Environmental Conservation **29** (3): 308–330 © 2002 Foundation for Environmental Conservation DOI:10.1017/S037689290200022X

Riverine flood plains: present state and future trends

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Date submitted: 19 October 2001 Date accepted: 10 April 2002

Dedicated in Memoriam to Professor Gernot Bretschko

SUMMARY

Natural flood plains are among the most biologically productive and diverse ecosystems on earth. Globally, riverine flood plains cover > 2 × 10⁶ km², however, they are among the most threatened ecosystems. Floodplain degradation is closely linked to the rapid decline in freshwater biodiversity; the main reasons for the latter being habitat alteration, flow and flood control, species invasion and pollution. In Europe and North America, up to 90% of flood plains are already 'cultivated' and therefore functionally extinct. In the developing world, the remaining natural flood plains are disappearing at an accelerating rate, primarily as a result of changing hydrology. Up to the 2025 time horizon, the future increase of human population will lead to further degradation of riparian areas, intensification of the hydrological cycle, increase in the discharge of pollutants, and further proliferation of species invasions. In the near future, the most threatened flood plains will be those in south-east Asia, Sahelian Africa and North America. There is an urgent need to preserve existing, intact flood plain rivers as strategic global resources and to begin to restore hydrologic dynamics, sediment transport and riparian vegetation to those rivers that retain some level of ecological integrity. Otherwise, dramatic extinctions of aquatic and riparian species and of ecosystem services are faced within the next few decades.

Keywords: conservation, restoration, catchment, biodiversity, connectivity, wetland, climate change

INTRODUCTION

Riverine flood plains are among the Earth's most distinctive landscape features. In the natural state they are characterized by high biodiversity and productivity, and corresponding recreational and aesthetic values. Flood plains are of great cultural and economic importance; early civilizations arose in fertile flood plains and throughout history people have learned to cultivate and use their rich resources. Riverine flood plains have also served as focal points for urban development and exploitation of their natural functions.

Several comprehensive books on flood plains have been published during the last 20 years, including monographs on the Pongolo flood plain (South Africa; Heeg & Bren 1982), the Hadejia-Nguru flood plain (Nigeria; Hollis *et al.* 1993), the Gearagh (a small anastomosing river in Ireland; Brown *et al.* 1995), the Luznice (a small meandering river-floodplain system in the Czech Republic; Prach *et al.* 1996), the Amazon (South America; Junk 1997), the Pantanal (South America; Heckman 1998), Czech flood plains and the effects of water management (Penka *et al.* 1985, 1991) and British flood plains (Bailey *et al.* 1998). Further, there are textbooks on floodplain fisheries (Welcomme 1975, 1979), on forested wetlands including flood plains (Lugo *et al.* 1990) on floodplain processes (Anderson *et al.* 1996), on the geomorphology of lowland rivers (Carling & Petts 1992), on macroinvertebrates in North American flood plains and wetlands (Batzer *et al.* 1999), on biodiversity in wetlands and flood plains (Gopal *et al.* 2000, 2002), on wetland ecology and management (Mitsch & Gosselink 2000), on European floodplain forests (Klimo & Hager 2001), and on the restoration of river-floodplain systems (Middleton 1999; Smits *et al.* 2000).

Flood plains, with an estimated global extent ranging from 0.8×10^6 km² to 2×10^6 km² (Mitsch & Gosselink 2000; Ramsar & IUCN [World Conservation Union] 1999) represent a primary wetland type that will deserve increased attention as a key global resource in the near future. This review is seen therefore as a necessary and overdue summary on riverine flood plains that complements reviews on other continental wetlands. Brinson and Malvaréz (2002) review the status of temperate wetlands and Junk (2002) treats subtropical and tropical wetlands in a more general way. Moore (2002) focuses on cool temperate bogs, while Malmqvist and Rundle (2002) review the state of rivers, and Williams (2002) summarizes the present and future state of inland saline water bodies.

The present review provides an overview on the actual extent of riverine flood plains, the major economic and ecological services they provide, and the multifaceted threats that make them to one of the most endangered landscapes worldwide. Further, we discuss their changing ecological status and finally we predict the conditions of flood plains

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in the year 2025 (see Foundation for Environmental Conservation 2001) under different scenarios of conservation/exploitation. Since flood plains, wetlands and freshwater systems are not always clearly distinguished in the published literature, general examples on fresh waters or wetlands are included in the present review if necessary.

Definition and classification of flood plains

Flood plains are defined as 'areas of low lying land that are subject to inundation by lateral overflow water from rivers or lakes with which they are associated' (Junk & Welcomme 1990). This definition includes fringing flood plains of lakes and rivers, internal deltas and the deltaic flood plains of estuaries. Brinson (1990) and Brinson and Malvaréz (2002) proposed a hydrogeomorphic classification of wetlands that is based on the (1) geomorphic setting, (2) water source, and (3) hydrodynamics. Considering these components, riverine flood plains are located on low-gradient alluvial 'shelves'; water sources are primarily from lateral overspill of river water, although other sources may also contribute to floodplain inundation; and, although primarily unidirectional, water flow is characterized by highly complex, multidimensional exchange pathways. Four sources of water are recognized as contributing to floodplain inundation: lateral overflow, groundwater, upland sources and direct precipitation. Flood plains can be solely fed by rainfall such as the Flooding Pampa grasslands in Argentina (Perelmann *et al.* 2001); however, several sources normally contribute to inundation (Tockner *et al.* 2000*a*).

As riparian zones, flood plains are usually defined as ecotones between terrestrial and aquatic realms (Gregory *et al.* 1991; Malanson 1993) that extend from the low-water mark to the high-water line and also include the terrestrial vegetation influenced by elevated groundwater tables or extreme floods (Nilsson & Berggren 2000; Naiman *et al.* 2000). In practice, there are several transition zones, and riverine flood plains may contain a complex of different wetland types.

Flood plains develop in all geographic regions and at different locations along river corridors (e.g. Tockner *et al.* 2000*a,b*). For streams in the USA, the estimated average floodplain width ranges from 3 m for small rivers to about 1 km for the largest rivers (Table 1). Total floodplain area (all stream segments combined) is similar across different stream orders (Table 1). Riverine corridors are often composed of flood plains sequentially arrayed between canyons or bedrock constrained segments from the headwaters to the ocean. The floodplain segments can be as large as 90 000 km^2 as for the Nile River (Sudd, Sudan), although they range mostly from tens to hundreds of ha in small and medium-sized rivers (Stanford & Ward 1993). Along large tropical rivers such as the Amazon, the Orinoco or the Magdalena, average floodplain widths are 32 km, 9 km and 35 km, respectively (Hamilton & Lewis 1990). The immense area that natural flood plains may cover is demonstrated by the Fly River (Papua New Guinea), one of the largest intact floodplain rivers in Australasia; 60% of the 76 500 km^2 catchment area becomes seasonally inundated, and the average floodplain width of the lower 800 km is more than 40 km (Swales *et al.* 1999).

Table 1 Stream order, estimated number of streams, average and total length of rivers and streams, average riparian width and total floodplain surface area in the USA (modified from Leopold *et al.* 1964).

Stream order	*Number*	*Average length (km)*	*Total length (km)*	*Estimated floodplain width (m)*	*Floodplain surface area (km²)*
1	1 570 000	1.6	2 526 130	3	7578
2	350 000	3.7	1 295 245	6	7771
3	80 000	8.5	682 216	12	8187
4	18 000	19.3	347 544	24	8341
5	4200	45.1	189 218	48	9082
6	950	103.0	97 827	96	9391
7	200	236.5	47 305	192	9082
8	41	543.8	22 298	384	8562
9	8	1250.2	10 002	768	7681
10	1	2896.2	2896	1536	4449

Flood plains are centres of biodiversity and bioproduction

Flood plains are considered as centres of biocomplexity and bioproduction although this has never been rigorously tested in a regional landscape context (e.g. Megonigal *et al.* 1997). Indeed, more species of plants and animals by far occur on flood plains than in any other landscape unit in most regions of the world. In the Pacific coastal ecoregion (USA), for example, approximately 29% of wildlife species found in riparian forests are riparian obligates (ranging from 12% of mammals to 60% of amphibians; Kelsey & West 1998). Although $< 1\%$ of the landscape of the western USA supports riparian vegetation, this vegetation provides habitat for more species of breeding birds than any other vegetation association. For example, of all bird species breeding in northern Colorado, 82% occur in riparian vegetation, and about half of south-western species depend upon riparian vegetation (Knopf & Samson 1994). Riparian areas in semi-arid zones are also critical in providing stopover areas for *en route* migrants (acting as 'dispersal filters'), and therefore affect the breeding success of northern bird populations (Skagen *et al.* 1998). In tropical Asia, many nominally terrestrial mammals are associated with riverine wetlands for part of their life cycle, including important representatives of the 'charismatic megafauna' (e.g. Malayan tapir, Indian rhino; Dudgeon 2000*a,b*). However, the biodiversity associated with rivers and streams has been neglected in most areas of the world such as Asia or Africa. For example, the Mekong River contains 500 known fish species, although perhaps 1200 are expected (Dudgeon 2000*a,b*). A significant proportion of this diverse fish fauna depends on the rich resources provided by intact flood plains.

In Europe, 30% of threatened bird species are inland wetland-dependent species and 69% of the important breeding areas for birds contain wetland habitats, primarily flood plains (Tiker & Evans 1997). In Switzerland, 10% of the entire fauna is restricted in its occurrence to riverine flood plains, although flood plains only cover 0.26% of the country's surface. Moreover, 28% of the fauna frequently uses flood plains and about 44% is occasionally found in flood plains (Table 2). In total, about 80% of the fauna occurs in riverine flood plains. A high proportion of the riparian obligates (47%) is listed as endangered, compared to 28% for the entire fauna (Walter *et al.* 1998).

Flood plains are important centres of biological diversification. Fittkau and Reiss (1983) assumed that riverine flood plains belong to those aquatic ecosystems where biota of lentic areas (standing water bodies) started their evolution. The temporal continuity of riverine systems and their associated disturbance regime allowed the permanent presence of lentic and semi-lentic water bodies throughout time. The speciation of groundwater crustaceans is also supposed to be favoured by the lateral shifting of river channels that lead to the isolation of former connected channels (e.g. cyclopoid copepods in the alluvial aquifer of the Danube; P. Pospisil, personal communication 1996).

Flood plains are among the most productive landscapes on Earth, owing to continual enrichment by import and retention of nutrient-rich sediments from the headwaters and from lateral sources, and they are more productive than the parent river and adjacent uplands. Net primary production in riparian forests ranges between 750 and 1370 g m^2 yr^{-1} (mean: *c.* 1000 g m^2 yr^{-1}; Mitsch & Gosselink 2000). The production of wetland/floodplain animals is probably 9.0 g m^2 yr^{-1}, which is 3.5 times the value for terrestrial ecosystems (Turner 1982, cited in Keddy 2000). Production depends on hydrology. In Virginia flood plains (USA), aquatic invertebrate production ranges between 1.1 and 6.12 g m^2 yr^{-1}, with highest values in the most dynamic segments (Gladden & Smock 1990). Rivers derive nearly all their fish productivity from flood plains (e.g. Welcomme 1979; Bayley 1988). There is a positive correlation between fish catch and the maximum inundated floodplain area in African rivers, with fish yield being most influenced by the flood state in previous years (Welcomme 1975, 1979). The so called 'flood-pulse advantage' (*sensu* Bayley 1995) was recognized by the ancient Egyptians, since taxes were based on the extent of the annual flood of the Nile. On a worldwide basis, there is a quantitative relationship expressed as: fish catch (kg) = 5.46 × floodplain area (ha). Care has to be taken, however, as these studies are somehow conjecture since fish catch does not equate to fish production. Fish catch is usually adults, which may have achieved their production elsewhere, and not juveniles. Fish concentrate in flood plains and are often easier to catch there (Galat & Zweimüller 2001).

