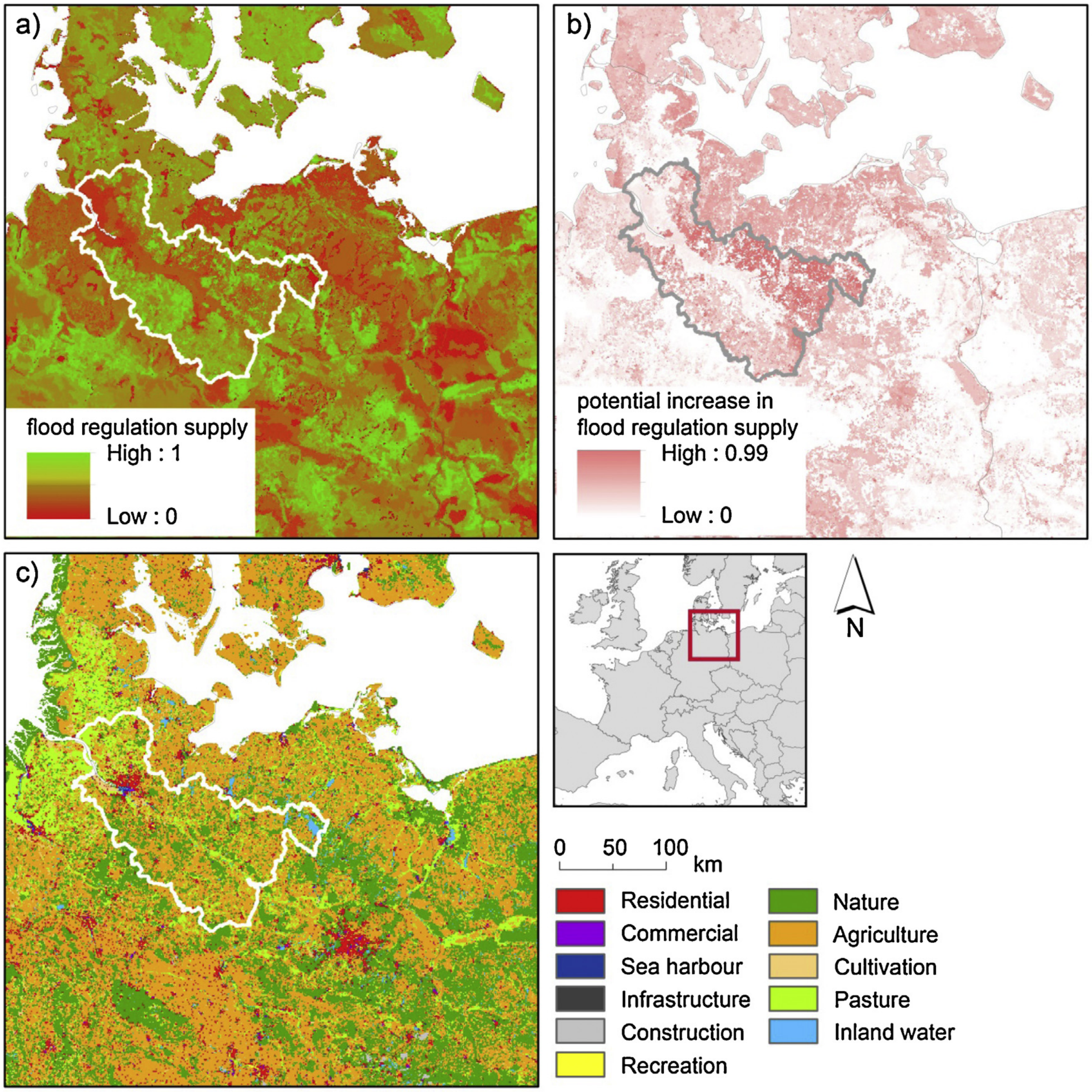

Fig. 7. (a) Flood regulation supply indicator. (b) Potential increases in flood regulation supply under potential vegetation scenario. (c) Aggregated CORINE land cover classes representing current state of land use. The lower Elbe catchment is highlighted for orientation.

potential upstream SPA. High demands are apparent in central Europe, at the foothills of the Alps, and, in general, upstream of aforementioned agglomerations (Fig. 6d). Higher demands become apparent in regions not identified based on the damage map alone, i.e., large parts of Poland, Northern Spain or Slovakia. Low demands for flood regulation are detected in large parts of Sweden and Spain, Portugal, Greece, Estonia and Eastern Finland. The affected regions are mainly characterized by a low population density and thus, less urban area, which is assigned the highest values in the approach applied.

The datasets representing both demand and supply of flood regulation can be downloaded from http://www.ivm.vu.nl/floodregulation.

