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Broad-scale ecosystem services of European wetlands—overview of the current situation and future perspectives under different climate and water management scenarios

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Abstract An appropriate hydrological regime within a wetland is essential to maintain its goods and services. This regime is related to the source of the water, which differs for particular kinds of wetlands. This paper presents an overview of the ecosystem services of European wetlands, based on a representative sample of 102 protected wetlands larger than 5000 ha, and the implications of hydrological alterations caused by future climate and socio-economic changes. Six major ecosystem services of wetlands were assessed namely: biodiversity in terms of plants and animals, biomass production, nutrient removal, carbon storage and fish production. Data showed that, on average, four services were present in each wetland. The impact of climate change, water management and land-use change was examined under different future scenarios. Major potential changes in hydrological regime (i.e. precipitation, groundwater recharge and river flow) were quantified up to the 2050s using simulated runoff and river flow data of the WaterGAP model driven by the climate input of two different general circulation models (GCMs), IPCM4 and MIMR. Thresholds of hydrological change that would endanger each ecosystem service were identified. The impacts of future scenarios were distributed across Europe with potential threats to ecosystem services of European wetlands resulting in the loss of between 26 and 46% of all identified ecosystem services in 2050. The models and scenarios suggest that the most significant loss of ecosystem services is likely to occur in Central Europe (Hungary, Germany, France, Belarus, Poland). In general, the most fragile services (the largest number lost) are projected to be those connected to the surface water dynamics—mostly the services of wetland birds and fish spawning. Ecosystem services dependent on groundwater dynamics and water balance changes are seemingly more buffered against the expected hydrological stress.

Key words wetlands; climate change; hydrology; ecosystem services; water management

Les services écosystémiques à grande échelle des zones humides européennes: aperçu de la situation actuelle et perspectives sous différents scénarios climatiques et de gestion de l'eau

Résumé Un régime hydrologique approprié des zones humides est essentiel pour maintenir leur valeur et leurs services. Ce régime est lié à l'origine de leurs eaux, qui est particulière pour chaque zone humide. Cet article présente un aperçu des services des écosystèmes des zones humides européennes, fondé sur un échantillon représentatif de 102 zones humides protégées de plus de 5000 ha, et les implications des modifications hydrologiques causées par le climat futur et les évolutions socio-économiques. Six services écosystémiques importants des zones humides ont été évalués, à savoir la biodiversité en termes de plantes et d'animaux, la production de biomasse, l'élimination des nutriments, le stockage du carbone et la production de poissons. Les données ont montré que, en moyenne, quatre services étaient présents dans chaque zone humide. L'impact du changement climatique, la gestion de l'eau et les changements d'affectation ont été examinés sous différents scénarios. D'importants changements potentiels du régime hydrologique (c'est à dire la précipitation, la recharge des nappes souterraines et le débit des rivières) ont été quantifiés jusqu'en 2050 sur la base de la simulation par le modèle WaterGAP du ruissellement et du débit des rivières des résultats des modèles de circulation générale

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(MCG) IPCM4 et MIMR. Les seuils des changements hydrologiques qui mettraient en danger chacun des services écosystémiques ont étéidentifiés. Les impacts des scénarios ont été distribués à travers l'Europe avec leurs menaces potentielles pour les services écosystémiques de ses zones humides, qui diminueraient de 26 à 46% en 2050. Les modèles et les scènarios suggèrent que les pertes les plus importantes de services écosystémiques se produiraient en Europe centrale (Hongrie, Allemagne, France, Biélorussie, Pologne). En génńral, les services les plus fragiles (diminution les plus importantes) sont ceux qui sont reliès è la dynamique des eaux de surface–surtout ceux concernant la faune avicole des zones humides et le frai des poissons. Les services des écosystèmes dépendants des changements de la dynamique des eaux souterraines et du bilan hydrologique sont apparemment plus tamponné contre le stress hydrologique prévu.

Mots clefs zones humides; changement climatique; hydrologie; services des écosystèmes; gestion d'eau

INTRODUCTION

Wetlands have been increasingly appreciated as areas of outstanding natural beauty for their landscape and wildlife (Finlayson and Moser 1991, Dugan 1990, Mitsch *et al.* 2009, Keddy 2010). Much of wetland bio-production has been utilized by man for many centuries, including fish for protein, peat for fuel and timber and reeds for building materials (Maltby 1986). More recently, it has been shown that wetlands play a key role in the hydrological cycle, controlling flood generation, groundwater recharge, and dry season flows (Bullock and Acreman 2003) and water quality (Verhoeven *et al.* 2006). To maintain goods and services, an appropriate hydrological regime within a wetland is essential (Acreman and Mountford 2009). This regime is related to the source of water, which is different for particular kinds of wetlands (Acreman and Miller 2007) and is vulnerable to alteration due to climate change (Acreman *et al*. 2009). This paper presents an overview of ecosystem services of European wetlands based on a representative sample of 102 protected wetlands larger then 5000 ha, and assesses the implications for those services of alterations in the hydrological regime of the wetlands caused by changes in climate and socio-economic activity in the future.

Ecosystem services

Ecosystem services are natural assets (Barbier 2011, this volume); they are the processes by which the environment produces resources utilised by humans such as clean air, water, food and materials, and contributes to social and cultural well-being (Fischer *et al*. 2009) and much of what we call quality of life (Acreman 2003). The concept of ecosystem services was developed to a great extent by wetland scientists (Maltby and Acreman 2011, this issue) and has been used to aid understanding of the human use and management of natural resources. For example, the Millennium Ecosystem Assessment (MEA 2005) produced a comprehensive appraisal of the global environment, focusing on ecosystem services and how changes in them have affected and will have impacts upon human well-being. The report showed that human activities have changed most ecosystems, with the greatest impact on freshwater systems, and threaten the Earth's ability to support future generations. In the MEA the following classification of ecosystems services were used:

1. Provisioning services: products obtained from ecosystems, including food, fibre, fuel, genetic resources, natural medicines, pharmaceuticals and fresh water.
2. Regulating services: benefits obtained from the regulation of ecosystem processes, including air quality, climate, water, erosion, disease, pests and hazard, such as floods.
3. Cultural services: non-material benefits obtained from ecosystems through spiritual enrichment, cognitive development, reflection, recreation and aesthetic experiences, including landscape value.
4. Supporting services: services necessary for the production of all other ecosystem services including soil formation, photosynthesis, primary production and nutrient cycling.

Types of wetlands

There is no strictly correct answer to the question: "What is a wetland?" Depending on who is asking and for what purposes the answer will be used, there are many wetland definitions and the terms in use are often confusing and even contradictory. From the commonly used definition of wetlands (Ramsar Convention, US Fish and Wildlife Service, Committee on Characterization of Wetlands) three main wetland features may be distinguished. Areas classified as wetlands: (a) can be recognized by the presence of water, either at the surface or within the root zone; (b) often have unique conditions that differ from terrestrial or fully aquatic environments (accumulate organic plant material that decomposes slowly); and (c) support a variety of plants (*hydrophytes*) and animals adapted to the saturated conditions. Unfortunately, the terminology for describing wetlands varies both among human societies, and among their scientific communities (Gore 1983, Keddy 2010).

To avoid the confusing number of terms and names, for purposes of this work, freshwater wetlands were divided into four different classes based on peat accumulation and major hydrological characteristics. Wetlands where peat has or is being accumulated are called mires. On the basis of the main source of water, mires can be divided into bogs and fens. In cases where the peat is being drained for agricultural, farming, peat extraction or any other purposes, we use the term peatland. Wetlands in which peat is not present are called marshes. Swamps are wetlands where generally peat will not form, although in some habitats this process may occur; they are characterized by prolonged inundation each year. (Many authors use the word "swamp" as a synonym of wetland forest, with almost permanent water presence above the soil surface, but we do not use this specific definition.)