Table 2 Species pool of selected faunal groups in Switzerland and the number of species that are floodplain obligates (K1), that are found frequently in flood plains (K2 + K3) and that occur occasionally in flood plains (K4), and the relative proportion (%) of species within each category (K1–K4) in the total fauna (data from Walter *et al.* 1998; Tockner & Ward 1999).

Group	*Total number of species*	*Obligatory (K1)*	*Frequently (K2–K3)*	*Occasionally (K4)*
Mollusca (terrestrial)	211	12	17	87
Odonata	82	10	48	19
Heteroptera	750	47	170	530
Saltatoria	117	12	30	68
Rhopalocera, Hesperidae	204	6	29	120
Carabidae	523	139	132	159
Apoidea	585	24	246	125
Amphibia	24	7	16	1
Reptilia	15	3	8	4
Aves	391	33	123	158
Mammalia	83	7	21	57
Total	2985	300 (10%)	840 (28%)	1328 (44%)

Economic importance of flood plains

The estimated worldwide value of the services provided by flood plains is US$ 3920 × 10^9 yr^{-1}, assuming that total floodplain area is about 2 × 10^6 km^2 and area-based value is US$ 19 580 ha yr^{-1} compared to US$ 969 ha yr^{-1} for forests and US$ 92 ha yr^{-1} for cropland (Constanza *et al.* 1997). In total, flood plains contribute > 25% of all terrestrial ecosystem services, although they cover only 1.4% of the land surface area (for discussion on floodplain area see Aselman & Crutzen 1989; Mitsch & Gosselink 2000). The major services of flood plains include disturbance regulation (37% of their total value), water supply (39%) and waste treatment (9%). Value of floodplain land in Illinois (USA) was quantified as high as US$ 7500 ha yr^{-1}, with 86% based on regional flood water storage (Schaeffer *et al.* 2002). Nitrogen removal, an important floodplain service, varies from 0.5 to 2.6 kg N ha^{-1} day^{-1} (e.g. 2.6 kg NO_3–N ha^{-1} day^{-1} in a Danubian flood plain; Tockner *et al.* 1999). Flood plains along the Danube are valued at EUR 384 ha^{-1}yr^{-1} for recreation and nutrient removal (Andréasson-Gren & Groth 1995; 1 EUR = 0.88 US$, March 2001). Similarly, the nitrogen reduction capacity of Estonian coastal and floodplain wetlands is worth EUR 510 ha^{-1} yr^{-1}. Barbier and Thompson (1998) valued the weighted aggregate of agricultural, fishing and fuelwood benefits of a Sahelian flood plain at US$ 34–51 ha^{-1} yr^{-1}. The natural value of the flood plain would be even higher if other important benefits such as the role in pastoral grazing and recharging groundwater were included. Agricultural benefits of a planned irrigation project would, however, be only in the range of US$ 20–31 ha^{-1} yr^{-1}.

Firewood, recession agriculture, fishing, and pastoralism generate US$ 32 per 1000 m^3 flood water, compared to US$ 0.15 per 1000 m^3 water for irrigation. In the Inner Delta of the Niger River over 550 000 people with about 1 million sheep and 1 million goats use the flood plain for post-flood dry season grazing (Dugan 1990). There are many other examples of how local communities make use of the diversity and productivity of flood plains and wetlands. Especially in drylands, the benefits of natural flood plains are very high and multifaceted.

Extensive development in flood plains has increased flood damages at unprecedented rates over the past years (e.g. Burby 2002). For example, there is a 26% chance of a property in the 100-year flood plain being damaged by flooding over the 30-year life of a standard mortgage (compared to 1% chance of fire damage; Burby 2002). In the USA, with 6 million buildings located within the boundaries of a 100-year flood plain, flood losses are widespread and losses from flood hazards have increased dramatically over the last decades (averaging US$ 115 million per week) and will continue to do so in the next decades (Congressional Natural Hazard Caucus Work Group 2001).

ENVIRONMENTAL FORCING FACTORS

Natural influences

Flood plains are disturbance-dominated ecosystems characterized by a high level of habitat heterogeneity and diverse biota adapted to the high spatio-temporal heterogeneity. The formation and maintenance of flood plains is closely tied to fluvial dynamics (Hughes 1997; Ward *et al*. 1999*a*; cf. Fig. 1). Fluvial dynamics, including the expansion/contraction of surface waters ('flood and flow pulses'), is also the driving force that sustains connectivity in flood plains (Junk *et al*. 1989; Petts 1990; Tockner *et al*. 2000*a*; Ward *et al*. 2002; Table 3). Hydrologic connectivity, a key process in riverine flood plains, refers to water-mediated transfer of energy, matter and organisms within or among elements of riverine corridors. Inundation of flood plains is a complex phenomenon caused by different water sources via multiple pathways. Small changes in the relative contribution of individual water sources may drastically alter species composition and species diversity. For example, local groundwater upwelling is often associated with a higher standing crop of algae, higher zoobenthos biomass, faster growth rates of

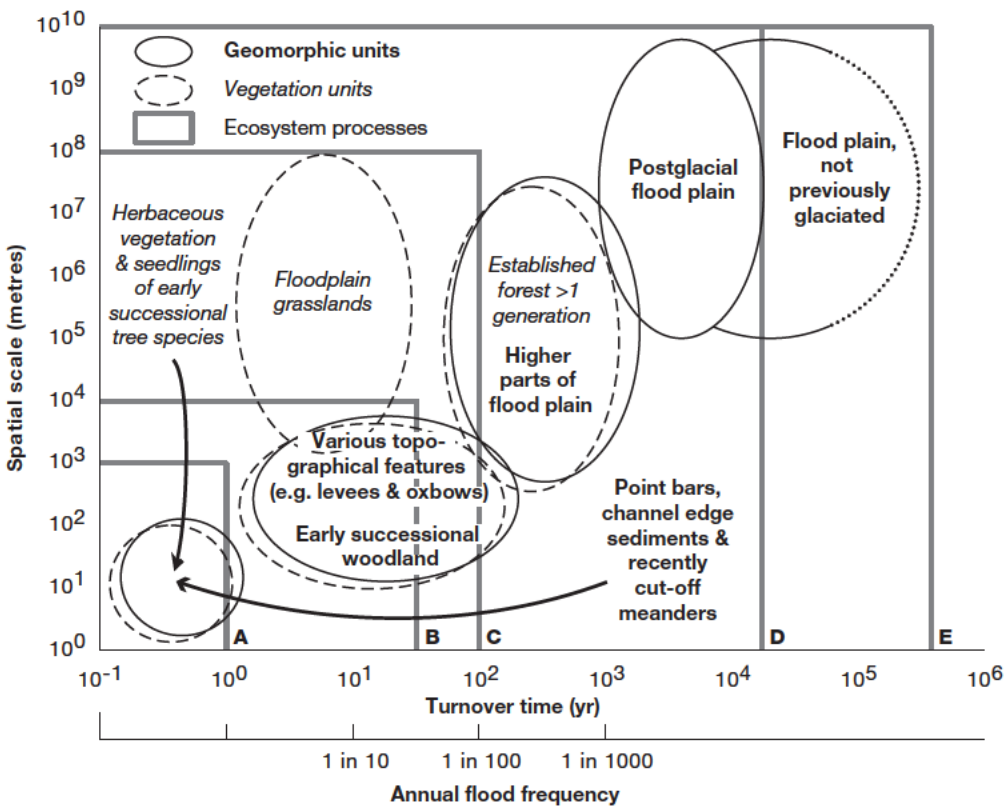

Figure 1 The organization of floodplain components and processes as a spatiotemporal hierarchy (after Hughes 1997). A = primary succession of herbaceous vegetation and early successional woody species, associated with annual flood; B = primary and secondary floodplain succession, associated with medium-magnitude/frequency floods; C = long-term floodplain succession, widespread erosion and reworking of sediment, associated with high magnitude/low-frequency floods; D = species migration upstream/downstream, local species extinction, long-term succession on terraces, and life-history strategies, associated with climate and base-level change, and the influence of postglacial relaxation phenomena on hydrological and sediment inputs to flood plains; and E = species evolution, and changes in biogeographical range, associated with tectonic change, eustatic uplift and climate change.

Table 3 The estimated relative importance of environmental factors that determine the properties of wetlands in general (after Keddy 2000) and flood plains specifically (empirical values).

Environmental factor	*Wetland (%)*	*Flood plain (%)*
Hydrology	50	60
Fertility	15	<10
Salinity	15	<5
Disturbance	15	30
Competition	<5	<5
Grazing	<5	<5
Burial	<5	<5

Table 4 Information on the relative importance (percentage) of different threats for 1880 (75%) of the 2490 imperiled species in the USA, and for amphibians and fish separately. Categories are non-exclusive and therefore do not sum up to 100 (Wilcove *et al.* 1998).

Cause	*All species* $n = 1880$	*Amphibians* $n = 60$	*Fish* $n = 213$
Habitat degradation/loss	85	87	94
Alien species	49	27	53
Pollution	24	45	66
Overexploitation	17	17	13
Disease	3	5	1

cottonwood trees and a higher species richness of woody and herbaceous plants (J.A. Stanford, personal communication 2001). Despite its overwhelming importance in flood plains, hydrology is often given only cursory attention in restoration and mitigation projects (e.g. Bedford 1996).

Human influences

Flood plains are among the most altered landscapes worldwide and they continue to disappear at an alarming rate, since floodplain 'reclamation' (i.e. elimination) is much higher than for most other landscape types (Vitousek *et al.* 1997; Olson & Dinerstein 1998; Ravenga *et al.* 2000). The net result is vast constriction of flood plains, sometimes by more than 50% of the historic expanse (Snyder *et al.* 2002). As a consequence, the decline of freshwater biodiversity, including the rich floodplain diversity, is much greater than in terrestrial systems. For example, 47% of all animals federally endangered in the USA are freshwater species (Stein 2001). Although no specific data are available, we may expect a disproportional contribution by floodplain species (see Table 2). The major factors responsible for the decline of freshwater biodiversity are habitat alteration, pollution, competition for water, invasive species and overharvest (Abramovitz 1996). Among these factors, land transformation is the single most important cause of species extinction (Vitousek *et al.* 1997). Habitat degradation and loss contribute to the endangerment of 85% of the imperiled species in the USA (Wilcove *et al.* 1998; Table 4). For freshwater groups, water development projects account for 91% of threats to endangered fish and 63% to endangered amphibians.

Habitat alteration

Habitat alteration includes both the degradation of the natural landscape and the modification of the hydrologic regime. Worldwide, more than 500 000 km of waterways have been altered for navigation and more than 63 000 km of canals have been constructed (e.g. Abramovitz 1996). In the USA, only 2% (about 100 000 km) of rivers have sufficiently high quality features to be worthy of federal protection status (Benke 1990). These free-flowing sections are often single-thread rivers that lack extensive flood plains. In Austrian rivers with catchment areas $> 500\,km^2$, it is the floodplain segments that have been most severely impacted. Today, less than 2% of former braided, anastomosing and meandering Austrian rivers are in a semi-pristine state, compared to 25% of single-thread headwater streams (Muhar *et al.* 1998).