4.3. Spatial analyses of supply and demand

The look-up table for flood regulation supply presented in Section 3.1.3 is also used for a scenario of potential vegetation distribution in Europe. All other variables are kept the same. In Fig. 6b, potential increases in flood regulation supply by means of land use modifications calculated based on this approach are shown. For clarity, potential increases were aggregated to the catchment level. In catchments featuring high increases of potential supply, enhancing the flood regulation capacity of the catchment is possible by means of informed land use modifications, e.g., reforestation, but also smaller changes in land use configuration or management intensity. The effect of land use modifications is dependent on three components: (1) the flood regulation supply under current state (see Fig. 6a), (2) the crop factor associated with potential land cover (see Fig. 3), and (3) the sensitivity of the flood regulation supply index to land use, which is dependent on the catchment and precipitation type under consideration (compare Fig. 5). For some regions, Fig. 6b shows clear responses of a shift in land use to potential vegetation. Particularly in Northern Italy, Austria and parts of France, potential increases of flood regulation supply are high and could contribute to alleviate currently existing demands. Minor increases are either the result of a high current supply (i.e., NW Spain), or a result of other inhibiting factors as a low WHC (i.e., Southern Sweden).

Within the river catchments, land use changes have different potentials to increase flood regulation as indicated by the results presented in Fig. 5. Fig. 7 provides a sample of the results for a region

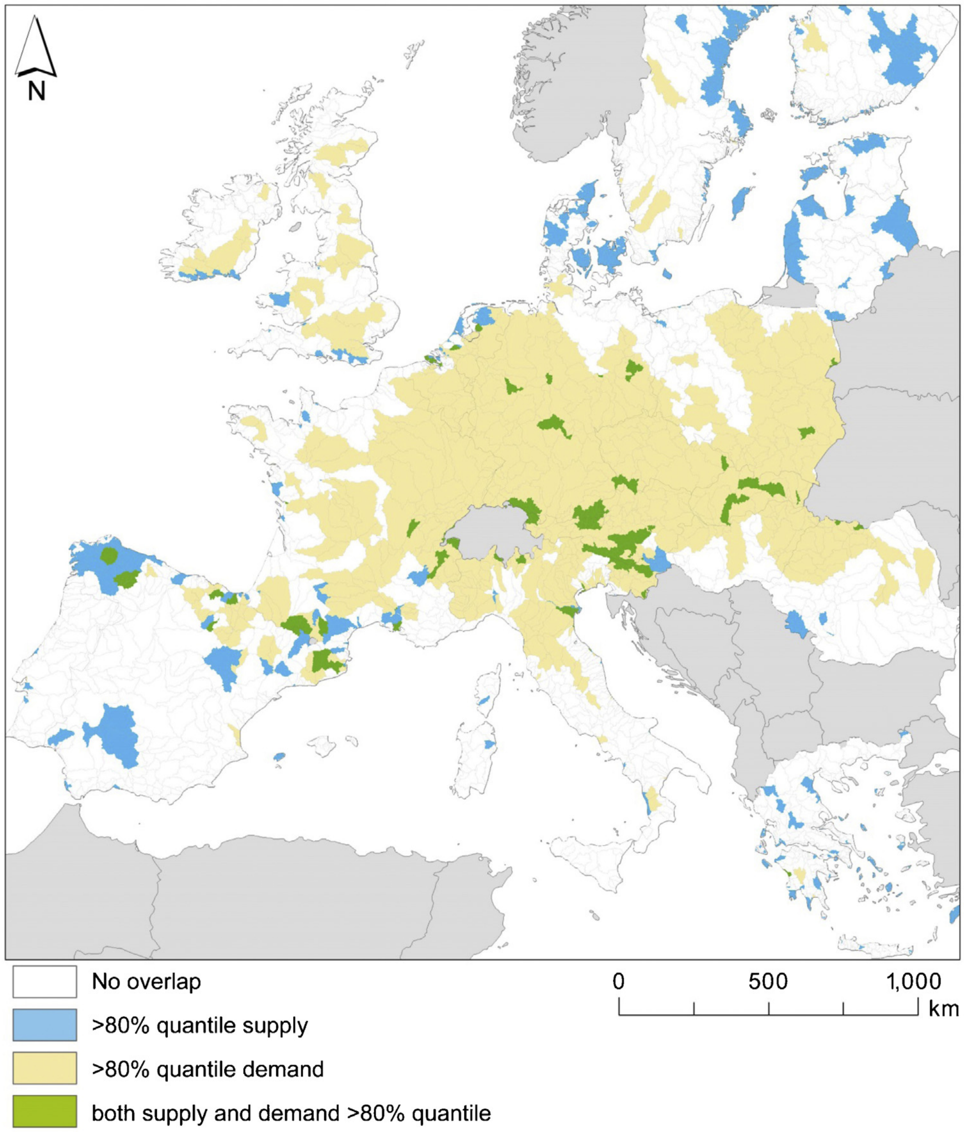

Fig. 8. Spatial distribution of flood regulation supply and demand in Europe. River catchments featuring flood regulation supply (blue), or demand (orange) greater than the 80% quantile of the distribution are shown. Catchments featuring both (none) are depicted green (white). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

in Northern Europe. For orientation, the lower Elbe catchment is highlighted. Current flood regulation supply is highest in upstream areas of the catchment and comparatively low in the flood plains (see Fig. 7a). Potential increases in flood regulation are highest in land currently occupied by agriculture, pastures and built-up area (Fig. 7b, compare with c). However, in large parts of the flood plains, potential gains in flood regulation supply are low. These locations are, therefore, less suited for land management aimed at enhancing flood regulation.