Fens usually form in land depressions or river valley bottoms. They are fed mainly by groundwater, but often have additional inputs of surface water and rain. Considerable water movement through the shallow peat layers provides minerals that ensure rich vegetation. Due to alkaline reactions, fen vegetation is dominated by grasses (especially sedges), reeds and tree communities, such as willows (*Salix* sp.), birches (*Betula l.*) and alders (*Alnus* sp.).

Bogs are formed in two ways, either in landscape locations where rainfall has no drainage network and locally inundates the surface for a long period, or where the peat layer builds-up and then separates the fen from its groundwater supply. When this occurs, the fen receives fewer nutrients and may transform into an acidic bog, fed only by direct rainfall. It can then continue to grow, above the level of the fen. Rain not only washes the hydroxide ions out of the peat, but also adds carbonic acid dissolved in rainwater carbon dioxide, making the soil pH more acidic. Nutrients are provided entirely by precipitation, which accounts for their low plant nutrient status. A key characteristic of bogs is the presence of vegetation adapted to acidic conditions: e.g. *Sphagnum* moss and small sedges, pines and dwarf birches rooted in deep peat.

Fens, together with bogs, are mostly a Northern Hemisphere phenomenon and are generally associated with low temperatures and short growing seasons, where ample precipitation and high humidity cause excessive moisture to accumulate. Examples of fen-type wetlands include the extensive peat accumulating areas in Russia, as well as smaller seepage areas (fens) or watershed zones (bogs) throughout the temperate zone in Poland, the Baltic states and Germany.

As indicated, there is no commonly accepted definition of swamps. In the USA, a swamp is defined as a wetland with a prevalence of tree or shrub cover. In Europe, both forested fens (alder forest) and wetlands dominated by reed grass are also called swamps. In this paper it is assumed that a swamp is a wetland dominated by reed grass (*Phragmites*), woody vegetation (mostly *Alnus* sp.) or papyrus (subtropical wetlands only). This type of wetland is permanently inundated by shallow water bodies (Okruszko and Kiczko 2008) with substantial number of hummocks or dry-land protrusions. Unlike fens and bogs, swamps are not always peat accumulating wetlands. In a number of cases the major soil type developing here is alluvium. Due to environmental conditions, swamp vegetation is adapted to growing in standing or slowly flowing water. As with other wetland types, water in swamps is rich in tannins from decaying vegetation, which gives it a characteristic brownish colour. Swamps are usually associated with adjacent rivers or lakes.

A marsh is a frequently or continually inundated wetland, which is shallower and has less open water than a swamp. The flooding phenomenon is much more dynamic leading to the development of alluvial soils. Also, in contrast to a swamp, a marsh has no woody vegetation. Marshes receive most of their water supply from surface water, although sometimes they are also fed by groundwater. Nutrients are plentiful and the pH is usually neutral leading to an abundance of plant and animal life. Flora colonizing marshes are typically herbaceous, dominated by grasses, rushes, reeds, typhas and sedges. Plants are rooted in mineral soil substrate and they are perfectly adapted to temporary saturated soil conditions. Marshes are also subject to grazing by wild animals and domestic cattle which suppresses woody vegetation and maintains characteristic grassland communities.

In order to make the picture complete, we have added estuarine habitats as transitional between freshwater and marine ecosystems. For this purpose we have adopted the definition used by the EU Water Framework Directive: " . . . *bodies of surface waters in the vicinity of river mouths which are partly saline in character as a result of their proximity to* *coastal waters but which are substantially influenced by freshwater flows.*"

The aim of this paper is to present a broad overview of ecosystem services of different types of European wetlands based on a representative sample and identify potential threats for them in the future.

METHODS

Wetlands choice

Within the 6th EU FP SCENES (Water Scenarios for Europe and for Neighbouring States) project, a wetland geodatabase was established containing the spatial extent and attributes of a wide range of European wetlands. The geodatabase was created according to the data-filtering and data preparation procedure shown in Fig. 1.

In the first step of the approach, data on wetlands were collected from readily available and accessible sources. For example, Natura 2000 and Corine Land Cover 2000 (http://www.eea.europa.eu/publications/COR0-landcover/page001.html) were used as spatial reference data sets. In some cases, remote sensing open-source data were used to define precisely the location of individually identified wetlands, termed objects. This approach brought together more than 4000 wetland objects within Europe. These are necessarily large wetlands as analysis at this European scale did not permit small wetlands to be identified and incorporated. In the second step, results of this analysis were selected by applying an areal threshold set at 5000 hectares. As a result of this filtering, 402 objects were captured as an input to our database for the following steps of the analysis (Fig. 2).

In the third step, the database of 402 objects was divided into regional, country-wide sets. Data sets were sent to national wetland experts to gather site-specific information. Additionally, experts were asked for the details regarding selected wetland objects, mainly related to water supply mechanisms and hydrological descriptions of particular wetlands. Literature surveys were also undertaken to permit access to scientific publications on objects of interest. In many cases, insufficient or no information was available, so the sites were rejected. The output of this exercise was a wetland data set with 102 objects. In the fourth step, a data set of the various wetlands and their spatial extent was created. For the data obtained, the geodatabase was set up with GIS software. The final reviewed database was unified into one comprehensive data set that consists of tables and ESRI shapefiles (*.shp) associated in topologic layers (Fig. 3). All the data provided in feature sets are referred to the WGS84 coordinate system.

Every object is referenced to a set of unique attributes, including the individual name of the object, country, spatial extent, type of water supply mechanism (surface water, groundwater, precipitation and potential influence of saline water), and a type of wetland: marsh, mire (bog or fen), swamp and estuary. In cases where there was more than one type of wetland present within the spatial extent of the object, additional types of wetland were specified (e.g. type 1 – fen, type 2 – swamp). Furthermore, for the

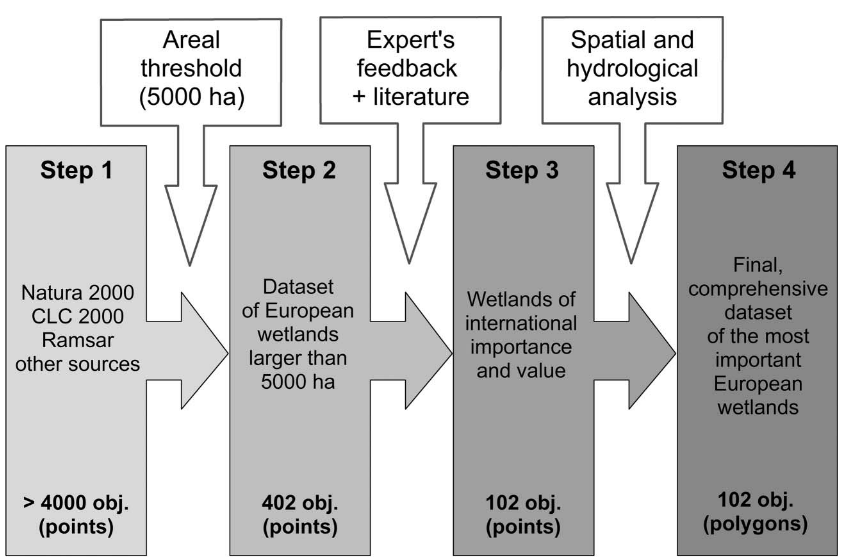

Fig. 1 Wetland selection procedure chart.