To evaluate the effect of river regulation on selected Central European river–floodplain systems, we used shoreline length (the interface between the terrestrial and the aquatic compartments of the flood plain) as an index of habitat quality (Schiemer *et al.* 2001; K. Tockner, personal communication 2001). In dynamic systems (e.g. the Tagliamento River, Italy), shoreline length can be up to 25 km per river km and remains high throughout the annual cycle, except during major flood events. In channelized rivers, however, shoreline length drops to about 2 km per river km (Fig. 2). Reduction in shoreline length not only affects habitat availability of already endangered communities but also impedes the exchange of matter and organisms between the river and its riparian area (Naiman & Decamps 1997).

Hydrology is by far the single most important driving variable in flood plains (see Table 3). Changes in river flow alter the extent, duration and frequency of floodplain inundation. After dam closure the Nile showed a reduced annual

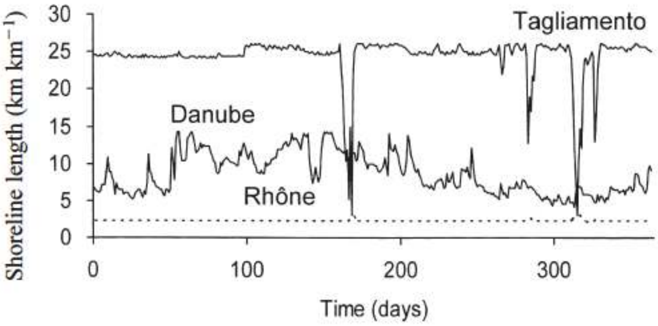

Figure 2 Shoreline length (km per river-km) in natural (Tagliamento, north-east Italy), constrained (Danube, Alluvial National Park, Austria) and channelized (Rhône, Switzerland) river-floodplain systems. All flood plains are characterized by a dynamic hydrology (Van der Nat *et al.* 2002; K. Tockner, personal communication 2001). The Rhône and the Tagliamento River are comparable in discharge and catchment area. In its pristine state, the Rhône was morphologically similar to the present Tagliamento.

discharge, truncated annual floods, higher base flow rates and a several month shift in the timing of the flood peak. The maximum-to-minimum discharge ratio decreased from 12:1 to 2:1, with far-reaching consequences for floodplain inundation (Fig. 3). The Senegal River, however, showed a gradual decrease in peak, average, and low water discharge, primarily as a result of increasing water abstraction for irrigation (Fig. 3). During the dry season, the Senegal now frequently ceases to flow. The Danube River (downstream of Vienna, Austria) has a relatively unaltered hydrology with frequent 'flood' and 'flow' pulses (Fig. 3). However, the flood plain is disconnected from the main channel by artificial levees, which drastically reduce the duration and frequency of floodplain inundation (Tockner *et al.* 2000*a,b*; see also Fig. 2).

At present, about 3800 km^3 of water is withdrawn annually worldwide, primarily for agriculture (Ravenga *et al.* 2000). Hydrological alterations by water withdrawal can be extreme in some systems; for example, less than 1% of the natural flow of the Colorado River reaches the mouth. The Murray River in Australia now discharges only 36% of its natural flow into the sea, flood duration on the fringing flood plains has decreased from two months to a matter of days, and the timing of floods has shifted from spring to late summer (Jolly 1996).

At present, more than 40 000 large dams ($>$ 15 m high) impound the world's rivers, inundating more than 400 000 km^2, increasing water storage capacity by 700%, reducing sediment transport, and changing the chemistry of river inputs, with long-term consequences for coastal ecosystems (e.g. Ittekot *et al.* 2000). Countless smaller dams modify river dynamics locally (e.g. more than 2.5 million dams $<$ 8 m high are estimated for the USA alone; Richter *et al.* 1997). In the USA, at least 90% of the total discharge of rivers is strongly altered hydrologically, mainly by damming and water abstraction (Jackson *et al.* 2001*a*).

Riverine systems are strongly threatened by changing land-use patterns in the whole catchment and especially along the riparian margin of rivers and streams. Based on data from 145 major catchments around the world (data from Ravenga *et al.* 1998), human impacts at both the catchment and the riparian level can be discerned (Fig. 4). Analysis of these data elucidates several patterns. Riparian areas are significantly more severely impacted than the total catchment (Wilcoxon matched pairs test, $p < 0.0001$, $z = 6.28$; Fig. 4*a*). The most impacted riparian corridors with respect to land use are found in Europe and in the densely populated areas in Asia (catchments with population densities $>$ 200 people per km^2; Fig. 4*b*). There, between about 60% and 99% of the entire riparian corridor has been transformed to cropland and/or is urbanized, the latter in particular in Europe. The Seine River (France) shows the highest impact of all rivers investigated. There is a positive and linear relationship between human population density and land use of the riparian zone for Asian and African rivers ($y = 0.28x + 10.41$, $r^2 = 0.73$, $p < 0.0001$; Fig. 4*b*). However, this relation is logarithmic rather than linear for European and American rivers ($y = 15.4 \ln(x) + 2.48$, $r^2 = 0.57$, $p < 0.001$; Fig. 4*b*), where riparian zones are already highly 'developed' at a low level of population density (e.g. Mississippi, USA). The present analysis only considers areas with intensive agricultural development, mosaics of cropland and natural vegetation being excluded. Low land-use values for African and many Asian river corridors, therefore, can be explained by more traditional and sustainable use of their riparian area. Based on the data, 11% of the riparian area of African rivers (mean population density: 24 people per km^2) is intensively cultivated compared to 46% for North American rivers (excluding northern Canada and Alaska; mean population density: 24 people per km^2) and 79% for European rivers (mean population density: 75 people per km^2).

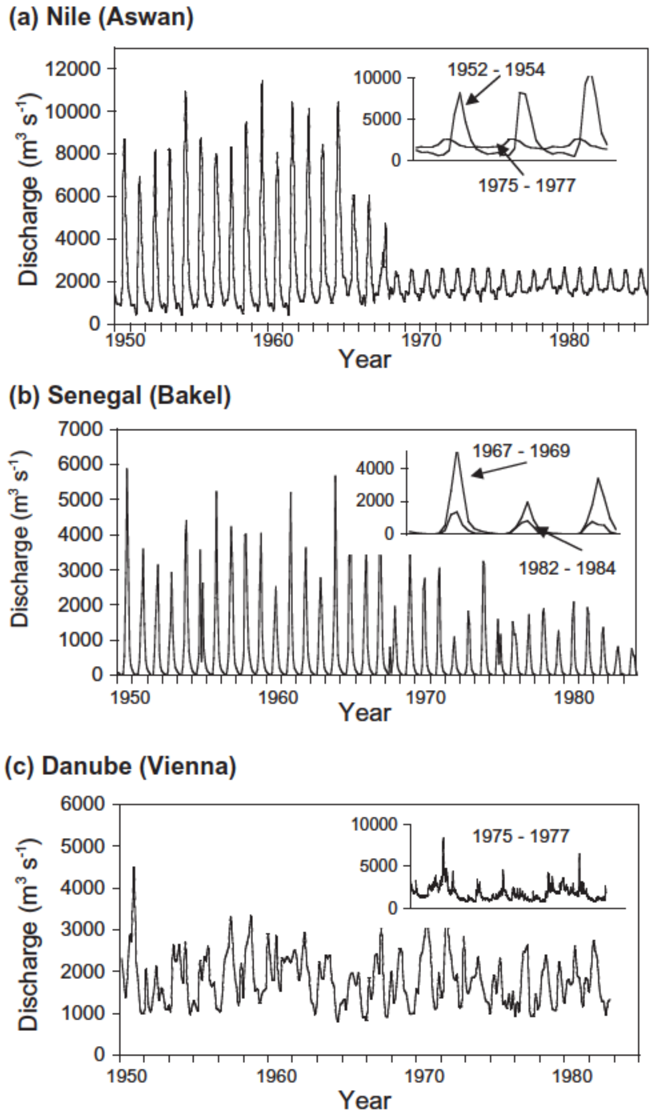

Figure 3 Discharge patterns of selected rivers: (*a*) Nile River below the Aswan dam (UNESCO 1995), (*b*) Senegal River at Bakel (UNESCO 1995) and (*c*) Danube River downstream of Vienna (WSD Wasserstrassendirektion, Vienna, unpublished data, 1996).

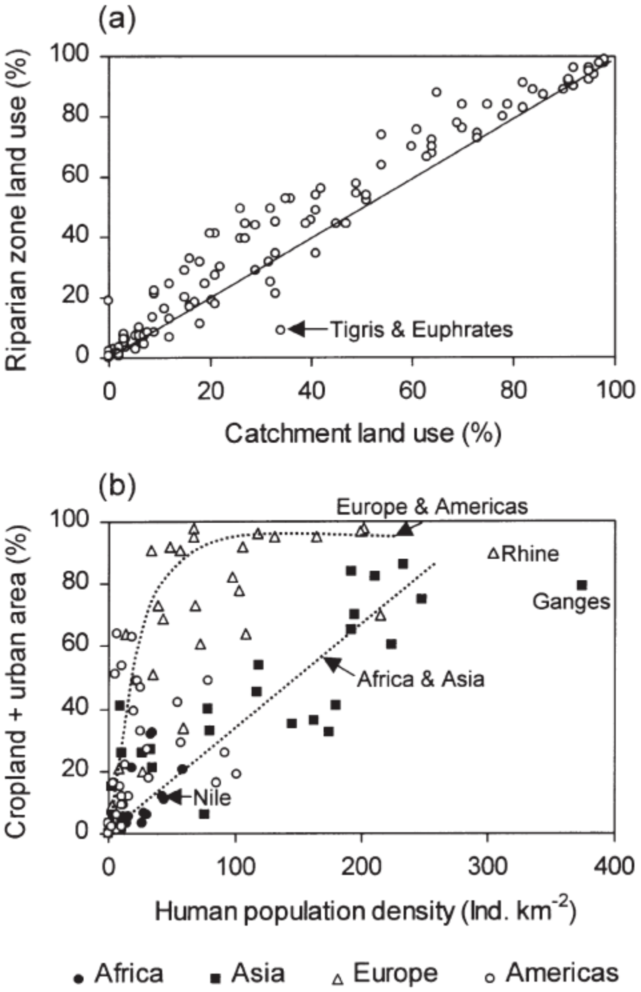

Figure 4 Land-use patterns in major catchments of the world. (*a*) Correlation between land-use in the total catchment and within the riparian corridor. (*b*) Correlation between land-use and human population density (individuals per km^2) in river catchments of different continents (data from Ravenga *et al.* 1998). Correlation between human population density and land use is indicated by broken lines for Africa/Asia and Europe/Americas. The areas of intensive agricultural land use and the urban areas were combined to calculate the relative proportion of intensively altered land for each of the 145 catchments and for riparian areas along the rivers. The riparian zone was defined as land within 5 km of major rivers within each catchment. The land-cover database was derived from 1 km resolution satellite data (April 1992–March 1993; Ravenga *et al.* 1998, 2000). The distribution of urban areas was based on satellite images of night-time lights for 1994–1995 (5 km resolution stable-light database, National Oceanic and Atmospheric Administration-National Geophysical Data Center 1998).

