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

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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

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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.

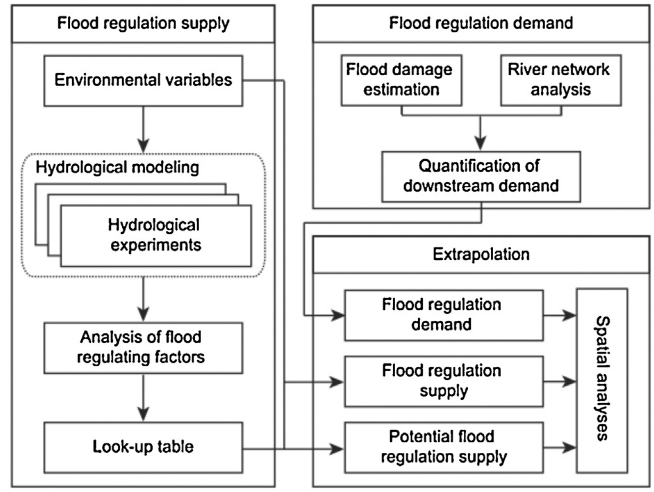

Fig. 1. Overview of the approach.

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