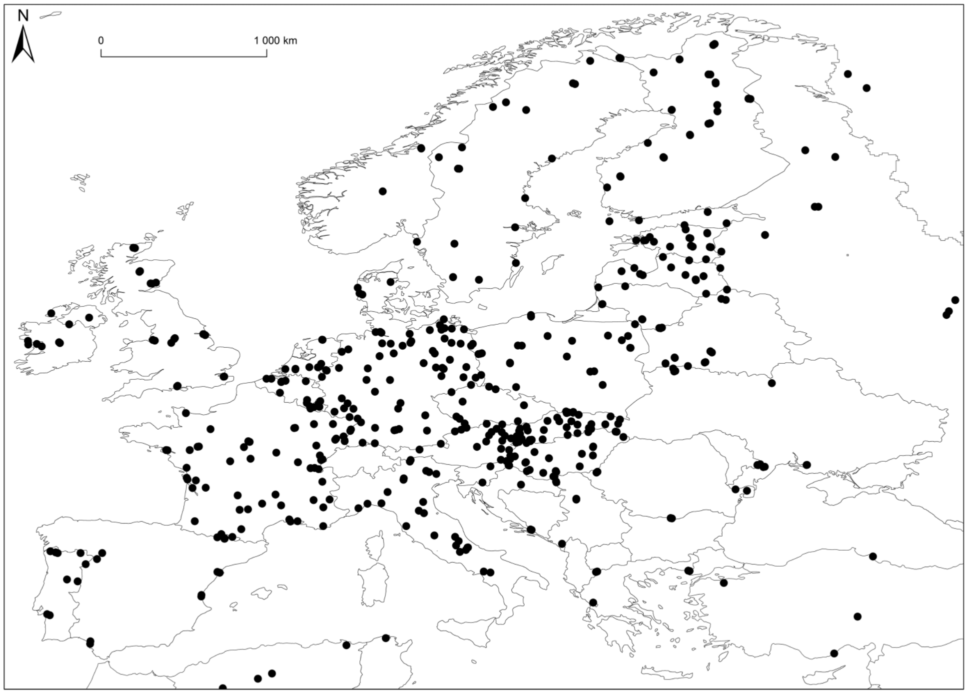

Fig. 2 European wetlands—areal threshold of 5000 hectares.

riparian wetlands, objects in the database were combined with the adjacent river or lake which influenced the wetland hydrological supply mechanism. The final database consisted of 21 fens, 24 bogs, 34 marshes, 15 swamps (i.e. 49 riparian wetlands) and eight estuaries (Fig. 4).

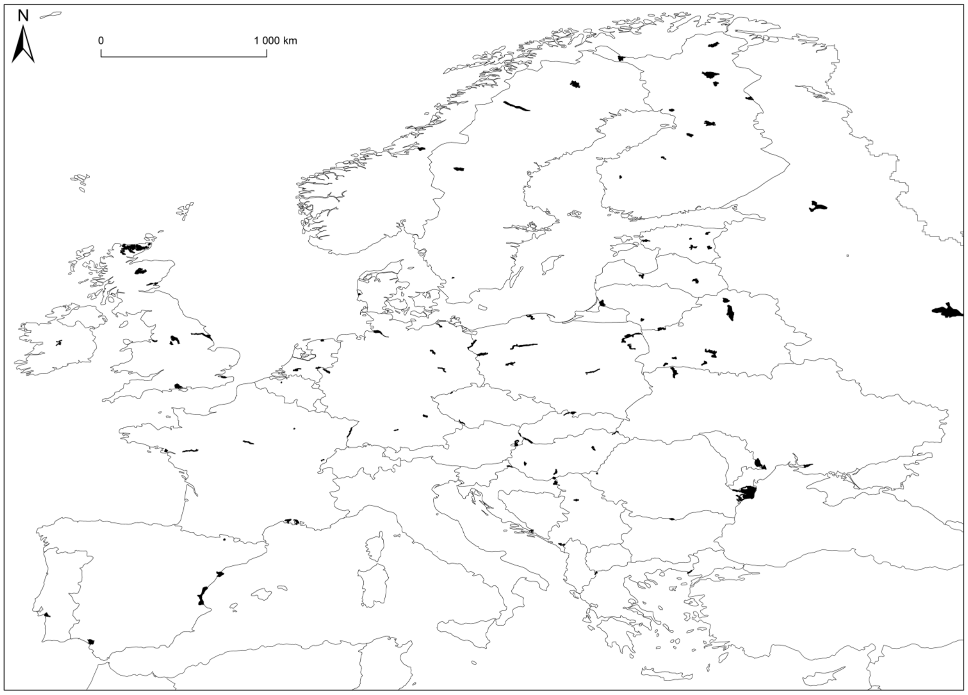

Fig. 3 Output of the analysis—102 selected wetland objects within Europe of known hydrological features and spatial extent.

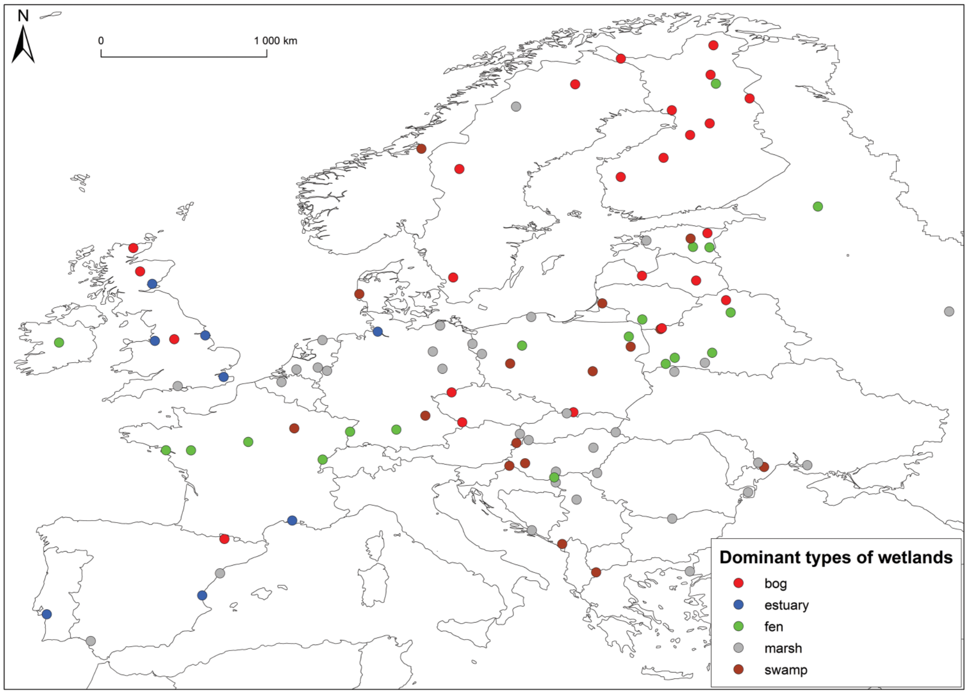

Fig. 4 Dominant types of wetlands in particular database objects.

Identification of ecosystem services

Information on the status of ecosystem services within each wetland object was gathered into the comprehensive data set. The primary sources of information were scientific publications and official websites that described particular areas of interest.