Species invasion

Species invasion is the second most important cause of the overall decline in aquatic biodiversity, leading to an accelerated rate of redistribution of the freshwater fauna. In riverine systems, the combination of land transformation, altered hydrology, and numerous deliberate and accidental species introductions has perpetuated widespread invasions. Many river systems are already dominated by alien species. Non-native species comprise 79% of the fish fauna of the Colorado River, 38% of the fish of the Columbia River or 21% of the fish of the Rhine River (Galat & Zweimueller 2001). The higher percentage of exotic plants and animals observed in flood plains compared to the uplands demonstrates the vulnerability of the riparian zone to invasion (Pysek & Prach 1993). In fact, the same factors supporting high diversity in riparian habitats (transport of propagules, flooding disturbance, water availability) may also increase their susceptibility to invasion by exotic species (e.g. Pysek & Prach 1993). Along the Adour River, France, 198 riparian plant species disappeared between 1989 and 1999, and, by 1999, there were 153 new species (Tabacchi & Planty-Tabacchi 2000). Today, invaders account for one-quarter of the total species richness of 1558 species and can locally constitute up to 40% of all species. Despite great differences in climate, species richness and land-use history, the proportion of invasive species along the Adour River is similar to rivers in the Pacific North-West of the USA and to South African Rivers (20–30%; Hood & Naiman 2000). In the southern USA, as a result of widespread human-induced changes in hydrology and land use, native cottonwood-willow stands are being replaced by non-native woody species such as Russian olive (*Eleagnus angustifolia*) and tamarisk *Tamarix* sp. (saltcedar). Saltcedar now covers about 500 000ha of flood plain in the western USA, its superior drought tolerance relative to native phreatophytes and its ability to produce high density stands and high leaf area indices being major reasons why it is favoured by in-stream flow reductions (e.g. Cleverly *et al.* 1997). Based on a cost-benefit calculation, the presence of saltcedar in the Western USA will cost an estimated US$ 7–16 billion in lost ecosystem function within the next decades (*c.* US$ 15 600–24 600 ha^{-1}; Zavaleta 2000).

Pollution

Species composition and productivity of flood plains are influenced by the quality of the inflowing water. Artificially high nutrient inputs, for example, lead to an impoverishment of floodplain communities (e.g. lower Rhine; Van den Brink *et al.* 1996). Alternatively, the flood plain itself can serve as a major source of nutrients and pesticides when intensively cultivated; along many south-east Asian rivers huge amounts of pollutants are discharged into the main river during seasonal floods (e.g. Dudgeon 2000*b*).

In developing countries an estimated 90% of wastewater is discharged directly into rivers and streams without treatment, and in many parts of the world rivers are so polluted that their water is unfit even for industrial uses (Johnson *et al.* 2001). In China, 80% of the 50 000 km of major rivers are too polluted to sustain fisheries and in 5% fish have been completely eliminated (FAO [Food and Agricultural Organization of the United Nations] 1999). Despite major treatment efforts, pollution is still a major problem in the

Northern hemisphere (e.g. Van Dijk *et al.* 1994). For example, 75% of the water in the Vistula, Poland's largest river still containing many semi-natural flood plains, is unsuitable even for industrial use (Oleksyn & Reich 1994). High nutrient concentrations of the parent river are also a major obstacle to restoring flood plains along many rivers such as the Danube or the Rhine (Buijse *et al.* 2002).

PREDICTED LONG-TERM TRENDS

Because rivers and wetlands are among the most threatened ecosystems worldwide (Vitousek *et al.* 1997; Ravenga *et al.* 2000), one of the major challenges is to meet increasing resource demands of a burgeoning human population while conserving aquatic ecosystems and the ecological services they provide for future decades. Many developing countries will experience a large increase in the relative water demand, in particular due to rapidly expanding cities (Vörösmarty *et al.* 2000; Johnson *et al.* 2001). Flood plains are particularly sensitive to changes in river hydrology, to increased alterations of the land–water interface, and to inputs of nutrients and toxicants (e.g. Naiman & Décamps 1997; Ward *et al.* 1999*a*; Nilsson & Berggren 2000; Ravenga *et al.* 2000).

Changing water cycle

Within the next decades, the sharp increase in human population combined with economic expansion will lead to greater pressures on freshwater resources, mainly through infrastructure development, water abstraction for agriculture and industry, conversion of land for resource development, and expansion in water withdrawal and consumption (e.g. Fig. 5). The effects of growing water consumption will be accentuated by land-use changes and by changes in the flow and flood

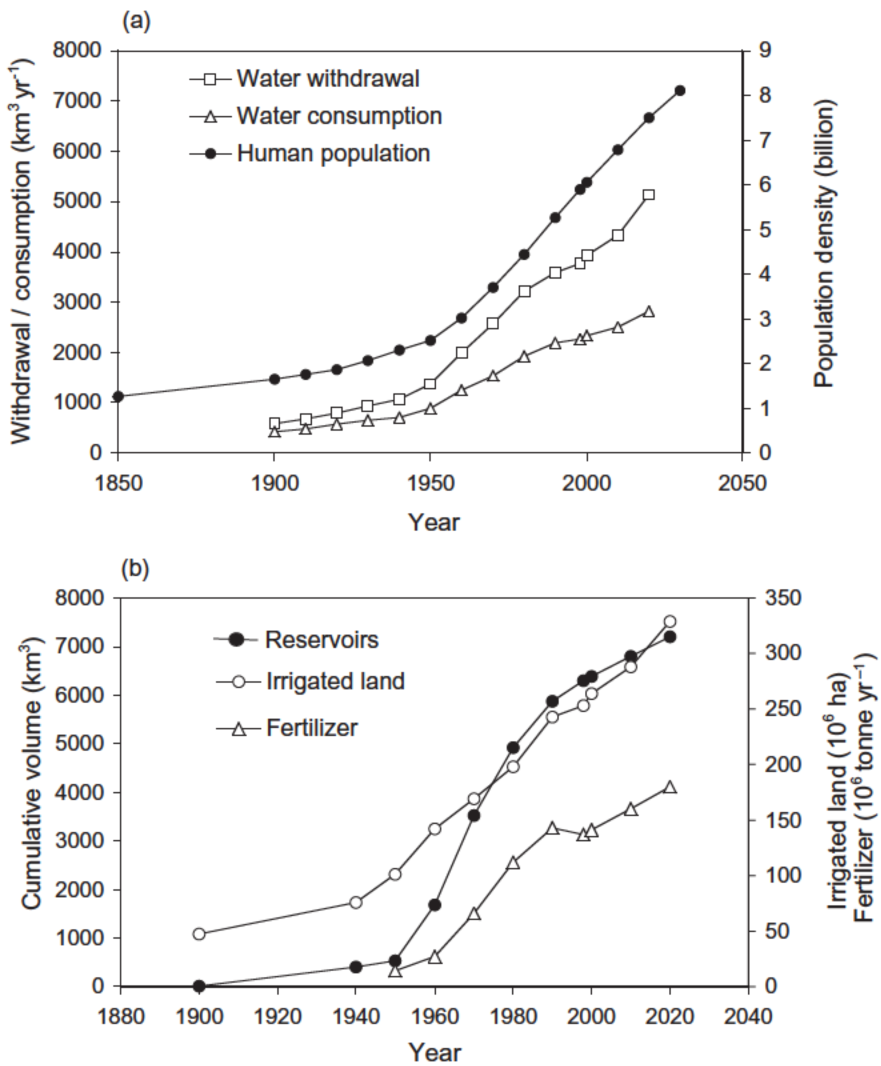

Figure 5 Global long-term trends with forecast to 2025 of (*a*) human population growth (UN 1998), water withdrawal and water consumption (Shiklomanov 1998) and (*b*) reservoir volume (Cosgrove & Rijsberman 2000), irrigated land (Gleick 2000) and total use of fertilizers (Worldwatch Institute 2001).

regime driven by climate change (IPCC [Intergovernmental Panel on Climate Change] 2001). This growing imbalance among freshwater supply, consumption and human population will cause a great intensification of the Earth's hydrological cycle (e.g. Jackson *et al.* 2001*a*). In the year 2025, 17–50% more water for irrigation will be needed. A rise of only 17% will be achieved only if water use efficiency is as high as 70%, food consumption per person does not increase, and the relative contribution of irrigation to food production remains constant (Fig. 5). Most of the increase in irrigation will occur in the developing countries, particularly in south-east Asia and Africa (Serageldin 1999). In Europe, future quantitative pressures on natural water resources might tend to stabilize in the central and northern countries, but will increase greatly in the southern and eastern countries. Increases of up to 100% by 2025 have been predicted for many Mediterranean countries making the remaining wetlands and flood plains particularly vulnerable (Margat & Vallee 1999).

About 300 large dams (> 15 m) are currently built every year, in particular in developing countries (Fig. 5). New dams, despite major concern about expected environmental and socio-economic impacts will threaten most of the present large free-flowing rivers. In the Brazilian Amazon alone, a total of 79 major hydrologic dams (100–13 000 MW) are planned. As many as 278 dams could be constructed in the La Plata basin in Argentina and 32 dams are either planned or have been built in the Magdalena basin, Colombia (Pringle 2001). Along the mainstem Mekong River, 12 sites for dams have been identified that will completely alter the ecosystem (Dudgeon 2000*c*). The Three-Gorges dam along the Yangtze River will probably not be able to prevent future damage by floods, a major rationale for its construction. The hydraulic retention capacity of the impounded reservoir only compensates for the natural retention capacity of floodplain lakes lost during the last decades (e.g. the Dongtin floodplain lake alone lost about 40% of its immense volume between 1954 and 1983; Zong & Chen 2000).

Projected changes during the 21st century caused by climate change include more intensive precipitation events over many areas (very likely), increased summer drying over most mid-latitude continental interiors and associated risks of drought (likely) and higher minimum temperatures (very likely; IPCC 2001). Changes in climate could increase the risk of abrupt and non-linear changes in many ecosystems, which would affect their function, biodiversity and productivity. A warming of 3–4°C is predicted to eliminate 85% of all remaining wetlands (UNEP-WCMC [United Nations Environment Programme-World Conservation Monitoring Centre] 2001). The flow regime of the River Rhine, for example, will change from a combined rain-fed/snow-fed to a predominantly rain-fed regime, associated with an increase in interannual variation and larger floods (Middelkoop & Kwadijk 2001). Projected effects for flood plains include low water during the growing season and higher water temperatures. The return period of extreme precipitation events will decrease almost everywhere. In 2070, for example, floods that presently have 20-year return periods are projected to occur twice as often (Zwiers & Kharin 1998). For North Carolina, USA, an increase in precipitation of 15% (5–30%) is predicted by 2100, which will shift floodplain boundaries and make recent human developments in floodplain areas especially vulnerable to flood damage. Similar effects are predicted for the Pacific North-West.

Changing floodplain area

Accurate global assessments of wetland extent are elusive due to their complexity and highly dynamic nature (Finlayson & Davidson 1999), but, based on recent estimates, wetlands cover nearly 10% of the Earth land surface; of these 2% are lakes, 30% are bogs, 26% are fens, 20% are swamps and 15% are flood plains (Ramsar & IUCN 1999). Estimates of floodplain area vary as a function of the criteria used to delineate them. The area of a flood plain can be delineated by hydrologic (area inundated by a 100-year flood), geomorphic (area covered by recent alluvial deposits) or ecological criteria (area colonized by organisms adapted to flooding).

