Chapter 20

Inland Water Systems

Coordinating Lead Authors: C. Max Finlayson, Rebecca D'Cruz
Lead Authors: Nickolay Aladin, David Read Barker, Gordana Beltram, Joost Brouwer, Nicholas Davidson, Laurie Duker, Wolfgang Junk, Michael D. Kaplowitz, Henk Ketelaars, Elena Kreuzberg-Mukhina, Guadalupe de la Lanza Espino, Christian Lévêque, Alvin Lopez, Randy G. Milton, Parastu Mirabzadeh, Dave Pritchard, Carmen Revenga, Maria Rivera, Abid Shah Hussainy, Marcel Silvius, Melanie Steinkamp
Contributing Authors: Vyascheslav Aparin, Elena Bykova, Jose Luis García Calderón, Nikolay Gorelkin, Ward Hagemeijer, Alex Kreuzberg, Eduardo Mestre Rodríguez, Iskander Mirabdullaev, Musonda Mumba, Igor Plotnikov, Vladislav Talskykh, Raisa Toryannikova
Review Editors: Robert Costanza, Pedro Jacobi, Frank Rijsberman

---

BOXES

FIGURES

TABLES

*This appears in Appendix A at the end of this volume.

Main Messages

Inland water habitats and species are in worse condition than those of forest, grassland, or coastal systems (*medium certainty*). It is *speculated* that 50% of inland water habitats were lost during the twentieth century. It is *well established* that for many ecosystem services, the capacity of inland water systems to produce these services is in decline and is as bad as or worse than that of other systems. More than 50% of inland waters (excluding lakes and rivers) have been lost in parts of North America, Europe, and Australia, but on a global scale there is insufficient information on the extent of specific inland water habitats, especially those of a seasonal or intermittent nature, to substantiate the extent of habitat loss.

In addition to the loss of inland water systems, degradation is widespread. As with habitat loss, it has not, on the whole, been possible to quantify this with great confidence at a continental scale, although many site-specific instances have been well documented. The species biodiversity of inland waters is among the most threatened of all ecosystems, and in many parts of the world it is in continuing and accelerating decline. Global climate change is expected to exacerbate the loss and degradation of many inland water systems and the loss or decline of their species; however, projections about the extent of such loss and degradation or decline are not yet well established.

The loss and degradation of inland water systems have been driven directly by many pressures, acting individually and synergistically or cumulatively. The direct drivers of loss and degradation of inland waters are well known and documented and include changes in land use or cover due to vegetation clearance, drainage, and infilling, especially connected to expansion of agriculture; the spread of infrastructure, whether for urban, tourism and recreation, aquaculture, agriculture, or industrial purposes; the introduction and spread of invasive species; hydrologic modification; overharvesting, particularly through fishing and hunting; pollution, salinization, and eutrophication; and global climate change, which is expected (*high certainty*) to lead to even further degradation and to exacerbate existing pressures. While it is known that cumulative and synergistic effects between multiple pressures occur, there is insufficient quantitative analysis to readily tease out the relative individual and combined effects and their importance.

Agricultural development has historically been the principal cause of the loss of inland water systems worldwide (*high certainty*). It is estimated that by 1985, 56–65% of suitable inland water systems had been drained for intensive agriculture in Europe and North America, 27% in Asia, and 6% in South America. The construction of dams and other structures along rivers has resulted in fragmentation and flow regulation of almost 60% of the large river systems in the world. In many countries, the construction of large dams is still a controversial issue. Water pollution and eutrophication are widespread and in many countries have led to the degradation of many inland water systems. In addition to direct adverse effects on biodiversity, pollution has reduced the capacity of inland waters to filter and assimilate waste. Threats of water quality degradation are most severe in areas where water is scarce (dryland systems). Toxic substances and artificial chemicals are increasingly being released into waterways, with uncertainty about their long-term effects on ecosystems and humans. In recent years the devastation caused by invasive species has been increasingly recognized worldwide.

The decline of inland water systems has placed the ecosystem services derived from these systems and human well-being at increasing risk. Provisioning services from inland waters, such as fish, are essential for human well-being, with estimates of more than 50 million people involved directly in inland fisheries. At present almost 50% of the world depends on rice as a staple food item; this is expected to increase, and by 2020 some 4 billion people will depend on rice. Supporting and regulating services are critical to sustaining vital ecosystem functions.