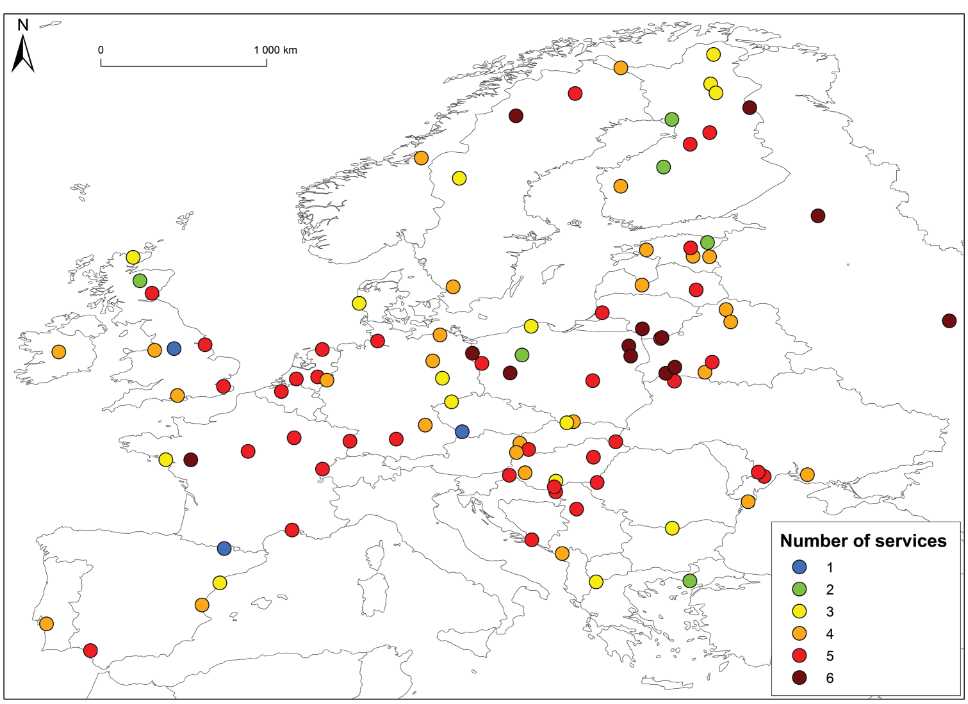

Fig. 5 Number of ecosystem services provided by selected wetlands.

Additionally, some of the data were supplied by national wetland experts and authorities.

In the approach presented here, six major ecosystem services of wetlands were classified and each was treated equally in the evaluation:

- Habitats for rare birds (cultural recreation service)
- Fish (food provisioning and cultural recreation service)
- Vegetation (supporting biomass service)
- Carbon sequestration (regulating service)
- Nutrient removal (regulating service)
- Reed production (provisioning service)

If for any wetland the ecosystem service was present and well developed (e.g. the population of a particular wetland bird species is high and internationally significant), the service is defined as present, and was valued as 1. If for any wetland object the criteria for particular wetland services were not present, then the object was valued as 0. Many wetlands consist of two or more types (most often there were fens and swamps or fens and marshes in the large river valleys). In these cases, the services of both components were included. As there were six services described, every wetland object can be attributed a maximum of six points.

Three services out of six focused on biotic components of the environment. To describe the first biotic ecosystem service of wetlands, objects were analysed as habitats for rare bird species that have strict requirements for constant water availability. Evaluation of this service was achieved through the species of bird that needs a biotope either seasonally inundated or having a shallow groundwater level. For each wetland, bird species were selected by their protection status and the size of their population. Although most of the bird species present on wetland areas are associated with certain elements of the hydrological regime, only birds directly dependent on open-water and groundwater were valued as 1. These birds are listed in Table 1.

The presence of other birds was valued as 0. A number of wetlands-supported birds are specified in Table 1 but if there was any written remark that the population of a certain bird was endangered or a continuous decrease in the number of birds of a particular species was recorded, the wetland bird service was valued as 0.

The second biotic ecosystem service of wetlands evaluated was fish production. In cases of seasonally and permanently inundated wetlands, flooded areas play an important role in fish spawning and population development (Welcomme 1979). Since our database of wetland objects consisted only of a general hydrological description, and fish survey data were not widely available, it was assumed that every wetland ecosystem defined as marsh and swamp can play an important role in the fish spawning processes. Floodplains and lowlands inundated in spring provide relatively warmer water than in the river channel. Such areas are widely used by early foraging fry (Górski *et al*. 2010). In the case of some freshwater fish species, a relationship was observed between the flood frequency and the efficiency of natural spawning (Petr 2005). Within Europe, the main fish that is adapted to natural spring flooding in valleys is the Northern pike (*Esox lucius*). Therefore, all the ecosystems that have developed in seasonally flooded conditions with shorter (marshes) and longer (swamps) inundation periods and that were defined within the natural spatial extent of the Northern pike population (Backiel 1965), were valued as providing a fish spawning service. Other types of inland wetlands, fens and bogs, were valued as 0. Estuaries were valued as 1, as the brackish water conditions provide the specific spawning conditions of a number

Table 1 Species used to define bird habitat services.

Aquatic Warbler (*Acrocephalus paludicola*)
Black-throated Diver (*Gavia arctica*)
Red-throated Diver (*Gavia stellata*)
Common Snipe (*Gallinago gallinago*)
Geese (*Anser anser, Anser erythropus*)
Crane (*Grus grus*)
Species of waders (*Charadriiformes*)
Herons (*Ardea cinerea*, *Ardea alba*, *Ardea purpurea*)
Night Heron (*Nycticorax nycticorax*)
Great-Crested Grebe (*Podiceps cristatus*)
Pelican (*Pelecanus*)
Yellow Wagtail (*Motacilla flava*)
Great Cormorant (*Phalacrocorax carbo*)
Certain species of ducks (*Anas clypeata*, *Aytha nyroca*)
Corncrake (*Crex crex*)
Eurasian Curlew (*Numenius arquata*)
Common Shelduck (*Tadorna tadorna*)
Osprey (*Pandion haliaetus*)
Smew (*Mergellus albellus*)
Little Tern (*Sternulla albifrons*)
Eurasian Golden Plover (*Pluvialis apricaria*)
Ringed Plover (*Charadrius hiaticula*)
Pink Flamingo (*Phoenicopterus roseus*)
Glossy Ibis (*Plegadis falcinellus*)
Dunlin (*Calidris alpina*)
Wood Sandpiper (*Tringa glareola*)
Ruff (*Philomachus pugnax*)
Meadow Pipit (*Anthus pratensis*)
Little Ringed Plover (*Charadrius dubius*)
Little Grebe (*Podiceps ruficollis*)
Pied Avocet (*Recurvirostra avosetta*)

of species of fish that move between freshwater and saltwater.

The third biotic ecosystem service of wetlands, analysed was wetland vegetation. Hydrological conditions of wetlands, such as shallow groundwater occurrence and seasonal or permanent flooding, lead to the development of characteristic plant communities. Thus, the natural function of water circulation within a wetland permits valuable plant communities to develop; the association is sufficiently strong that the presence of particular plant species is often used as an indicator of water supply mechanisms and the hydrological status of the wetland (Wheeler *et al*. 2004). The main criterion of this study with regard to the wetland vegetation service was the presence of certain plant communities within each wetland object. Only wetland plant communities that are strongly dependent on wet conditions were taken into account. Criteria established by Natura 2000 were used as an indicator (Table 2). Value 1 was assigned for the wetland vegetation service, if at least one of the valuable plant communities is present and well developed within the range of particular wetland.

Abiotic wetland ecosystem services refer to the quantitative and qualitative parameters of a biotope. The most important of these ecosystem services in mires is carbon storage. Peatland ecosystems function as sinks for carbon, when the peat forming processes lead to the accumulation of organic matter. Few detailed analyses are available for carbon budgets of European wetlands (Byrne *et al*. 2004), so quantitative carbon accumulation information was not widely available. Instead, a generic indicator was employed. Thus, all the mires in which hydrological conditions have not been significantly degraded were valued 1.

Table 2 Wetland plant communities applied as the reference in the approach (Natura 2000 codes in brackets).