In the following, we provide an overview of global floodplain distribution patterns and discuss their present and future state. This is a difficult task since many estimates of floodplain size are based on old references, and there are major inconsistencies between different sources (see Table 6 later). An added difficulty is that adequate information on the extent and status of flood plains is not available for large geographic regions, such as the central and eastern parts of the former USSR. Flooding along the Lena River in the year 2000, as a result of extensive ice-jams, has shown that vast areas of lowland Siberia are composed of fringing flood plains. At a global scale, total floodplain area estimates vary from 0.8×10^6 km^2 (Aselmann & Crutzen 1989) to 1.65×10^6 km^2 (flood plains and swamps; Constanza *et al.* 1997) to 2.2×10^6 km^2 (flood plains along rivers and lakes; Ramsar & IUCN 1999).

Flood plains vary markedly in size. The largest gap and uncertainty in floodplain characterization is the size and duration of floodplain inundation. Sahagian and Melack (1998) suggested that floodplain extent should be expressed in terms of hectare-days (or equivalent units), thereby allowing both spatial and temporal analysis of key ecological and biogeochemical functions. In Table 5, we list expansion and contraction patterns of selected flood plains. The large geographic differences in the timing and the extent of flooding are further complicated by human impacts such as water abstraction and regulation. Along the lower Mississippi, for example, the ratio of high water (HW):low water (LW) area decreased from about 17 before regulation to < 5 at present (Table 5). Decline in inundation area is often associated with a shift in inundation timing (e.g. Nile River; Fig. 3). Most flood plains experience large seasonal and interannual fluctuations. Flood plains in the Mediterranean as well as in other dry areas are particularly sensitive to

Table 5 Inundated floodplain area (km^2) at low water (LW) and high water (HW), the timing of flooding and the ratio of HW:LW areas for selected temperate and tropical floodplain rivers. [1] Floodplain segment; flooding may occur at any time of the year; [2]channel network length (km); [3]frequently, there are also winter floods; and [4]seasonal flood regime has been greatly modified during recent decades.

Flood plain	*Low water (LW)*	*High water (HW)*	*Timing of flood*	*HW:LW*	*Reference*
Europe					
Tagliamento (Italy)[1]	0.10	1.43	Oct–Nov	14.3	Van der Nat *et al.* (2002)
Danube (Austria)[1]	0.52	5.2	Apr–June	10	Tockner *et al.* (2000b)
Val Roseg (Switzerland)[2]	5.8	21.2	June–Sept	3.7	Tockner *et al.* (1997)
Lower Rhine (The Netherlands)[3]	118.1	384.3	Apr–June	3.3	T. Buijse (personal communication 2001)
Americas					
Ogeechee	0.10	7.46	Feb–Apr	75	Benke *et al.* (2000)
Lower Mississippi (before regulation)	2550	42 825	Mar–June	16.8	Baker *et al.* (1991)
Lower Mississippi (present)[4]	1620	7970	Mar–June	4.9	Baker *et al.* (1991)
Orinoco: fringing flood plain	400	7000	July–Sept	17.5	Hamilton and Lewis (1990)
Amazon (Brazil, mainstem)	19 000	91 000	May–July	4.8	Sippel *et al.* (1998)
Africa					
Hadejia-Nguru (Nigeria)	4.9	2350	July–Oct	480	Hollis *et al.* (1993)
Senegal flood plain (Senegal, Mauretania)	500	4560	Aug–Sept	9.1	Howard-Williams and Thompson (1985)
Sudd (Sudan)	10 000	92 000	Aug–Sept	9.2	Rzóska (1974)
Barotse plain (Zambia)	330	5120	Mar–Apr	15.6	Welcomme (1975)
Pongolo River (South Africa)	26	100	Jan–Feb	3.8	Heeg & Bren (1982)
Kafue flat (Zambia)	13 000	28 000	Feb–Apr	2.2	Thompson (1996)
Chari & Lagone rivers (Chad system)	6300	63 000	July–Dec	10	Thompson (1996)

Table 6 Distribution and extent of selected fringing riverine flood plains (including a few rain-fed flood plains). Area of flood plain is during the season of maximum inundation. [a] The reported areas differ substantially between reference sources: Upper Nile Swamps (Sudd): > 30 000 km^2 (Mitsch & Gosselink 2000), 50 000 km^2 (Groombridge 1992) and > 90 000 km^2 (Howard-Williams & Thompson 1985). Central Niger Delta: 30 000 km^2 (Howard-Williams & Thompson 1985) and 320 000 km^2 (Mitsch & Gosselink 2000). Middle Congo depression: 70 000 km^2 (Howard-Williams & Thompson 1985) and 200 000 km^2 (Mitsch & Gosselink 2000). Several major 'flood plains' listed are composed of different wetland types including swamps, wet grasslands or shallow lakes (e.g. Kagera valley, Central Congo basin, Sudd, Orinoco delta). [b] Data compiled by Howard-Williams and Thompson (1985) and Thompson (1996). Flood plains in Mozambique or Angola are not included since not enough information was available at the date of compilation (Howard-Williams & Thompson 1985; Thompson 1996). [c] Dadnadji and Van Wetten (1993) report that wetlands along the Lagone and Chari cover 78 000 km^2 including inundated flats, riverine floodplains, marshes and smaller lakes. [d] Plantations cover 50% of the remaining flood plains.

Drainage system/geographic area	*Area (km^2)[a]*	*Major flood plains/reference*
Africa[b]		
Zaire/Congo system	70 000	Middle Congo depression, Kamulondo, Malagarasi
Niger/Benue system	38 900	Niger central delta, Benue River
Nile system	93 000	Sudd, Kagera basin
Zambesi system	19 000	Kafue flats, Barotse plain, Liuwa plain
Western systems	19 000	Flood plains along the Senegal (excluding delta), Volta and Ouémé
South-east systems[b]	100	Pongolo flood plain
Eastern systems	8600	Kilombero, Rufiji, Tana River
Chad system[c]	63 000	Chari & Lagone River system
Gash River	3000	Inner Delta in Sudan (primarily woodland and savannah; Kirkby & O'Keefe 1998)
Tana Delta	670	Endangered by upstream dams
Europe		
Switzerland	110	In total, 169 flood plains of national importance (BUWAL 1993)
The Netherlands	498	Area regularly flooded by rivers (primarily meadows; Yon & Tendron 1981)
Danube National Park (Austria)	93	The last remaining semi-natural flood plain along the Upper Danube (Tockner *et al.* 2000*a*)
Tagliamento	150	The last morphologically-intact river corridor in the Alps (Ward *et al.* 1999*b*)
Lonjsko polje (Save River, Croatia)	507	One of largest and best preserved flood plains in Europe (Spanjol *et al.* 1999)

Drainage system/geographic area	*Area (km²)[a]*	*Major flood plains/reference*
Kopacki rit (Croatia)	177	Semi-natural flood plain at the intersection of the Danube and the Drava (Spanjol *et al*. 1999)
Upper Rhine	70[d]	Originally, flood plains covered 1000 km^2 (Carbiener & Schnitzler 1990)
French Rhône (fringing flood plain)	70	Mostly functionally extinct flood plains. Former extent: 830 km^2 (Bravard 1987)
Rhône (delta, Carmargue)	750	Former delta: 1644 km^2 (Bravard 1987)
Guadiana River (Spain)	450	Floodplain marshes in the Donana National and Nature Parks (Benayas *et al*. 1999)
Danube delta	5800	Danube Delta Biosphere Reserve, *c*. 50% this area belongs to the 'Danube Delta' (Riza 2000)
Danube islands (Bulgaria)	107	75 islands in the main stem (Bulgarian Ministry of Agriculture and Forests 2001)
Dnieper River delta (Ukraine)	*c*.500	Hydrologic impact by unpredictable flood releases from upstream dams, pollution (Timchenko *et al*. 2000)
Volga delta	18 000	Largest European delta (Czaya 1981)
Tisza (Hungary, Ukraine, Romania)	1800	Remaining area represents only 4.7% of former flood plains (Haraszthy 2001)
Poland	820	Originally, flood plain forests covered 27 800 km^2 (Sienkiewicz *et al*. 2001)
European part of Russia	9000	Approximate estimation (Shatalov 2001)
North America		
Ogeechee	150	Subtropical river in south-east USA (Benke *et al*. 2000)
Kissimmee (Lower basin)	180	Disconnected at present, will be partly restored (e.g. Warne *et al*. 2000)
Altamaha and Tone Rivers	400	Mertes (2000)
Upper Mackenzie river	60 000	A complex of marshes, fens and flood plains (Fremlin 1974)
Mackenzie delta	13 000	Including 24 000 lakes (Marsh *et al*. 1999)
Lower Missouri River flood plain	7700	At present mainly agricultural land (D. Galat, personal communication 2001)
Mississippi River flood plain	20 000	Remaining bottomland hardwood forests out of formerly 85 000 km^2 (Llewellyn *et al*. 1996)
Rocky Mountain states (USA)	*c*. 4000	Abernethy and Turner (1987)
Washington and Oregon	12 500	Abernethy and Turner (1987)
Alaska	120 000	*c*. 50% of present floodplain area in USA (Mitsch & Gosselink 2000)
South America		
Amazon River	890 000	Large and small river flood plains combined (Aselman & Crutzen 1989; Sippel *et al.* 1998)
Orinoco delta	30 000	Complex of flood plains, marshes and swamps (Groombridge 1992)
Orinoco fringing flood plain	7000	Hamilton and Lewis (1990)
Pantanal	130 000	The 'largest' single wetland complex on earth (Hamilton *et al.* 1996)
Parana	20 000	Fringing flood plains (Welcomme 1979)
Magdalena	20 000	Deltic flood plain (Welcomme 1979)
Flooding Pampa grassland (Argentina)	90 000	80% of the area still covered by natural grasslands, fed by rain (Perelman *et al*. 2001)
Asia		
China	80 000	Riverine and partly lacustrine wetlands in the Yangtze and Yellow-Huaihe Basin (Lu 1995)
Lena and Yana deltas	38 700	Largest northern delta complex
Mekong (Kampuchea)	11 000	Inundated forests along the Mekong and the shores of Le Grand Lac (Pantulu 1986)
Irrawady (Burma)	31 000	Welcomme (1979)
Indonesia	119 500	Primarily in Kalimantan and Irian Jaya (Lehmusluoto *et al*. 1999)
Bangladesh	98 000	Primarily cultivated, including 28 000 km^2 of rice fields (Welcomme 1979).
Ganges and Brahmaputra (India)	23 000	Flood prone area, heavily cultivated (FAO 2001)
Yellow River (China)	120 000	Including parts of the Hai and Huai Rivers (DHI Water & Environment 2001)
Tigris and Euphrates	20 000	Mesopotanic region; cultivated flood plain (Al Hamed 1966); about 7600 km^2 has disappeared since 1973 (UNEP 2001)
Australasia		
Fly River (Papua New Guinea)	45 000	Swales *et al*. (1999)
Kakadu National Park (Australia)	260	13% of the park area (Gill *et al*. 2000)
Chowilla anabranch (Australia)	200	Largest remaining natural floodplain forest along the lower Murray River (Jolly 1996)
Cooper Creek and Paroo River (Australia)	106 000	Endorheic flood plains in Central Australia (Kingsford *et al.* 1998)

hydrologic alterations, and they will experience a major future reduction in the HW:LW ratio.