The flood regulation supply was aggregated to the catchment scale. The catchments exhibiting supply and demand greater than the 80% quantile are indicated in Fig. 8. An overlap of high demand and supply denotes that valuable ecosystem services are delivered. If there is a high demand, but no high supply, this indicates enhanced potential shortage of supply and the need for enhanced regulation or other measures of flood regulation or protection. Areas which do not feature a high downstream demand are identifiable as less significant for flood regulation enhancement strategies. In Fig. 8, it is apparent that high levels of both demand *and* supply are rarely found in one catchment; overlaps are scattered throughout Europe with a higher occurrence in mountainous areas, i.e., parts of the Alps and Pyrenees (green shaded areas). Highest demands are found in central European catchments, areas where current supply is relatively low (orange shaded areas).

5. Discussion and conclusions

5.1. Demand and supply of flood regulation services

In this paper, we presented an approach for mapping the demand and supply of the ecosystem service flood regulation through creating indicators based on the underlying biophysical and socio-economic processes. The advantages of the chosen index approach are the relatively low data requirements that correspond well with the data available at the European level, and the experimental design in which detailed model-based assessments in a number of catchments are extrapolated to the European scale. The indicators can also be used to analyze the consequences of historical and projected land use changes on flood regulation services.

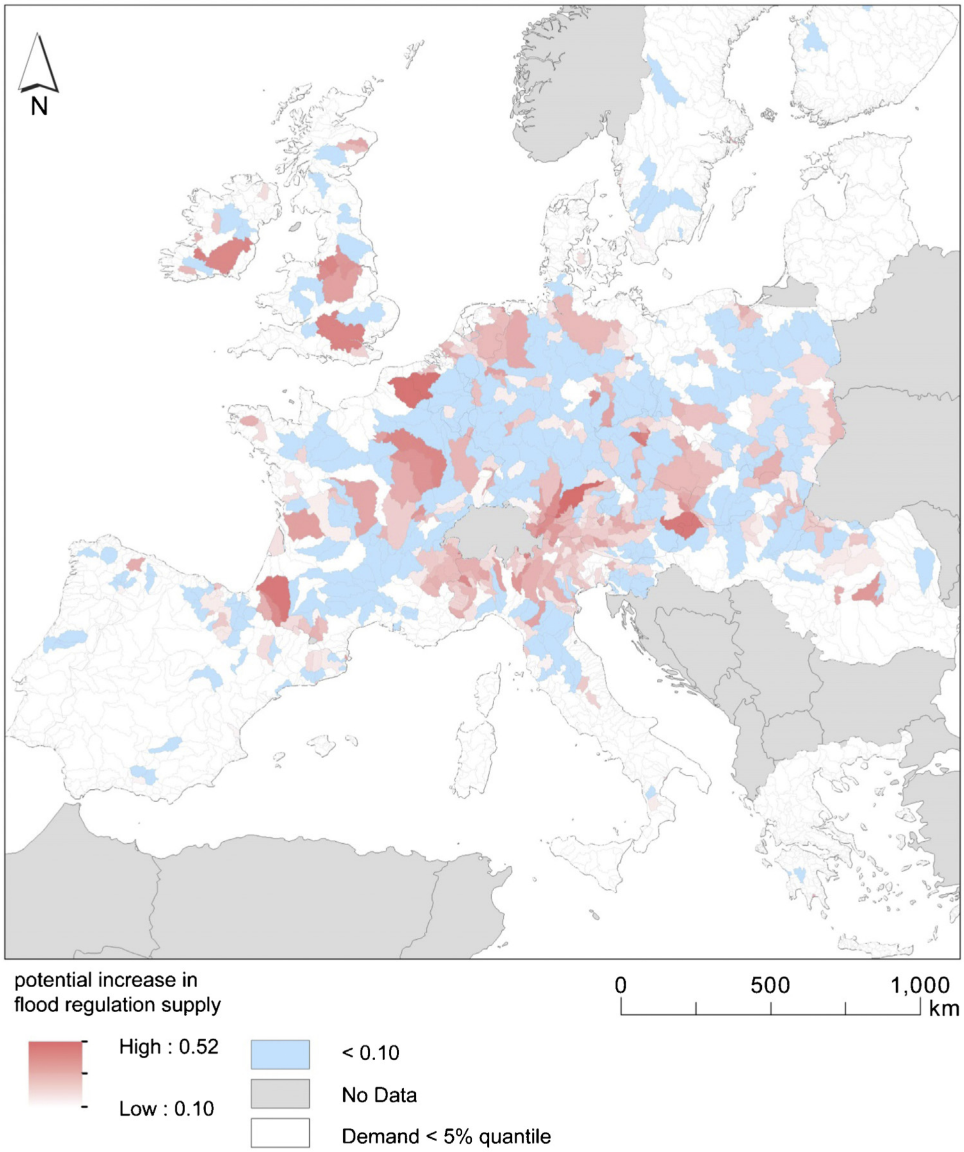

Fig. 9. Potential increase in flood regulation supply in river catchments exhibiting a relevant demand (red gradient). River catchments displaying a demand greater than the 5% quantile but without a potential supply increase greater than 10 percentage points are shaded blue. Catchments exhibiting a demand lower than the 5% quantile are shaded white, and potential increases in flood regulation supply are disregarded. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

In most catchment types, the potential supply of flood regulation is strongly dependent on the spatial distribution of soil and land use. The test catchments representing *hills* and *mountain* catchments feature a very similar relationship between land use, the location of the different land uses within the catchment, and the flood regulation. Increasing levels of stream flow regulation by land use are found when moving upstream the catchment. This relationship is less distinctive in the catchment type *lowlands*, and reversed in *large plains*. A reason for the different response in these catchment types can be the comparatively low slopes (<4°), which may stress the role of flood plains as buffer zones for lateral surface flows (Muscutt et al., 1993). In these catchments, restoration and maintenance of the flood plains and adjacent hillslopes may be as beneficial for flood regulation as increasing water retention capacities more upstream in the catchment.