Ox-bow lakes and natural eutrophic waters waters with *Nympheion* and *Potamion* (3150)
Flooded muddy river banks (3270)
Koelerion glaucae (6120)
Molinion (6410)
Adenostylion alliarie and *Convulvuletalia sepium* (6430)
Arrhenaterion elatrioris (6510)
Transitional bogs, mostly with *Scheuchzerio-Caricetea* (7140)
Mountain and lowland alcalic mires (7230)
Galio-Carpinetum and *Tilio-Carpinetum* (9170)
Vaccinio uliginosi-Betuletum pubescens, *Vaccinio uliginosi-Pinetum*, *Pino-murgu sphagnetum*, *Sphagno girgensohnii-Piceetum* (91D0)
Salicetum albo-fragilis, *Populetum albae*, *Anenion-glutinoso-incanae*, *Alnetum* (91E0)
Ficiaro-Ulmeteum (91F0)
Quercetelia pubescent-petraeae (91I0)

The second abiotic wetland ecosystem service analysed in the study was nutrient removal (Jordan *et al*. 2011), which is a crucial process in wetlands situated in river valleys where over-bank inundation occurs. As with carbon sequestration, site specific data were not available for most wetland objects. In this approach, marshes were classified as providing the nutrient removal service. Certain swamps located in floodplains also provide the nutrient removal service.

Additionally, production of wetland-specific goods that are a result of wetland functions was classified as an economic service of the ecosystem. Within Europe, the main goods that come from wetlands for human economic activity are reed for roofing and willow harvest, as well as extensive hay-making on meadows (those which are economically supported by agri-environmental schemes).

Hydrological threats to the wetlands ecosystem services

The natural flow paradigm (Poff *et al*. 1997) promotes the concept that the river ecosystem has developed according to the natural hydrological regime, in which one or more ecosystem processes, functions and services are dependent on each characteristic of the flow regime. For example, lateral connectivity between rivers and their floodplains during flood events, with associated exchange of nutrients, energy and carbon, is a key driving force for the river ecosystem (Junk *et al*. 1989). Maintenance of ecosystem services thus relies on the range of natural intra- and inter-annual variation of the hydrograph (Biggs *et al*. 2008). Richter *et al.* (1996) recommended that the primary characteristics of the flow hydrograph could be captured with 32 indices, including the number of flood events per year and their average duration. Using redundancy analysis, Olden and Poff (2003) suggested that 11 indices could define the major characteristics retaining specific flood indicators.

It is widely recognised that in the future, climate change, increasing water use and land-use change are likely to affect the flow regimes of European rivers. In this study, a hydrological threshold has been used to identify significant threats to wetland ecosystem services. The ability of wetlands to provide the services depends on a number of factors, particularly the hydrological regime. Due to the general character of this study, we have concentrated on the concept of generic elements of hydrological regime being indispensable and essential conditions rather than on defining precise relationships between hydrological parameters and wetland functions at specific wetland sites. Thresholds have been defined in such a manner that meeting them ensures functioning of the wetland. The other factors that can also impact a particular service (e.g. water quality, minor modification of the hydrological regime, land-use types on the floodplain and in the surrounding areas, management options for open vegetation including grazing and mowing) were not included in this exercise. It means that the results are biased to the situations where our current knowledge indicates with a high level of certainty that a particular ecosystem service will be lost.

Habitats of rare bird species The service is lost if there is no flooding of riparian wetlands (swamps or marshes) or there is a change in the timing of flooding by more than one month. In the case of mires, a change from a surplus of water to a water deficit indicates a decrease in soil water table level, which has a negative impact on the wading birds.

Fish The service is lost if there is no inundation of riparian wetlands (swamps or marshes) or there is a change in the timing of flooding by more than one month. In the case of estuaries, loss of an arbitrary threshold, i.e. a minimum of 25% freshwater inflow to an estuary, would result in a significant salinity increase and change the spawning conditions (Craft *et al.* 2002, Eliot and Hemingway 2002).

Habitat for wetland vegetation This is lost when there is a lack of inundation of the riparian wetlands or the peat-forming process reverses (so-called moorshing process) in the case of bogs and fens. A lack of inundation is the most commonly referenced reason for loss of riparian forests and sedge vegetation. The mire habitat becomes a peatland habitat with an abundance of nutrients compared with nutrient limitation in the case of growing peat. This second process in mires is indicated by a change from water surplus to water deficit in the multi-year water balance.

Carbon storage Changes to carbon emission in mires (bogs and fens) occur when, instead of peat growth, decay of peat occurs due to mineralization. Again this is indicated by a change in the water balance.

Nutrient removal This function of the floodplain (riparian wetlands) relies on periodic inundation of sufficient duration to allow biochemical processes to occur that remove or transform nutrients. This may be a physical process, such as deposition of phosphorus bound to sediments, or biological, such as the uptake of nitrogen by plants.

Production of goods This is lost when there is an absence of inundation of riparian wetlands, or when fens and bogs become too wet for any agricultural practices due to swampy conditions. The lack of inundation is particularly significant for reed beds (the source of thatch or "roofing reed") and lack of flooding can also have serious impacts on willow communities. We assumed that the mire habitat becomes too wet for any agricultural purposes when the positive water balance has doubled.

To quantify the scale of ecosystem services provided in the future, the following rules were applied:

- –1 was assigned to the wetland when a particular service has been lost from the whole area;
- –0.5 was assigned in the case of wetlands that are comprised of two types and only one type has lost its function.

The second case was introduced in order to quantify the situations when wetlands composed of two types were analysed. In most cases they were big river valleys with swamp or marsh (riparian wetland) close to the river and fen (groundwater part) at the edge of the valley. In the situation, when, for example, a riparian zone has lost its birds value, but the fen zone remains intact, the partial loss in ecosystem services can be recorded appropriately.

Modelling of current and future daily time series

To assess the impact of climate change and water use scenarios on future hydrological regimes in Europe, the large-scale water model WaterGAP (Water – Global Assessment and Prognosis) was applied. WaterGAP consists of two main components: a Global Hydrology Model (Alcamo *et al.* 2003, Döll *et al.* 2003) to simulate the characteristic macro-scale behaviour of the terrestrial water cycle, and a Global Water Use Model (Döll and Siebert 2002, Flörke and Alcamo 2004, Aus der Beek *et al*. 2010) to estimate water withdrawals and water consumption of five different water-use sectors. The model version applied in this study, WaterGAP3, herein referred as WaterGAP, performs its calculations on a 5 × 5 arc minutes grid cell raster (longitude and latitude) which relates to roughly 6 km × 9 km in Central Europe (Verzano 2009).

The Global Hydrology Model calculates, for each individual grid cell, daily water balances for land areas and open water bodies. Thereby, spatially distributed physiographic characteristics, such as land cover, soil properties, hydrogeology, elevation and slope, as well as location and extent of wetlands, lakes and reservoirs are taken into account. The vertical hydrological processes of the land area are described by considering the water balances of the canopy, snow and soil water. Depending on the slope characteristics, the runoff from land is partitioned into fast surface/subsurface runoff and groundwater recharge which flows into the groundwater storage. The water balance for open water bodies is determined by the difference between precipitation and evaporation and defines the runoff from freshwater areas. Runoff from both land and open water bodies makes up the total simulated runoff of each individual grid cell. Water flow between grid cells is assumed to occur as river discharge, and so the total simulated runoff of each grid cell is routed along a predefined drainage direction map (DDM5; Lehner *et al.* 2008) to the next downstream cell. The simulated river discharge is calibrated and validated against measured annual discharge data from the Global Runoff Data Centre (GRDC 2004) at 221 gauging stations in Europe. The effect of a changing climate on future runoff is taken into account via the impacts of temperature and precipitation on the different water balances considered in the model. In recent years, WaterGAP has been improved with a special focus on its ability to simulate single flow events. The main improvements of the model include: (1) a revised snow routine on a sub-grid scale (Verzano and Menzel 2009), (2) a variable flow velocity algorithm (Verzano *et al.* 2005), (3) a better representation of river length through individual meander information for each grid cell (Lehner *et al.* 2008), and (4) implementation of 590 dams from the European Lakes and Reservoir Database (Eldred2, EEA), including dam management rules (Hanasaki *et al.* 2006).