In Africa, by far the most extensive wetlands are seasonally-flooded savannah and forested flood plains, which comprise nearly half of the total wetland area of that continent. Howard-Williams and Thompson (1985) listed 44 large African flood plains or wetlands that have major floodplain elements. Nineteen of these floodplain complexes cover a total area of 307 000 km^2 (Thompson 1996). This is probably a great underestimation since large areas like the Central Congo basin (at least 100 000 km^2) or flood plains along the rivers in Mozambique and Angola as well as the countless smaller flood plains are not included. Many of the large African flood plains are still relatively untouched, however they are disappearing or are being transformed at an accelerating rate as a result of water management activities, in particular by large-scale irrigation schemes and the ongoing construction of dams (Fig. 3). For example, the inundated area of the Hadejia-Nguru flood plain in northern Nigeria decreased within the last decade from 2350 km^2 to between 700 and 1000 km^2 as a result of altered hydrology (Barbier & Thompson 1998). The floodplain forests of the Tana River (Kenya) are drying up mainly because of the truncation of floods by the construction of upstream dams (e.g. Hughes 1988). In many Sahelian flood plains, water depth is very shallow during inundation, making them extremely sensitive to even minor hydrological changes (e.g. Senegal River; Fig; 3). For example, the flood plain of the Sudd (Sudan) is covered on average by water of about 1 m depth, although the area inundated can be up to 90 000 km^2. Along the Nile, the construction of the Aswan High Dam completely changed the seasonal flood dynamics. Effects persist for more than 1000 km downstream, with further impacts on the fisheries of the Eastern Mediterranean, erosion of the deltic area and salt intrusion upstream (Abu Zeid 1989).

North America has lost about 50% of its original wetland cover. The largest decline of any wetland category was for forested freshwater wetlands, primarily riverine flood plains. Originally, flood plains covered 7%, or about 700 000 km^2, of all land in the USA (Kusler & Larson 1993). Nowadays, pristine flood plains are primarily limited to Alaska, where about 50% of the extant flood plains occur. Along the Missouri River in the state of Missouri, between 1879 and 1972 channel length was shortened by 73 km, aquatic surface area decreased by 50%, 97% of islands and 63% of the riparian forest disappeared, cultivated land increased by 65% and commercial fishery yield dropped by 85% (Galat *et al.* 1998). Along the Mississippi 90% of the flood plain (former area: 123 000 km^2; Sparks *et al.* 1998) is leveed. During the 1993 flood, however, about 70% of the 2530 km long artificial levees were damaged (Myers & White 1993). Remaining floodplain forests on the Mississippi alluvial plain downstream of the Ohio River confluence cover 18 700 km^2, corresponding to a loss of about 80% of the original cover (Llewellyn *et al.* 1996). During the great flood in 1927, however, flood waters of the Mississippi inundated about 52 000 km^2 downstream of Cairo, Illinois, USA. Along the Upper Mississippi, 10 380 km^2 of flood plain are still unleveed and retain seasonal flood pulses, one of the few such situations in the developed world.

About 20% of the South American tropical lowlands are regularly flooded (Junk 1997, 2002). In the upper Amazon basin, 26% of the present-day lowland forests have the characteristics of recent erosional and depositional dynamics, and 12% are in successional stages along the active river channels (Salo *et al.* 1986). Along the Peruvian lowland Amazon (including local tributaries) about 100 000 km^2 are classified as flood plains (Krist & Nebel 2001).

In Siberia, the Lena River forms the largest northern delta and contains up to 150 separate river branches. In China, more than 600 000 km^2 are covered by wetlands, although about 60% are artificial (mainly paddy fields; Lu 1995). In 1953 and 1998, the Yangtze River (China) flooded areas of 475 500 km^2 and 212 000 km^2, respectively, killing thousands of people and causing immense economic damage (Zong & Chen 2000). In Bangladesh, the landscape itself has an average age of less than 10 000 years, and the entire nation has essentially been created on a giant flood plain, the world's largest delta (Khalil 1990). More than 20% of the country is regularly flooded (23 000 km^2), with up to 70% inundation during an extreme flood event (e.g. in 1988). However, most of this giant flood plain has been transformed into productive agricultural land supporting one of the world's most densely populated regions. The use of climate change models predicts substantial increases in mean peak discharges within the next decades (Mirza 2002). Asian flood plains are likely to experience the greatest change within the near future (Dudgeon 2002). The main threats will be: deforestation and drainage-basin alterations that destroy in-stream and riparian habitats; river regulation including flow modification; pollution; and overharvesting (mainly fish and reptiles). The damming of the Tigris and Euphrates led to a dramatic drying of large parts of the Mesopotanian flood plains, one of the world's most significant wetland complexes and a biodiversity centre of international importance, with several endemic species now at risk of extinction. During the last decades more than 9000 km^2 of Mesopotanian wetlands disappeared (UNEP 2001).

In Australia, the combined area of flood plains along the Murray River is about 1000 km^2, with most of the individual flood plains being < 10 ha in size (Mackey & Eastburn 1990). Along Cooper Creek and the Paoo River in Central Australia, one of the world's largest endorheic drainage systems (catchment: 1.14×10^6 km^2), up to 106 000 km^2 become flooded (Kingsford *et al.* 1998). During major floods, water spreads over a maximum width of 60 km. In arid Australia climate change will result in a drying or reduced frequency of large flood events with catastrophic effects for many biota, particularly water birds, which use a mosaic of wetland habitats at broad spatial scales (Roshier *et al.* 2002).

European flood plains are presently in a critical situation (e.g. Wenger *et al.* 1990; Klimo & Hager 2001). European wetlands (excluding the European part of Russia) cover 404 000 km^2, about 4.4% of the land surface (WWF [World Wide Fund for Nature] & EU [European Union] 2001). This is a rough estimate since an adequate database is available for only six out of 44 countries. Overall, about 50% of the original wetlands are lost; however, the rate is much higher for riverine flood plains with a loss of up to 95% (Table 6). In Hungary, for example, as recently as the end of the 19th century, the lowland river Tisza, the largest Danube tributary, transformed half of the Great Hungarian Plain into a giant flooded lake almost every year at the time of the melting snows (Fig. 6). Lateral damming has reduced the flood plain by > 90%. However, during recent years, severe floods again inundated the entire former flood plain causing major damage. Switzerland has lost about 95% of its original flood plains during the last two centuries. The remaining areas, which are included in the inventory of 'flood plains of national importance', are heavily influenced by water abstraction, gravel mining, and fragmentation (BUWAL [Bundesamt für Umwelt, Wald und Landschaft] 1993). Eighty per cent of the flood plains of national importance are decoupled from the hydromorphological dynamics of the river. Today, the largest remaining floodplain fragment in Switzerland covers an area of only 3 km^2.

Many of the remaining European flood plains are far from pristine and have lost most of their natural functions. For example, of the former 26 000 km^2 floodplain area along the Danube and its major tributaries, about 20 000 km^2 were separated by levees and have therefore become 'functionally' extinct, which means that the basic attributes that sustain the flood plain such as regular flooding or morphological dynamics are missing (Busnita 1967; Nachtnebel 2000). The fringing flood plains along the Austrian Danube between Vienna and Bratislava have been designated as an internationally recognized national park, despite major morphological and hydrological modifications and heavy nutrient loads of the parent river (Tockner *et al.* 2000*b*). Although greatly impacted, these floodplain segments deserve protection since they are the most valuable areas remaining along the entire corridor. These flood plains show still a high degree of reversibility making them suitable focal points for restoration (e.g. Schiemer *et al.* 1999).

Because > 90% of European flood plains are already 'cultivated', even impacted systems that retain some semblance of natural functions, such as flood plains along the Oder River (Poland/Germany), the Danube River, or along eastern European river corridors, are worthy of protection.

Wetlands and flood plains are inhabited by a variety of 'endemic' human societies that are well adapted to wetland conditions and that have developed a rich local culture. Many of these people are already listed as threatened by the Society of Threatened Peoples (http://www.gfbv.de), and there is a great risk that the ongoing environmental impact on large river-floodplain complexes will also increase the future risk of their extinction. Examples include the Lozi people in the Borotse flood plain, the Tonga people in the Kafue

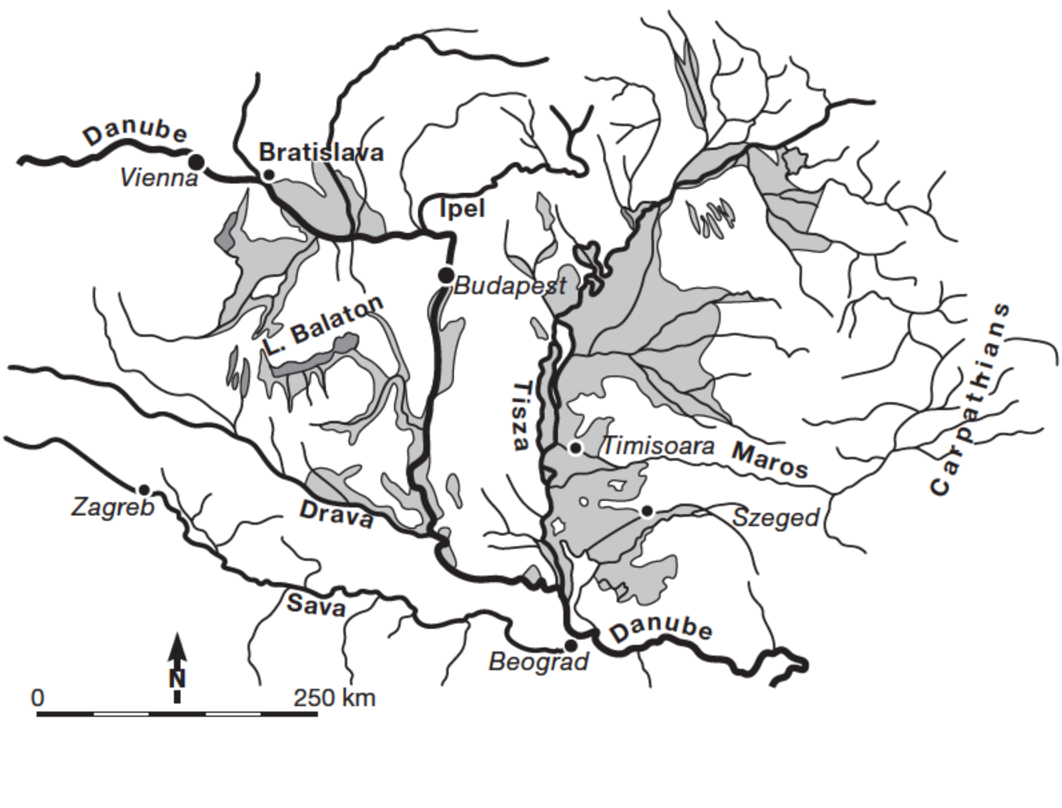

Figure 6 Former flood plains (grey areas) in Hungary and the neighbouring territories (redrawn from Czaya 1981).

flood plain, or the Ogani in the Niger delta; the latter are threatened by oil exploitation in addition to changing hydrology. The Nuer, Dinka and Shiluk in the Sudd area (Nile) are threatened by civil war and by the construction of the Jonglai Canal (see Society for Threatened People, http://www.gfbv.de). The Mesopotamian 'Marsh Arabs' (population size: 350 000–500 000), the ethnic link between present inhabitants of Iraq and the people ancient to Mesopotania, such as the Sumerans and Babylonians, are largely affected by the drying of wetlands, seeking refuge in nearby areas and urban centres (UNEP 2001).