We were able to identify areas with a high potential capacity to provide flood regulation in conjunction with land use modifications. While we based this capacity on the difference between the current land use and the potential vegetation, also smaller modifications in land use intensity and management can have positive impacts on the flood regulation capacity. Enhancing the flood regulating capacity of ecosystems is especially valuable in the identified hot spots of flood regulation demand in central Europe (Fig. 6d). Here, some of Europe's largest river basins are located, e.g., the Rhine, Elbe, Danube and Oder, and accordingly, the relative damages downstream accumulate. However, even smaller river basins can feature high demands if they contain large agglomerations, e.g., the Thames, Seine and Po basins.

By spatially comparing the patterns of demand and supply, the relevance and value of the ES flood regulation can be derived. We could show that catchments featuring high demands rarely display high supply (Fig. 7). This correspondence can be attributed to the fact that in catchments with a high population density, there are more assets at risk while at the same time human-dominated land uses have a comparatively low regulation capacity (Fig. 3). In Fig. 9, the distribution of catchments that feature at least 10 percentage points increase in the flood regulation supply index under the potential vegetation scenario are overlaid with the distribution of catchments exhibiting a relevant demand for flood regulation (defined as demand exceeding the 5% quantile of the distribution). Only in a fraction of the river catchments exhibiting a relevant demand, significant increases in flood regulating capacity are achievable by means of land use modifications, i.e., in parts of France, the Alps, The Netherlands and the UK. For other regions with relevant demands, flood mitigation policies focusing on land use allocation could effectuate only a relatively small increase of the aggregated river catchment's flood regulation supply, i.e., in large parts of Germany and Poland. Current flood risk has to be dealt with differently here, e.g., by means of adaptation measures decreasing the vulnerability of exposed assets and thus the demand for regulating services (Poussin et al., 2012). Particularly in catchments which display a relevant demand, but poor possibilities for flood regulation enhancements, land use changes that reduce regulation capacity should be considered carefully in order to not to aggravate downstream flood risk.

Similarly to land use change, climate change will potentially affect future patterns of supply and demand. In this study, the effect of climate change has not been examined. The impact of climate change on supply and demand patterns is uncertain. Climate change projections suggest that river floods in Europe, particularly summer floods as modeled in this study, are likely to become more frequent due to increasing frequencies in heavy precipitation events (Kundzewicz et al., 2005). On the other hand, evaporation rates are projected to increase, which might increase supply (Arnell, 1999).

5.2. Strengths and limitations of the approach

Regulating capacity was made dependent on environmental variables and land use characteristics including agricultural intensity, forest productivity and land management types. This allows for a more refined land use typology that goes beyond traditional approaches that only consider land cover types. Including supplementary land use information provides insights into the effects of less pronounced land use changes, e.g., changes in the intensity of agricultural management.

A limitation of the approach relates to the variation in biophysical characteristics of river catchments throughout Europe. Even though we account for catchment heterogeneity across European landscapes by taking geomorphological properties into account in the catchment typology and the selection of representative test catchments, this only captures part of the variation in catchment responses across Europe. Whereas large differences between catchment types are reflected by this approach, care should be taken in interpreting the results for individual catchments as a result of the simplified representation of catchment characteristics.

Like Nedkov and Burkhard (2012), we quantified the demand for flood regulation and compared it to the spatial patterns of a supply indicator. The advantage of the employed approach in this study is the incorporation of actual flood regulation demands in European river catchments based on land use dependent, direct, monetary flood damage estimates for 1/50 floods and the extent of SPA. This approach specifies the demand much further than quantifying demands solely based on the land's exposure to floods, as used in other ecosystem service assessment tools such as InVEST (Tallis et al., 2011). In contrast to other current efforts thriving to investigate patterns of demand and supply of ecosystem services (e.g., Burkhard et al., 2012), the presented approach does not rely on a location-based perspective but links remote damages to specific service providing areas, adding a spatial component to ES explorations as argued for by Hein et al. (2006) and others.

Other frameworks employed for the quantification of flood regulation, e.g., ARIES (Bagstad et al., 2011), also implement damage-based demands and can link demands to runoff *sinks* by employing a flow model. However, the ARIES framework is very data demanding and a similar approach at the European scale is not feasible. Accordingly, the chosen approach is especially suitable at this scale of analysis while more detailed flow modeling may be more appropriate within studies focused on specific catchments (e.g., Eigenbrod et al., 2011).

While accounting for catchment heterogeneity in the approach, the resulting index is strongly dependent on the extrapolation of relationships established in the modeled test catchments. Although these relationships are tested to be robust against variations in catchment layout, the approach introduces some uncertainty. Therefore, the results should be used for European scale assessment and are not suitable for local planning purposes as results may deviate for specific catchments.