In addition to dam storage impacts, river discharge is affected by water consumption and land-use changes. The Global Water Use Model calculates water consumption for domestic, thermal electricity production (power station cooling), manufacturing, irrigation and livestock sectors using available data and future projections of climate, population growth, economic development and electricity demand as well as irrigated area and livestock numbers. In addition, further technological improvements (e.g. drip irrigation systems) and structural changes, in terms of the commitment to save water, are taken into account. While water use for irrigation, livestock and electricity production is simulated on the 5 × 5 arc minutes grid scale, domestic and manufacturing water use is calculated at a national scale, which is then downscaled to the grid size within the respective countries using simple allocation schemes (e.g. demographic data). Finally, the grid cell-specific water use of all sectors is removed from the related grid cells by subtracting it from surface waters.

Land-use change and land-cover information, as well as area statistics for irrigation were modelled with LandSHIFT (Land Simulation to Harmonize and Integrate Freshwater availability and the Terrestrial environment). LandSHIFT is a spatially-explicit dynamic model for simulating land-use change at continental and global scales, and employs a multi-scale spatial hierarchy. Here, macro-level is defined by spatial entities such as national, district or socio-economic units. The model was developed and improved at the Centre for Environmental Systems Research (Schaldach and Koch 2009).

Parameters of interest

Different elements of the hydrological regime were analysed in this study, guided by knowledge of the hydrology of wetland types and water sources. For riparian wetlands (i.e. swamps and marshes), which depend on a natural pattern of inundation, the "bankfull flow approach" was applied at representative grid cells to indicate important high-flow events (Schneider *et al*. 2010). In this approach, bankfull flow was estimated by applying the partial duration series of river flows fitted with a Generalized Pareto Distribution (Davison and Smith 1990) and an increasing threshold censoring procedure (Begueria 2005). The underlying 42-year time series (1961–2002) of daily discharge data was modelled by WaterGAP and a return period of 0.92 years was employed as a best estimate of bankfull flow (Dunne and Leopold 1978). Then, all overbank flows were analysed in terms of flood volume and event timing. To investigate the impact of climate change on the hydrological regimes, these two parameters were also determined for the future. Here, daily river discharges were calculated for the simulated 30-year time series 2010–2039 representing the 2025s, as well as 2040–2069 representing the 2050s.

In this study we assumed that the primary impact on estuaries is from alterations to freshwater inflow.

Therefore, mean annual river discharge was determined at representative grid cells on the inflowing rivers immediately upstream of the estuaries. In the case of bogs and fens, water balances were calculated considering mean annual values for precipitation and potential evapotranspiration (PET) for bogs, and in addition mean annual values of groundwater recharge for fens. The analysis was carried out for all grid cells that touch a fen or bog. Finally, the grid cell values were aggregated, resulting in a single water balance for each wetland.

Water management and climate change scenarios

The future of Europe's waters will be influenced by a combination of many important environmental, socio-economic, energy-related, political and policy drivers, such as climate change, population and economic development, land-use change, increasing electricity demand as well as technological improvements. The SCENES project (Water Scenarios for Europe and Neighbouring States; Kämäri *et al*. 2008) is a multi-faceted integrated project that aims to address the complex questions about the future of Europe's water resources up to 2050. For this study, two SCENES scenarios that span a broad variety of socio-economic developments for the future were selected to visualize possible futures of Europe's freshwater resources:

- "Economy First" (EcF) is an economically-oriented scenario encompassing globalisation and liberalisation, characterized through intensified agriculture and slow diffusion of water-efficient technologies. Global demand for food and biofuels drives this intensification of agriculture with an increasing need for irrigation and new cultivation areas. The slow adoption of water-efficient technologies and low water-saving consciousness leads to higher water use.
- "Sustainability Eventually" (SuE) is a scenario that sketches the transition from a globalizing, market-oriented Europe to environmental sustainability where quality of life becomes a central focus. Economic development is an important factor, but is characterized by slow growth. Improvements in technology lead to increases in water-use efficiency and investments in water-related R&D activities are initiated to share technological benefits within Europe. Water demand is strongly reduced by water savings and behavioural changes.

WaterGAP was used to calculate water withdrawals and consumption for the base year (2005) and the two scenarios for all European countries. In the base year approximately 480 km^3 of water are withdrawn from Europe's freshwater reservoirs by households, factories, thermal power plants and irrigation projects. The agricultural sector was the major water user in Europe, accounting for about 40% of the total water withdrawn, followed by water withdrawn for cooling purposes (33%) and the domestic (15%) and manufacturing (12%) sectors. Under the EcF scenario an increase in total water withdrawals of 32% was estimated, whereas the SuE led to a decrease of around 58%. However, not only are total water withdrawals of freshwater resources likely to change, but also the profile of water use is expected to change in Europe. For the EcF scenario, it is expected that the electricity production sector will be the major water user, accounting for 41% of the water withdrawn, followed by the agricultural (30%), manufacturing (18%) and domestic (11%) sectors. An increase of total water withdrawals under EcF resulted from an assumed water-use behaviour that followed traditional patterns accompanied by reluctantly-adopted scientific and technological innovations and slow improvements in water-use efficiency. In contrast, the results of SuE show that the agricultural sector will be the main water user (62%), then the domestic (16%), manufacturing (15%) and electricity (6%) sectors. Decreases in water withdrawals in each sector under the SuE scenario resulted from a combination of behavioural and technological changes with the promotion of technology transfers and efficiency improvements.

The baseline climate input, including monthly information on precipitation, temperature and others, covers the time frame 1961–1990. For the model simulations, a combination of two data sets, CRU TS 2.1 (Mitchell and Jones 2005) and CRU TS 1.2 (Mitchell *et al.* 2004), is used and downscaled to a 5 arc minutes grid. Both CRU data sets provide monthly values for precipitation, temperature, cloud cover and the number of wet days per month. To simulate river discharges on a daily time step, the monthly climate input was downscaled from monthly to daily values. 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 using a two-state, first-order Markov Chain method.

To take account of uncertainty in climate modelling, two different GCM scenario realizations were analysed in this study. The following model and scenario combinations were selected within the SCENES project: (1) The IPSL-CM4 model from the Institute Pierre Simon Laplace, France, representing an A2 scenario (IPCM4-A2). This scenario indicates high temperature increase and low precipitation increase or decrease in Europe (warm and dry); (2) The MICRO3.2 model from the Centre for Climate System Research, University of Tokyo, Japan, representing an A2 scenario (MIMR-A2). In accordance with the IPCM4 model, the MIMR model projects a high temperature increase over Europe, but in combination with a high precipitation increase or small decrease (warm and wet). The original GCM outputs have a spatial resolution of 1.875° × 1.875° (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 future climate input was scaled by reference to the difference between the observed and simulated climate of the reference period ("delta change approach"; Henrichs and Kaspar 2001, Lehner *et al*. 2006). This scaling approach is frequently applied to force global-scale hydrological models for climate change studies.