Changing floodplain structure

A major way that fluvial processes influence biodiversity is the turnover of floodplain alluvium. One measure of turnover is the minimum age of the oldest parts of the floodplain sediment. Hughes (1997) reported sediment ages ranging from 100–600 years for most minimally impacted alluvial rivers, and 2000 years for the Amazon. This means that different spatio-temporal scales have to be considered in order to evaluate the effect of anthropogenic and natural impacts on riverine flood plains (see Fig. 1). For example, the duration of floods has been the most important variable driving riparian dynamics of the Yampa River, Colorado, USA (Poiani *et al.* 2000). With no flooding the predicted abundance of mature cottonwood would decrease from 40% at present to about 20% within a period of about 120 years, and would disappear completely in about 450 years (Fig. 7*a*). A similar story has been documented for the Old Man River in Alberta, Canada (Rood & Heinze-Milne 1989) and the Missouri River, Montana and South Dakota, USA (Johnson 1992). Flow stabilization below dams reduces floodplain size and flooded extent (Ward & Stanford 1995; Molles *et al.* 1998; Snyder *et al.* 2002). The effects of this reduction include disruption of the riparian ecosystem, alterations of trophic structure, and reduced diversity of organisms highly adapted to periodic inundation and the associated input of nutrients and sediments. Along Alpine rivers (e.g. the Isar and the Lech; Fig. 7*b*), areas with secondary successional stages of vegetation expanded dramatically after dam construction, leading to $>90\%$ decrease of pioneer communities within a period of less than 70 years. A post-dam equilibrium dominated by later successional species could be reached in about 150 years following dam closure. This projection excludes other potential land-use practices such as clear-cutting. However, flow regulation can permit widespread development of novel wetlands such as the productive and diverse marshes as along the Colorado River downstream of Glen Canyon Dam (Stevens *et al.* 1995).

In Europe, dense floodplain forests (e.g. Petts *et al.* 1989) fringe formerly braided rivers (e.g. the Upper Danube). These extensive forests are largely an ecological legacy of past flooding. These stands, although considered as extremely worthy for protection, are senescent, and in the absence of flood disturbance will not be replaced.

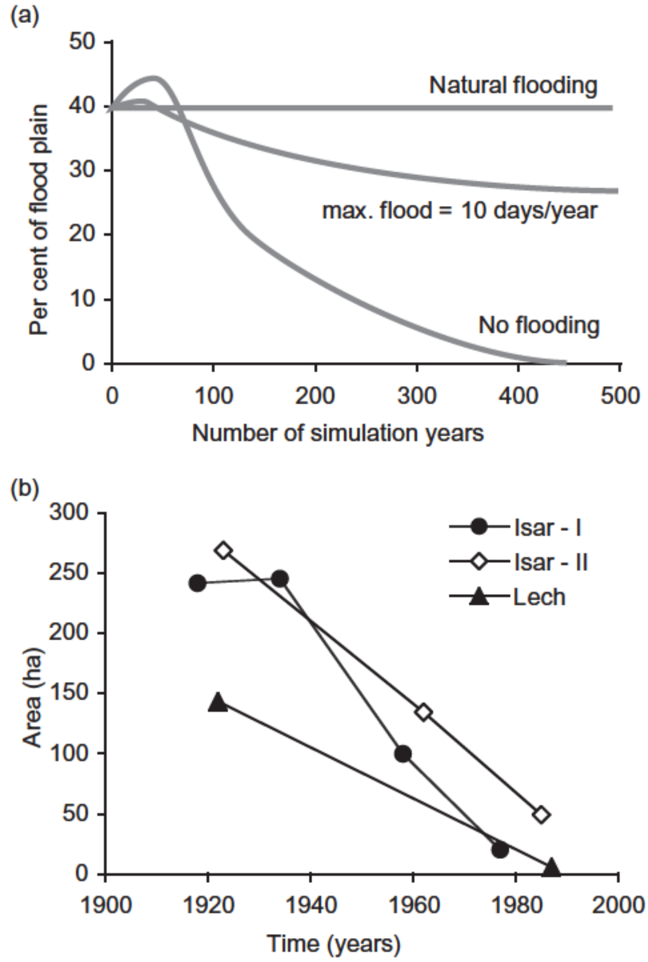

Figure 7 Changes in the riparian vegetation as a result of altered hydrology. (*a*) Simulation of riparian dynamics for the Yampa River in Colorado, USA. Variability in percentage of the flood plains occupied by mature cottonwood patches within the riparian ecosystem is predicted over a 500-year period under three different flooding scenarios (after Poiani *et al.* 2000). (*b*) Headwater flood plains in the Northern Alps (Isar and Lech Rivers, Germany) showing decrease in floodplain area occupied by early successional stages of riparian vegetation since 1900 (after Reich 1994).

Declining biodiversity

In the near future, flood plains will remain among the most threatened systems, and they will disappear faster than any other wetland type. In particular, Asian, African and South American flood plains will disappear at accelerating rates. The twelve most species-rich countries (based on total number of species and number of fish species per 1000 km^2) are all in the developing areas (except the USA which ranks sixth in total number of species), with gross primary productions of mostly $<$ US\$ 1000 yr^{-1} (based on the 1997 index). These countries will experience a rapid population growth combined with economic development that will increase the

Table 7 Vertebrate species listed as endangered in Africa, Asia and the Americas (IUCN 2000). Many of the species listed are wetland/floodplain species.

Group	*Africa*	*Asia*	*South America*	*North America*
Fish	104	216	103	190
Amphibians	12	47	27	27
Reptilians	29	104	76	35
Bird	53	521	353	84
Mammals	89	515	263	94
Total	287	1403	822	330

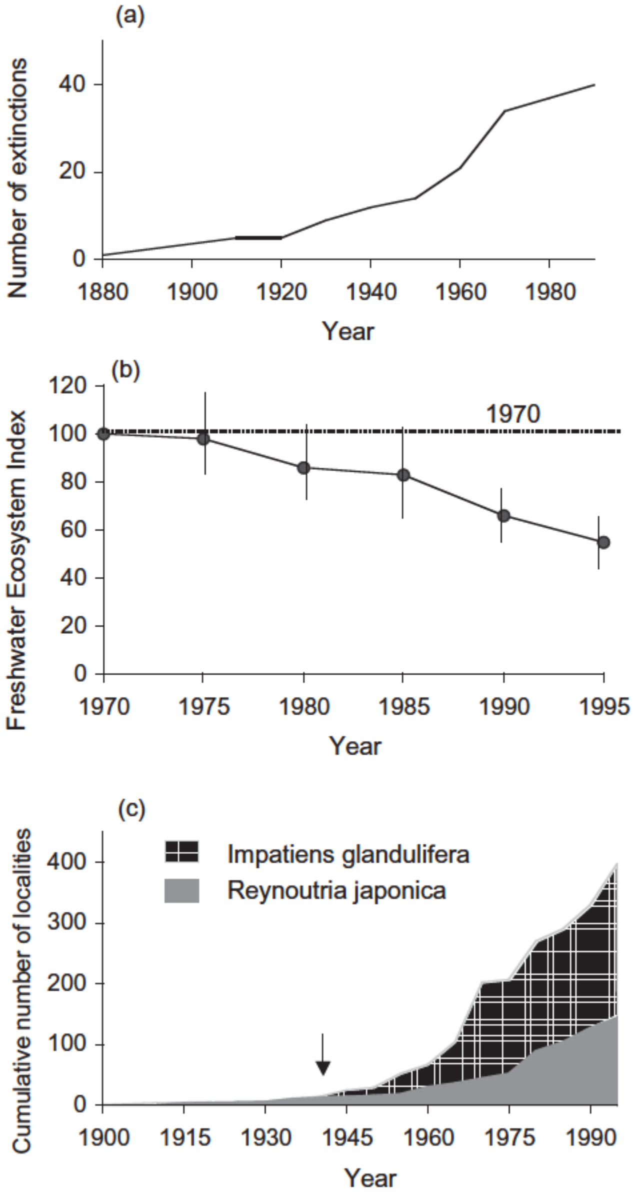

Figure 8 Long-term trends in freshwater systems: (*a*) cumulative fish extinctions in North America from 1880 to 1990 (Stiassny 1996), (*b*) Freshwater Ecosystem Index (average and 95% confidence limits) showing long-term decline of freshwater vertebrate populations (WWF 1999; see text for further explanation), and (*c*) invasion of riparian habitats in the Czech Republic by *Impatiens glandulifera* and *Reynoutria japonica*. Arrow marks the beginning of the exponential phase of population growth (redrawn from Pysek & Prach 1993).

pressure on their natural resources, in particular on fresh waters. The greatest decline in biodiversity is expected to occur in Asian fresh waters, where more than any other part of the world the most globally threatened ecosystems occur (Dudgeon 2002) and many more species are already listed as endangered (Table 7).

The projected mean future decline in aquatic biodiversity is about five times greater than the rate for terrestrial fauna and three times the rate for coastal marine areas. The rate of freshwater biodiversity decline is equivalent to the rate for tropical forest communities (Abramovitz 1996). For North America, for example, a future extinction rate of 4% per decade is predicted (Ricciardi & Rasmussen 1999). In North America 40 freshwater fish species disappeared between 1880 and 1990, with a sharp increase in the past 30 years (Fig. 8*a*). Although fish are among the best-investigated freshwater groups, many fish species will go extinct before they are discovered. During the past 10 years 200 new fish species have been described annually. The causes of extinction of freshwater fishes are habitat degradation (78%), introduction of exotics (68%), pollution and hybridization (38% each) and overharvest (15%).

The global population database comprises 4500 time series over 1800 animal species. This is an important resource of information in tracing long-term trends; however, it contains almost no wetland or floodplain species (NERC [National Environment Research Council] 1999). The Freshwater Ecosystems Index, based on the population trends of 102 freshwater vertebrate species for which time-series population data could be obtained, demonstrates an alarming density decline of freshwater vertebrate populations in the developed word (WWF 1999). On average, freshwater populations declined by about 45% between 1970 and 1995, compared to 35% for marine systems (Fig. 8*b*; WWF 1999). Although not specifically indicating the trend for wetlands or flood plains, this index includes many characteristic floodplain species (e.g. many mammals or amphibians). We may expect an even sharper decrease for wetland species, since a higher proportion of their species is endangered (cf. Table 2). Overexploitation of natural flood plains not only leads to biotic impoverishment, it also limits opportunities for developing a fuller understanding of the processes operating in these dynamic systems. For example, the limited knowledge of the dynamic hydrologic-morphologic interactions in natural wetlands/flood plains is the primary reason that so many restoration projects fail. About 80% of restoration projects examined by Lockwood and Pimm (1999) did not meet their major goals.