In the presented approach, the relation between ecosystem service supply and demand can only be assessed qualitatively. The analysis is based on indicators which do not have common units. Therefore, no statements can be made if the supply suffices the demand in a certain region. However, in case a large demand exists under the current conditions, it is clear that an improvement of the supply will provide further benefits. In areas where demand is very low, the benefits for further improving the supply are limited and the value of the ecosystem service provided low. By comparing the demand (under the current regulation capacity) and the supply of flood regulation, the benefits of the services provided are clarified. A shortcoming of the supply quantification is that only rainfall induced floods are considered. River floods in large parts of Europe are predominately a consequence of combined rainfall-snowmelt events (Barredo, 2007). It is however questionable if land use can alleviate rainfall-snowmelt events, considering the frozen and saturated soils and reduced evapotranspiration in the winter season. These can contribute to non-linear increases in the overland flow and entirely diminish the regulative effect (Niu and Yang, 2006).

The demand quantification is based on damage estimates. Magnitudes of damage estimates are highly dependent on the choice of quantification employed and the quality of the inundation estimates (Bubeck et al., 2011). Particularly in lowland landscapes, models often suffer from overestimations of the inundation extent which subsequently affect the absolute damage estimates within a river catchment. A further constraint is the scale and level of detail on which damages are based (Hall and Solomatine, 2008). The damage functions were applied to rather broad land use classes on a 100 m resolution grid, which of course disregards more complex damage patterns. Furthermore, the demand indicator is not entirely independent of the supply of regulating services. The demand indicator is based on the estimated damage under current flooding conditions, thus accounting for the current regulating capacity of the ecosystems. In case supply would increase, the demand would, everything else being equal, decrease. In interpreting the results the demand should be seen as valid under current conditions.

5.3. Ecosystem service mapping and planning

The presented approach addresses some challenges identified in the literature concerning the mapping and operationalization of ecosystem services (Burkhard et al., 2012; TEEB, 2010). The benefits of ecosystem service supply can only be assessed when both demand and supply, as well as their spatial interactions, are considered. We have presented a map of the state of natural flood regulation in Europe. Based on the findings presented in Fig. 9, priority areas for investments in land use based flood regulation can be identified. Land use and management modifications aiming to increase flood regulation hold the potential for synergies with other strategic objectives of the EU environmental policy.

In many cases, such measures could be integrated in conservation and land use planning targeting the mitigation of flood events in the EU (COM (2011) 571). In this respect, particularly the concept of green infrastructure is of interest (Benedict and McMahon, 2002). Implementing the concept of green infrastructure in land planning bears the potential to jointly increase the provision of multiple ES (i.e., flood regulation, prevention of nutrient loss, landslides and erosion) as well as to restore depleted, and protect and maintain undisturbed ecosystems while at the same time avert adverse effects on biodiversity caused by the extension of gray infrastructure. Contributions of ES to human well-being can vary considerably based on their spatial distribution and configuration. By integrating the beneficiaries' side in the ES exploration, the insights gained in this paper are a step toward making ES values explicit.

Acknowledgments

We are thankful for the provision of flood hazard data generated with LISFLOOD by Luc Feyen, Joint Research Centre. We acknowledge the E-OBS dataset from the EU-FP6 project ENSEMBLES (http://ensembles-eu.metoffice.com) and the data providers in the ECA&D project (http://eca.knmi.nl). We furthermore acknowledge the provision of river discharge data from selected gauge stations of the Global Runoff Data Centre, made available by EURO-FRIEND-Water. The HYDRO1k digital elevation model and derivatives are available from the U.S. Geological Survey. The work conducted in this paper was financed by the EU-FP7 projects VOLANTE and OPERAS.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecolind.2013.11.010.

References

Aerts, J.C.J.H., Kriek, M., Schepel, M., 1999. STREAM (Spatial tools for river basins and environment and analysis of management options): 'set up and requirements'. Phys. Chem. Earth Pt. B 24, 591–595.

Anderson, H.W., Hoover, M.D., Reinhart, K.G., 1976. Forests and Water: Effects of Forest Management on Floods, Sedimentation, and Water Supply. Pacific Southwest Forest and Range Experiment Station, Forest Service, US Department of Agriculture.

Andréassian, V., 2004. Waters and forests: from historical controversy to scientific debate. J. Hydrol. 291, 1–27.

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

Bagstad, K.J., Villa, F., Johnson, G.W., Voigt, B., 2011. ARIES – Artificial Intelligence for Ecosystem Services: A guide to models and data, version 1.0. ARIES report series n. 1.

Barredo, J., 2007. Major flood disasters in Europe: 1950–2005. Nat. Hazards 42, 125–148.

Bastian, O., Grunewald, K., Syrbe, R.U., 2012. Space and time aspects of ecosystem services, using the example of the EU Water Framework Directive. Int. J. Biodivers. Sci. Ecosyst. Serv. Manage. 8, 5–16.

Benedict, M.A., McMahon, E.T., 2002. Green infrastructure: smart conservation for the 21st century. Renew. Resour. J. 20, 12–17.