RESULTS

Current status of ecosystem services

The general analysis leads to the conclusion that most of the wetlands studied provide more than one ecosystem service. The most prevalent services were abiotic, i.e. nutrient removal was found in 83 (out of 102) places, and production of goods (79/102). The biotic services ranged from 75/102 in the case of fish production and wetlands birds protection, to 77/102 for vegetation. The service which occurs the least often and so has the smallest number, was found to be carbon storage, which was restricted to the mires included in this study. We identified a total of 441 services, which gives an average of more than four services for each wetland analysed. The spatial distribution of the wetlands analysed and the number of services provided by particular types of wetland are presented in Fig. 5 and in Table 3. It could be seen that there is a broad spread of services across Europe with no clear regional divisions, although a hot spot of many services is evident in central eastern Europe.

Table 3 Number of defined ecosystem services per particular wetland of dominant type; for objects, that contain the second type of wetland, services for both types of wetlands were taken into account.

Type of wetland	Average number of ecosystem services per object
Fens	4.36
Bogs	2.75
Marshes	3.65
Swamps	3.60
Estuaries	3.37

Risk to ecosystem services in future

The analysis of the future threats was performed for two time horizons, 2025 and 2050, including two water management scenarios and two climate change realizations for each time horizon. Results are shown on Figs 6 and 7 and summarized in Table 4.

The most significant reductions of ecosystem services can be observed in the EcF scenario, which assumes economic development of Europe with no major socio-political regard to the sustainable use or conservation of water resources. Within the SuE scenario, which assumes sustainability in socio-political development and water management, a reduction in the number of ecosystem services was also observed; however, the changes, especially in the longer period, do not appear as great as for the EcF scenario. It is also clear that the most important alterations were introduced by the different climate change realisations, where dry and hot IPCM4-A2 results were much more severe for wetland functioning than the warm and wet MIMR-A2 results. In general, it appears that the most vulnerable services (the largest number of services lost) are those associated with surface water dynamics—mostly the services of wetland birds and fish spawning. Ecosystem services dependent on groundwater dynamics and water balance changes (e.g. carbon storage) are seemingly more buffered to the hydrological stress.

Within the short time horizon (i.e. in the 2025s), hydrological stress quantified using the IPCM4-A2 climate projections resulted in losses of 95 (out of 441) and 93 services for the EcF and SuE scenarios, respectively. The relatively small difference between socio-economic scenarios, compared with the average loss of services under IPCM4, suggests that climate change impacts dominate over socio-economic impacts. The most significant reduction in

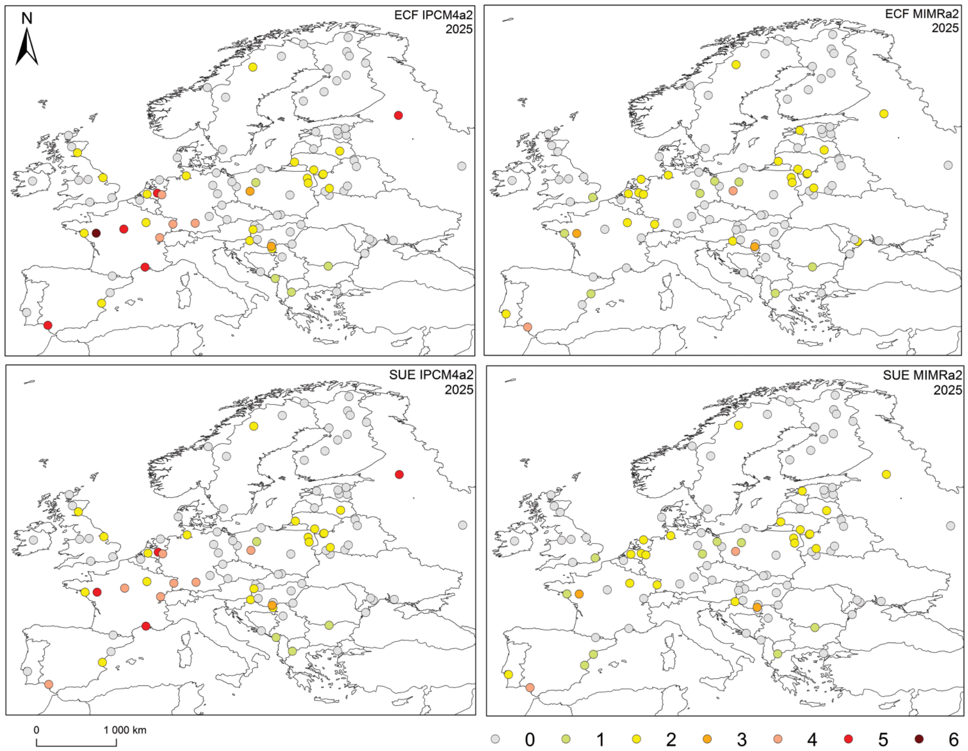

Fig. 6 Number of services lost by particular wetlands for different scenarios—time horizon 2025.

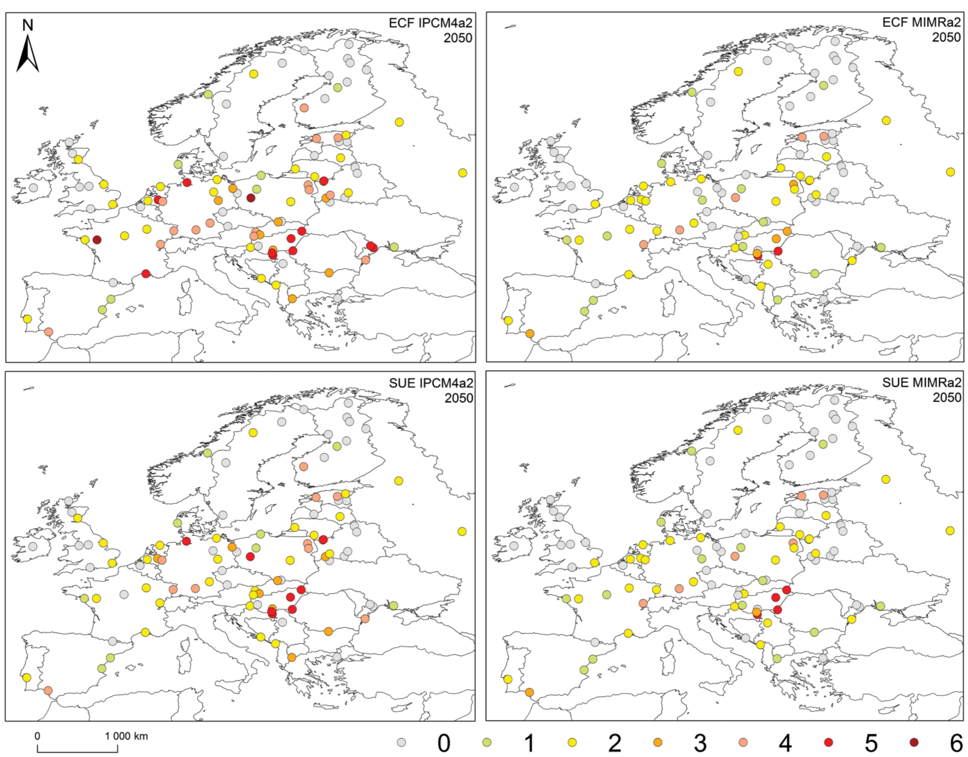

Fig. 7 Number of services lost by particular wetlands for different scenarios—time horizon 2050.

the number of ecosystem services can be observed in Western Europe (mostly in France, The Netherlands and southern Germany). Some important reductions were also recorded in Central Europe (Hungary, Belarus, Lithuania). Considering the MIMR-A2 climate projections, the modelled numbers of ecosystem services are almost equal for the EcF and SuE scenarios (losses of 64 and 63 services, respectively,

Table 4 Modelled number of ecosystem services of each kind and the amount of lost services in particular scenarios in the time horizons of 2025 and 2050.