Increasing invasion

Novel disturbances such as clear-cutting or intensification of natural disturbances such as siltation play a significant role in biotic invasion. The progression from immigrant to invader often involves a lag phase, followed by a phase of exponential increase that continues until reaching the bounds of its new range (see Fig. 8*c*). This makes it difficult to predict future invaders. For example, *Impatiens glandulifera*, native to the Himalayas, has invaded large areas of European and North American flood plains. Like many other invaders, it reduces the fitness of competitors, in this case simply by attracting many more pollinators (e.g. Chittka & Schürkens 2001). In the Czech Republic, *Impatiens glandulifera* and *Reynoutria japonica* (alien species from the Far East) exhibited exponential invasion rates after a lag phase of several decades. The time at which the exponential increase commenced was around 1940 for both species. Nowadays, they occupy more than 400 (*I. glandulifera*) and about 150 (*R. japonica*) riparian localities in the Czech Republic (Fig. 8*c*). Ongoing rapid anthropogenic alterations of riverine flood plains will increase the proliferation of such invading species.

POTENTIAL STATUS IN 2025

Although perhaps more severe, the major ecological consequences that we may expect by 2025 for flood plains are similar to those predicted for most aquatic systems (Naiman & Turner 2000; Malmqvist & Rundle 2002). The projected changes will be manifest as what has been termed the 'distress syndrome' (*sensu* Rapport & Whitford 1999), indicated by reduced biodiversity, altered primary and secondary productivity, reduced nutrient cycling, increased prevalence of diseases, increased dominance of invaders and a predominance of shorter-lived opportunistic species. Since many flood plains respond very slowly to anthropogenic impacts, the ultimate effect of a given impact may be even more severe that expected from short-term projections. Hydrological change and channelization have generated shifts in the physical habitat that will take sufficiently long to be reflected by the long-lived biotic elements of the flood plains (e.g. Hughes 1997). This means that the lag time differs between abiotic changes and biotic adjustments. Therefore, a high biodiversity still observed in many regulated flood plains has to be considered as a relict of former conditions, since unidirectional development of the flood plain can be slow but will finally lead to a substantial decrease in diversity and major shift in community composition.

Today, over 60% of the world population live within 1 km of surface water, primarily along rivers and along the coastline. Increasing urbanization in the developing countries will further increase the land-use pressure on riparian systems. By the year 2025, 60% of the projected eight billion humans are expected to live in large cities. The low intensity of present land use along rivers in Africa and Asia, compared to Europe and the Americas, is primarily due to the low rate of urbanization. Present urban growth rates in major African catchments range from 3.6% yr^{-1} in the Limpopo to 8.8% yr^{-1} in the Lake Tanganyika catchment (Ravenga *et al*. 1998). In the Mekong catchment, the population is projected to double within the next 25 years and the basin's economy to increase by 400% (Shiklomanov 1998). Increasing population growth and food production will further alter the global nitrogen cycle. By 2020 the global production of nitrogen fertilizer could increase to 134 Gt yr^{-1} from a level of 80 Gt yr^{-1} in 1994 (Galloway *et al*. 1994; see Fig. 5).

The 21st century has been proposed as the century of nature restoration. By 2025 an area equivalent to the size of the entire Great Lakes basin in North America, and water courses equivalent to the combined lengths of the Rhone and Rhine rivers, are expected to be restored to full health throughout the world (IUCN 2000). Such predictions may, however, be overly optimistic. For example, although 15 000 km of streams and rivers in Switzerland have been identified for restoration programmes, the annual rate of river–flood-plain restoration is only 11 km compared to 70 km lost during the same period by regulation (BUWAL 1993). Even if further degradation were to cease, it would take more than 1000 years to restore Switzerland's rivers and streams. Even this is an optimistic prediction, since it ignores the limited ecological success of most restoration projects.

Optimistic predictions (e.g. IUCN 2000) contrast sharply with the projected increases in population, water abstraction and economic development. The impending global-scale changes in human population and economic development over the 2025 time horizon will dictate the future relation between water supply and demand to a much greater degree than any other factor (e.g. Vörosmarty *et al*. 2000). The uncertainties in the changes in hydrology predicted for many regions translate to even greater uncertainties in how regional-scale biodiversity and biogeochemical cycles may change (Jackson *et al*. 2001*a*). In 2025, 48% of the world's projected population is projected to live in water-stressed basins (Johnson *et al*. 2001). Since growing water scarcity is intimately linked to the alarming decline in aquatic biodiversity, a major decline in aquatic biodiversity may be realized by 2025, particularly in the developing world. Together with waters in xeric regions and cataracts, riverine flood plains are the most threatened freshwater ecosystems (Olson & Dinerstein 1998; Hughes & Rood 2001). A change in the ecological status of flood plains is closely linked to hydrologic change. Even small decreases in flood volumes can result in large reductions in area flooded, particularly in semi-arid and arid areas. In the Murray-Darling basin (Australia), 87% of divertible water resources are already diverted, leaving almost no water for flood plains (Kingsford 2000).

In 2025, the most water-stressed countries will be located in Africa and in Asia. In 1989 a continent-wide water crisis was predicted for Africa for the year 2025, when 22 countries with two-thirds of the continent's population would be water stressed (Falkenmark 1989). Careful cost/benefit calculation of the services provided by natural flood plains are required to develop the rationale needed for their future preservation. In South America, many flood plains will become reduced in size, including extensive flood plains along the large (sub)tropical rivers. Pollution from expanding mega-cities, hydropower generation, construction of large navigation canals (e.g. crossing the Pantanal), and ongoing deforestation are the primary threats to South American flood plains (Junk 2002).

By 2025, an optimistic prediction for developed countries is to achieve a balance between river kilometres restored annually and those regulated annually. The lack of reference data from pristine systems, however, constrains the capability to restore flood plains and mitigate damage to them. In North America, the commendable policy of 'no net loss' of wetlands will nonetheless not prevent further degradation of semi-natural flood plains. Reconstructed wetlands and flood plains that are subject to large restoration programmes (e.g. Kissimmee, Mississippi) can only provide a pale reflection of their dynamic natural state. Moreover, we should be aware that it is easy to underestimate the degradation of flood plains because of their naturally high ecological resistance and resilience and the extended lag phase before the severity of human impacts becomes readily apparent. Ecological diversity and redundancy within trophic levels, coupled with the longevity of the most obvious species (trees, fish), are the most important reasons for delay between impact and ecological response; eventually, however, a sudden collapse of the entire ecosystem is to be expected. For comparison, in marine systems time lags of decades to centuries occurred between the onset of overfishing and consequent changes in ecological communities (Jackson *et al*. 2001*b*).
Most remaining and protected floodplain fragments in Europe and North America are in danger of becoming 'sinks' for their wildlife. In Switzerland, for example, more than 40% of the riparian-obligate species are listed as endangered (Table 2). These obligates are living in a highly fragmented landscape, and many populations can be expected to become extinct within the next decades, even if those flood plains are preserved.

The concept of 'minimum dynamic area' has already become an important consideration in the design of conservation areas (Poiani *et al*. 2000). Large-scale disturbances such as major flood events create a diverse, shifting mosaic of successional stages and habitats of different types and sizes (Ward *et al*. 2002). The minimum dynamic area must provide room for the geomorphic processes that reshape the flood plain and create and rejuvenate the complete array of patch types. Riparian ecosystems are dependent upon disturbance caused by occasional high flows. Resource managers concerned with maintaining floodplain systems need to consider ways to preserve flows that are crucial to the survival of native riparian species. One of the main lessons from the past 100 years of river-floodplain control is that to sustain the integrity of large alluvial rivers, restoration must find a place for change by 'changing flows (certainly) and moving channels (ideally)' (Petts 1996).

CONCLUSIONS

This analysis of the present and future state of riverine flood plains conveys a dismal prognosis indeed, despite recognition of the important services provided by these ecosystems. Perhaps the only hope for sustaining functional flood plains over the long term lies with highly enlightened management and restoration efforts.

As a first step a global database on the location and size of wetlands in general and flood plains and their complex wetlands in particular is urgently needed. Major biophysical features, including information on the expansion/contraction of floodplain areas and the timing of floods (see Table 5) must be included in this assessment. In a second step, a compilation of threats, land tenure, management and studies on the benefits and values of different wetland types are required. A third step is to initiate greater conservation of flood plains through creation of floodplain natural areas and riparian greenbelts along the entire corridors of rivers from headwaters to mouth. Conservation easements and purchases to silence development rights (e.g. for gravel mining and ex-urban development) to protect remaining intact flood plains are urgently needed. Natural uses of flood plains far outweigh the value of human activities that constrain floodplain structure and function. Finally, a more robust and predictive understanding of how changes in hydrological connectivity and habitat fragmentation affect floodplain communities is required to foster better and more proactive conservation practices. Flood plains need to be understood by the general public for the values they provide in the form of natural goods (harvestable fisheries) and services (natural cleansing of water).

Of course, many questions remain about floodplain ecology that need to be investigated within the next decades. They include: the synergistic effects of 'stressors', the identification of ecological thresholds, the minimum dynamic areas required for basic ecological functions, such as nutrient retention and transformation, long-term trends in floodplain populations, the role of flood plains in controlling processes at the catchment and corridor scale, and the interactions between aquatic and terrestrial communities. However, we must act now to protect these valuable ecosystems, based on the incomplete yet considerable information available. Restoration projects, carefully planned and monitored, may serve as large-scale field experiments for a better understanding of the dynamics and complexity of riverine flood plains.

Non-governmental organizations and multinational institutions such as IUCN, UNEP, UNESCO, Worldwatch Institute, World Resource Institute, WWF, Ramsar Bureau, Nature Conservancy or Birdlife International, among many others, play a leading role in transferring basic research information to the public and to decision makers and in securing protection for biodiversity hot spots. Their role in conserving and restoring flood plains and wetlands must increase in the near future in relation to the fast-growing scientific knowledge about the strategic importance of flood plains to healthy rivers that parallels the accelerating deterioration of remaining systems.

The clear and unavoidable conclusion is that governments must find the will and way to preserve existing intact flood plain rivers as strategic global resources, and begin to restore hydrologic dynamics, sediment transport and riparian vegetation to those rivers that retain some level of ecological integrity. Flood plains must be viewed as conservatories of regional biodiversity and as fundamental units of river ecosystems that facilitate clean water and provide renewable timber, fisheries and wildlife resources, among many other natural goods and services. Most importantly, flood plains are natural flood control structures and they should be used that way. Indeed, recent horribly-damaging floods on the Mississippi River (USA) and elsewhere clearly were exacerbated by the very revetments that were designed to allow human encroachment onto the flood plains. A new era of naturalization of flood plains is needed to protect the integrity of river corridors. Flood plains designated for conservation or restoration must be large enough to support key species and perform key functions. Conducting protection and restoration on small reaches, without considering longitudinal linkages of flood plains throughout their catchment basin, will simply not work. Rather, an expansive catchment view of river landscapes is required, a *leitbild* or set of normative conditions that restores enough flow and sediment to produce variability of landscape form within river corridors. Possible constraints on river flow must be removed so that flood plains can function in a normative way, allowing the river to do the conservation and restoration of floodplain habitats, as opposed to using heavy equipment to artificially engineer solutions (*sensu* Stanford *et al*. 1996). The goal is to maximize human benefits by capitalizing on the natural functional attributes of river landscapes for flood and drought control and maintenance of biota. Otherwise, a dramatic extinction of aquatic and riparian species and of ecosystem services is to be expected by 2025 and in the decades following.

ACKNOWLEDGEMENTS

We are very grateful to Professor J.V. Ward and to Drs David Galat, Tom Buijse, Brij Gopal and Nicholas Polunin for valuable comments on earlier versions of the manuscript and to three anonymous reviewers for their constructive criticisms. We also thank Dr Nicholas Polunin and The Foundation for Environmental Conservation for support.

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