Beven, K., Wood, E.F., 1983. Catchment geomorphology and the dynamics of runoff contributing areas. J. Hydrol. 65, 139–158.

Breuer, L., Eckhardt, K., Frede, H.G., 2003. Plant parameter values for models in temperate climates. Ecol. Model. 169, 237–293.

Brus, D., Hengeveld, G., Walvoort, D., Goedhart, P., Heidema, A., Nabuurs, G., Gunia, K., 2012. Statistical mapping of tree species over Europe. Eur. J. For. Res. 131, 145–157.

Bubeck, P., de Moel, H., Bouwer, L.M., Aerts, J.C.H.C., 2011. How reliable are projections of future flood damage? Nat. Hazards Earth Syst. Sci. 11, 3293–3306.

Burkhard, B., Kroll, F., Nedkov, S., Müller, F., 2012. Mapping ecosystem service supply demand and budgets. Ecol. Indic. 21, 17–29.

Burt, T.P., Butcher, D.P., 1985. Topographic controls of soil moisture distributions. J. Soil Sci. 36, 469–486.

Chen, L., Huang, Z., Gong, J., Fu, B., Huang, Y., 2007. The effect of land cover/vegetation on soil water dynamic in the hilly area of the loess plateau, China. Catena 70, 200–208.

Ciscar, J.C., Iglesias, A., Feyen, L., Szabó, L., Van Regemorter, D., Amelung, B., Nicholls, R., Watkiss, P., Christensen, O.B., Dankers, R., Garrote, L., Goodess, C.M., Hunt, A., Moreno, A., Richards, J., Soria, A., 2011. Physical and economic consequences of climate change in Europe. Proc. Natl. Acad. Sci. U.S.A. 108, 2678–2683.

Eigenbrod, F., Bell, V.A., Davies, H.N., Heinemeyer, A., Armsworth, P.R., Gaston, K.J., 2011. The impact of projected increases in urbanization on ecosystem services. Proc. R. Soc. B 278, 3201–3208.

Elosegi, A., Díez, J., Mutz, M., 2010. Effects of hydromorphological integrity on biodiversity and functioning of river ecosystems. Hydrobiologia 657, 199–215.

European Commission, 2011. Roadmap to a Resource Efficient Europe. COM (2011) 571 final, Available online at http://ec.europa.eu/environment/resource_efficiency/pdf/com2011_571.pdf (last accessed April 2013).

EEA (European Environment Agency), 2008. European river catchments (ERC) classified by ocean, Available online at: http://www.eea.europa.eu/data-and-maps/figures/european-river-catchments-geographic-view-1 (last accessed August 2013).

EEA (European Environment Agency), 2010. Mapping the Impacts of Natural Hazards and Technological Accidents in Europe. Publications Office of the European Union, Luxembourg.

EEA (European Environment Agency), 2011. CORINE Land Cover 2000 raster data – 100 m, version 15, Available online at: http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2000-raster-1 (last accessed March 2013).

Eurostat, 2012. Regional gross domestic product (PPS per inhabitant) by NUTS 2 regions. European Union, Available online at: http://epp.eurostat.ec.europa.eu/tgm/table.do?tab=table&init=1&plugin=1&language=en&pcode=tgs00005 (last accessed March 2013).

FAO, 2009. Harmonized World Soil Database (version 1.10). FAO/IIASA, Rome, Italy/Laxenburg, Austria, Available online at: http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/HWSD_Data.html?sb=4 (last accessed March 2013).

Farrell, D.A., 1995. Experimental watersheds: a historical perspective. J. Soil Water Conserv. 50, 432–437.

Fiener, P., Auerswald, K., Van Oost, K., 2011. Spatio-temporal patterns in land use and management affecting surface runoff response of agricultural catchments – a review. Earth-Sci. Rev 106, 92–104.

Fohrer, N., Haverkamp, S., Eckhardt, K., Frede, H.G., 2001. Hydrologic response to land use changes on the catchment scale. Phys. Chem. Earth Pt. B 26, 577–582.

Frei, C., Schöll, R., Fukutome, S., Schmidli, J., Vidale, P.L., 2006. Future change of precipitation extremes in Europe: intercomparison of scenarios from regional climate models. J. Geophys. Res. 111, D06105.

Gallaun, H., Zanchi, G., Nabuurs, G.J., Hengeveld, G., Schardt, M., Verkerk, P.J., 2010. EU-wide maps of growing stock and above-ground biomass in forests based on remote sensing and field measurements. For. Ecol. Manage. 260, 252–261.

García-Ruiz, J.M., Regüés, D., Alvera, B., Lana-Renault, N., Serrano-Muela, P., Nadal-Romero, E., Navas, A., Latron, J., Martí-Bono, C., Arnáez, J., 2008. Flood generation and sediment transport in experimental catchments affected by land use changes in the central Pyrenees. J. Hydrol. 356, 245–260.

Gomi, T., Sidle, R.C., Miyata, S., Kosugi, K., Onda, Y., 2008. Dynamic runoff connectivity of overland flow on steep forested hillslopes: scale effects and runoff transfer. Water Resour. Res. 44, W08411.

Grossmann, M., 2012. Economic value of the nutrient retention function of restored floodplain wetlands in the Elbe River basin. Ecol. Econ. 83, 108–117.