Scenario	Ecosystem service						Lost
	Wetland bird	Wetland vegetation	Carbon storage	Production of goods	Nutrient removal	Fish spawning	
2025_ECF_IPCM4-A2	43	67	46	72	72	46	**95**
2025_SUE_IPCM4-A2	43	67	48	72	73	45	**93**
2025_ECF_MIMR-A2	46	74	48	77	83	49	**64**
2025_SUE_MIMR-A2	47	74	48	77	83	49	**63**
2050_ECF_IPCM4-A2	21	47	36	55	54	21	**207**
2050_SUE_IPCM4-A2	28	55	40	59	60	30	**169**
2050_ECF_MIMR-A2	32	67	46	73	75	31	**117**
2050_SUE_MIMR-A2	32	67	46	73	75	30	**118**

which is about a 30% lower reduction in services than modelled with the IPCM4a2 climate projection). In general, relatively small differences were observed between the numbers of lost services modelled for SuE and EcF scenarios in the short time horizon.

Within a longer time horizon (results of hydrological and climatic stress modelling for the 2050s) the losses of ecosystem services predicted using the IPCM4-A2 climate data are approximately 50% higher than projected under the MIMR-A2 climate. Moreover, under the IPCM4-A2 climate realization, the most significant difference between the two socio-economic scenarios analysed was that the modelled loss of services in the EcF scenario is approximately 20% higher than in the SuE scenario. Such a result could indicate that, according to the assumptions applied within the ecosystem service criteria, as well as in the parameter application used in WaterGAP to model particular elements of the water balance, hydrological and climatic stress on wetlands has its most negative impact in the long time horizon. Under the MIMR-A2 climate realization, no significant difference between EcF and SuE was found. This can be explained by the land-use changes simulated by LandSHIFT, especially for cells in Belarus, Hungary, Ukraine and Lithuania. Here, water consumption is also higher under the EcF scenario and has a stronger impact on the hydrograph. However, this effect is outweighed by land-use changes in the 2050s modelled for the two scenarios and the underlying climate conditions. While under EcF in this area more cropland can be found, SuE has a higher fraction of land set aside. Set-aside of agricultural land causes higher evaporation in the winter half-year and so more depletion of soil water storage. Consequently, runoff and flood volume are more reduced under the SuE scenario in spring in comparison to the EcF scenario.

The most significant loss of ecosystem services modelled for the 2050s can be observed in Central Europe (Hungary, Germany, France, Belarus, Poland) under both climate realizations and socio-economic scenarios. Similarly, as within the short time horizon, the greatest loss was observed in the services of wetland birds and fish spawning. The most significant loss of all the services was for the EcF scenario simulated with the IPCM4-A2 climate projection; the wetland bird service was reduced by 78%, carbon storage service was reduced by 60%, fish spawning service was reduced by 52%, wetland vegetation service was reduced by 39%, nutrient removal service was reduced by 35% and the production service was reduced by 30%. In general, in both the time horizons analysed, the wetlands of Scandinavia and the British Isles did not lose as many services as wetlands in the European Lowlands.

It is likely that the water balance—assumed in this study to be the main indicator of changes in fens and bogs—and the volume of the overbank flow—indicator for riparian wetlands—are more stable in regions of a mild, oceanic climate with low variation in the relatively high amounts of precipitation. Services that seem to be the most vulnerable to the hydrological and climatic stress analysed are associated with the avifauna and ichthyofauna. The production of goods on wetlands seems to be relatively resistant to the hydrological and climatic pressures applied within the scenarios analysed and, hence, the most constant among the analysed ecosystem services. It is important to stress that under the worst-case scenario, Europe can anticipate losing almost half (207 of 441) of the services currently provided by wetlands.

CONCLUSIONS

Europe contains a wide range of wetland types, and of sizes of wetlands, reflecting the variation in climate from maritime to continental, Mediterranean to Arctic. Analysis is often limited by the accepted typology, because wetlands include many habitats, such as fens, marshes and floodplains, and individual wetlands are often made up of a mosaic of habitats fed by a variety of water mechanisms, including rainfall, river water and groundwater in different combinations and of different quality.

The 4000 wetlands located by the initial search are a small sub-set of all wetlands in Europe. We selected 402 large wetlands for analysis that fitted with the scale of the hydrological (WaterGAP) model and limits of GCM downscaling, but it is recognized that ecosystem services provision is not necessarily related to size and many small wetlands can provide key services (Blackwell and Pilgrim 2011, this issue) and be an important element of the river basin (Okruszko and Kijanska 2003).

The fact that good data could only be readily collated for 102 of the 402 wetlands bears testimony to the lack of systematic monitoring of wetlands and their historical treatment as wastelands. Nevertheless, our 102 wetlands provide a good geographical coverage across Europe, a good representation of the types we selected and a wide selection of ecosystem services. We have therefore documented the key ecosystem services of wetlands across Europe, including production, regulating and supporting services, and in a manner consistent with the global Millennium Ecosystem Assessment. We have found that, on average, each wetland provides more than four of services analysed, and that the combination of groundwater-fed fens (at the edge of the valley) with riparian marshes or swamps is the most fruitful combination in terms of number of ecosystems services provided. These are mostly located in the large river valleys in Central and Eastern Europe.

The analysis of impacts of future scenarios produced a realistic outlook of potential threats. In the worst case, almost half (207) of the 441 services provided currently by European wetlands could be lost. Comparing the two time horizons (2025 and 2050), the impact of socio-economic development and adaptation impacts of climate change highlights the significant alterations in wetlands and their ability to provide services, from likely future changes in climate.

We conclude that a focus on adaptation strategies is required, especially for wetlands located in Central Europe, which are the most threatened if the dry and warm climate projection occurs as simulated by IPCM4. The services that are most endangered and thus need special attention are those related to flooding events.

The WaterGAP model includes reservoirs and their operation, but only in a generic way, because local rules differ greatly between individual dams and over time. The difference in the number of services lost for sustainable and economy-oriented scenarios in the case of a dry and hot climate (IPCM4-A2) for the 2050s proves that operational water management plays a crucial role in the preservation of ecosystems in water-limited conditions. As we already know, reservoirs can significantly alter hydrological regimes downstream (Acreman *et al*. 2009) and can have significant impacts on wetland ecosystems (Acreman 2003). We see making reservoir management more ecologically sensitive as a key strategy for maintaining the ecosystem services provided by riparian wetlands, and special attention needs to be given to the services that are most vulnerable to hydrological and climate stress, particularly those related to the avifauna and ichthyofauna.

Hydrology is the key driving variable in wetlands, thus we believe that use of water-based scenarios captures the primary influences on wetlands. The WaterGAP model provides a scientifically-sound basis for future hydrological predictions when coupled with stakeholder-based scenarios. We are mindful of the uncertainties of using the GCM results (Anagnostopoulos *et al*. 2010) as well as downscaling of the GCM scenarios to hydrological models (Kundzewicz and Stakhiv 2010), and of the importance of other variables in determining wetlands' character and ultimately the services they provide, including temperature, geology and lithology, and management practices. It means that future case studies for different hydrological, morphological and ecological settings are required to understand the underlying mechanisms and develop mitigation strategies.

Because this work is unique it is not possible to find results in the literature for comparison. However, we hope that others will build on our restricted start and tackle some of the limitations of our work to define more precise implications for ecosystem services of wetlands in Europe in the future. The approach could be further developed and improved by specific inclusion of ecosystem functions and services measured at wetland sites.

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