Gupta, S.C., Larson, W.E., 1979. Estimating soil water retention characteristics from particle size distribution, organic matter percent, and bulk density. Water Resour. Res. 15, 1633–1635.

Haase, D., 2009. Effects of urbanisation on the water balance – a long-term trajectory. Environ. Impact Assess. Rev. 29, 211–219.

Haines-Young, R., Potschin, M., Kienast, F., 2012. Indicators of ecosystem service potential at European scales. Mapping marginal changes and trade-offs. Ecol. Indic. 21, 39–53.

Hall, J., Solomatine, D., 2008. A framework for uncertainty analysis in flood risk management decisions. Int. J. River Basin Manage. 6, 85–98.

Hargreaves, G.H., 1974. The estimation of potential and crop evapotranspiration. Trans. ASAE 17, 701–704.

Haylock, M.R., Hofstra, N., Klein Tank, A.M.G., Klok, E.J., Jones, P.D., New, M., 2008. A European daily high-resolution gridded dataset of surface temperature and precipitation. J. Geophys. Res. 113, D20119.

Hein, L., van Koppen, K., de Groot, R.S., van Ierland, E.C., 2006. Spatial scales, stakeholders and the valuation of ecosystem services. Ecol. Econ. 57, 209–228.

Hengeveld, G.M., Nabuurs, G.J., Didion, M., van den Wyngaert, I., Clerkx, A.S., Schelhaas, M.J., 2012. A forest management map of European forests. Ecol. Soc. 17, 53.

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2005. Very high resolution interpolated climate surfaces for global land areas. Int. J. Climatol. 25, 1965–1978.

Jongman, B., Ward, P.J., Aerts, J.C.J.H., 2012. Global exposure to river and coastal flooding: long term trends and changes. Global Environ. Change 22, 823–835.

Kramer, R.A., Richter, D.D., Pattanayak, S., Sharma, N.P., 1997. Ecological and economic analysis of watershed protection in Eastern Madagascar. J. Environ. Manage. 49, 277–295.

Kron, W., 2005. Flood risk = hazard × values × vulnerability. Water Int. 30, 58–68.

Kuemmerle, T., Erb, K., Estel, S., Haberl, H., Kastner, T., Levers, C., Lindner, M., Plutzar, C., Verburg, P.H., van der Zanden, E., 2012. European wide maps of recent changes in agriculture, forest systems and HANPP. Deliverable No: 3.1. EC Contract Ref: FP7 ENV 2010 265104, Available online at http://www.volante-project.eu/images/stories/DELIVERABLES/VOLANTE_D3._1_European-wide_maps_of_recent_changes_in_agriculture_forest_systems_and_embodied_HANPP.pdf (last accessed March 2013).
Kundzewicz, Z.W., Radziejewski, M., Pinskwar, I., 2006. Precipitation extremes in the changing climate of Europe. Clim. Res. 31, 51–58.
Kundzewicz, Z.W., Ulbrich, U., Graczyk, D., Krüger, A., Leckebusch, G.C., Menzel, L., Pinskwar, I., Radziejewski, M., Szwed, M., 2005. Summer floods in Central Europe – climate change track? Nat. Hazards 36, 165–189.
Levavasseur, F., Bailly, J.S., Lagacherie, P., Colin, F., Rabotin, M., 2012. Simulating the effects of spatial configurations of agricultural ditch drainage networks on surface runoff from agricultural catchments. Hydrol. Process. 26, 3393–3404.
Leyer, I., Mosner, E., Lehmann, B., 2012. Managing floodplain-forest restoration in European river landscapes combining ecological and flood-protection issues. Ecol. Appl. 22, 240–249.
Liquete, C., Zulian, G., Delgado, I., Stips, A., Maes, J., 2013. Assessment of coastal protection as an ecosystem service in Europe. Ecol. Indic. 30, 205–217.
Lloyd, S., 1982. Least squares quantization in PCM. IEEE Trans. Inf. Theory 28, 129–137.
Lugeri, N., Kundzewicz, Z.W., Genovese, E., Hochrainer, S., Radziejewski, M., 2010. River flood risk and adaptation in Europe – assessment of the present status. Mitig. Adapt. Strat. Glob. Change 15, 621–639.
Lytle, D.A., Poff, N.L., 2004. Adaptation to natural flow regimes. Trends Ecol. Evol. 19, 94–100.
Maes, J., Paracchini, M.L., Zulian, G., 2011. A European assessment of the provision of ecosystem services – towards an atlas of ecosystem services. JRC Scientific and Technical Reports. European Commission, Joint Research Centre, Institute for Environment and Sustainability.
McAllister, D.E., Craig, J.F., Davidson, N., Delany, S., Seddon, M., 2001. Biodiversity Impacts of Large Dams. IUCN (The World Conservation Union)/UNEP (United Nations Environment Programme)/WCD (World Commission on Dams).
Millennium Ecosystem Assessment, 2005. Millennium Ecosystem Assessment Synthesis Report. Island Press, Washington, DC.
Mitchell, T.D., Jones, P.D., 2005. An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int. J. Climatol. 25, 693–712.
Morisawa, M.E., 1962. Quantitative geomorphology of some watersheds in the Appalachian Plateau. Geol. Soc. Am. Bull. 73, 1025–1046.
Munich Re, 1997. Flooding and Insurance. Munich Reinsurance Company, Munich.
Muscutt, A.D., Harris, G.L., Bailey, S.W., Davies, D.B., 1993. Buffer zones to improve water quality: a review of their potential use in UK agriculture. Agric. Ecosyst. Environ. 45, 59–77.
Nedkov, S., Burkhard, B., 2012. Flood regulating ecosystem services – mapping supply and demand in the Etropole municipality, Bulgaria. Ecol. Indic. 21, 67–79.
Niu, G.Y., Yang, Z.L., 2006. Effects of frozen soil on snowmelt runoff and soil water storage at a continental scale. J. Hydrometeor. 7, 937–952.
Peel, M.C., McMahon, T.A., Finlayson, B.L., Watson, F.G.R., 2001. Identification and explanation of continental differences in the variability of annual runoff. J. Hydrol. 250, 224–240.
Planinšek, S., Finér, L., Campo, A., Alcazar, J., Vega-García, C., Dimitrov, D., Capuliak, J., 2011. Adjustment of forest management strategies to changing climate. Ecol. Stud. 212, 313–329.
Poussin, J.K., Bubeck, P., Aerts, J.C.J.H., Ward, P.J., 2012. Potential of semi-structural and non-structural adaptation strategies to reduce future flood risk: case study for the Meuse. Nat. Hazards Earth Syst. Sci. 12, 3455–3471.
Ramankutty, N., Foley, J.A., 1999. Estimating historical changes in global land cover: croplands from 1700 to 1992. Global Biogeochem. Cycles 13, 997–1027.
Reynard, N.S., Prudhomme, C., Crooks, S.M., 2001. The flood characteristics of large U.K. rivers: potential effects of changing climate and land use. Climatic Change 48, 343–359.
Saghafian, B., Julien, P.Y., Rajaie, H., 2002. Runoff hydrograph simulation based on time variable isochrone technique. J. Hydrol. 261, 193–203.
Schilling, K.E., Gassman, P.W., Kling, C.L., Campbell, T., Jha, M.K., Wolter, C.F., Arnold, J.G., 2013. The potential for agricultural land use change to reduce flood risk in a large watershed. Hydrol. Process., http://dx.doi.org/10.1002/hyp.9865.
Syrbe, R.U., Walz, U., 2012. Spatial indicators for the assessment of ecosystem services. Providing, benefiting and connecting areas and landscape metrics. Ecol. Indic. 21, 80–88.
te Linde, A.H., Bubeck, P., Dekkers, J.E.C., de Moel, H., Aerts, J.C.J.H., 2011. Future flood risk estimates along the river Rhine. Nat. Hazards Earth Syst. Sci. 11, 459–473.
Tallis, H.T., Ricketts, T., Guerry, A.D., Wood, S.A., Sharp, R., Nelson, E., Ennaanay, D., Wolny, S., Olwero, N., Vigerstol, K., 2011. InVEST 2.2.2 User's Guide. The Natural Capital Project, Stanford.
TEEB, 2010. The Economics of Ecosystems and Biodiversity: Mainstreaming the Economics of Nature: A Synthesis of the Approach, Conclusions and Recommendations of TEEB.
Temme, A.J.A.M., Verburg, P.H., 2011. Mapping and modelling of changes in agricultural intensity in Europe. Agric. Ecosyst. Environ. 140, 46–56.
Thornthwaite, C.W., Mather, J.R., 1957. Instructions and tables for computing potential evapotranspiration and the water balance. Publications Climatol. X, 183–243.
Tomar, V.S., O'Toole, J.C., 1980. Water use in lowland rice cultivation in Asia. A review of evapotranspiration. Agric. Water Manage. 3, 83–106.
Turner, B.L., Janetos, A.C., Verburg, P.H., Murray, A.T., 2013. Land system architecture: using land systems to adapt and mitigate global environmental change. Global Environ. Change 23, 395–397.
Uchida, T., McDonnell, J.J., Asano, Y., 2006. Functional intercomparison of hillslopes and small catchments by examining water source, flowpath and mean residence time. J. Hydrol. 327, 627–642.
United States Geological Survey, 2007. HYDRO1k Documentation, Available online at: http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30/README (last accessed March 2013).
Valentin, C., Poesen, J., Li, Y., 2005. Gully erosion: impacts, factors and control. Catena 63, 132–153.
van Berkel, D.B., Verburg, P.H., 2011. Sensitising rural policy: assessing spatial variation in rural development options for Europe. Land Use Policy 28, 447–459.
van der Knijff, J.M., Younis, J., De Roo, A.P.J., 2010. LISFLOOD: a GIS-based distributed model for river basin scale water balance and flood simulation. Int. J. Geogr. Inf. Sci. 24, 189–212.
van Deursen, W.P.A., Kwadijk, J.C.J., 1993. RHINEFLOW: an integrated GIS water balance model for the river Rhine. In: Kovar, K., Nachtnebel, H.P. (Eds.), IAHS Publication No. 211. , pp. 507–519.
van Seters, T.E., Price, J.S., 2001. The impact of peat harvesting and natural regeneration on the water balance of an abandoned cutover bog, Quebec. Hydrol. Process. 15, 233–248.