Flow regulation within and between inland waters and links between surface and groundwater are critical ecosystem services that have been degraded on a global scale. The disruption of natural flooding regimes has devastated many riverine habitats and led to decreased sediment transport and a loss of flood buffering and nutrient retention. Flooding can cause severe hardship to humans, with the 1998 floods in China causing an estimated $20 billion worth of damage, but it is also essential for maintaining sediment-based fertility of floodplains and supporting fish stocks in large rivers.

In addition, inland waters have significant aesthetic, artistic, educational, cultural, and spiritual values, and they provide invaluable opportunities for recreation by many communities and, increasingly, for tourism. The economic value of these services is known for many local habitats but not necessarily well quantified economically nor recognized by policy-makers and given priority within resource development and conservation agencies in most countries.

Trade-offs between services from inland waters have been considerable, yet poorly considered. Alteration of rivers through infrastructure has improved transportation, provided flood control and hydropower, and boosted agricultural output by making more land and irrigation water available. At the same time, rivers have been disconnected from their floodplains and other inland water habitats, water velocity in riverine systems has decreased, in some places rivers have been converted to a chain of connected reservoirs, and groundwater recharge has been reduced. In other places, infrastructure has increased the likelihood of flooding by diverting water and increasing flows. These changes have, in turn, affected the migratory patterns of fish species and the composition of riparian habitat, opened up paths for exotic species, changed coastal ecosystems, and contributed to an overall loss of freshwater biodiversity and inland fishery resources. Irrigation has led to increased food production in drylands but in many cases is unsustainable without extensive public capital investment as waterlogging and pollution (especially eutrophication and salinization) degrade the system and other services and encourage the introduction or spread of human disease vectors.

The assessment of the extent and change of inland water systems at a continental level is compromised by the inconsistency and unreliability of data (*high certainty*). Estimates of the extent of inland water systems vary from 530 million to 1,280 million hectares. The extent and distribution of inland waters is unevenly or even poorly known at the global and regional scales, partly due to confusion over definitions as well as difficulties in delineating and mapping habitats with variable boundaries as a result of fluctuations in water levels. Larger wetlands, lakes, and inland seas have been mapped along with major rivers; there are some 10,000 lakes that are over 1 square kilometer, and peatlands are estimated to cover more than 400 million hectares. Smaller habitats that are critical for many communities are not well mapped or delineated.

On the whole, available information focuses on the broader regional or global scales. This introduces uncertainty into many assessments and necessitates caution when attempting to make comparisons between data sets, especially when collected at different spatial scales. Innovative tools for effective assessment of the status and trends of inland water systems and their species, especially in those parts of the world where data are lacking, inadequate, or in need of updating, are required.

20.1 Introduction

Inland water systems encompass habitats such as lakes and rivers, marshes, swamps and floodplains, small streams, ponds, and cave waters. These have a variety of biological, physical, and chemical characteristics. As coastal wetlands (such as estuaries, mangroves, mudflats, and reefs) are considered in Chapter 19, the broad definition of wetland adopted by the Convention on Wetlands in 1971, which includes inland, coastal, and marine habitats, is not used in this chapter. All inland aquatic habitats, however—whether fresh, brackish, or saline—as well as inland seas are considered.

As there is no clear boundary between inland and coastal ecosystems, this delineation is indicative only and is not strictly applied where there are strong interactions between the biodiversity, services, and pressures that affect inter-connected habitats. Rice fields, aquaculture ponds, and reservoirs are included in this chapter's analysis. The supply of fresh water and its regulation, both in terms of water quality and flow, are considered in Chapters 7, 15, and 16. Groundwater as a system is addressed here, recognizing that important links occur with many surface-water habitats.

This chapter provides a brief description of the services provided by inland waters, together with the condition and trends of their habitats and species. More detailed information on the specific services derived from inland waters (such as water supply and waste processing) is found in other Chapters. Where information is available, the drivers of change in the condition of these habitats and their species are related to the condition of the services and any subsequent effects on human well-being. Trade-offs and responses to changes in the habitats and species are also presented (with further information being provided in the MA *Policy Responses* volume).

Inland water systems have a temporal dimension—varying from perennial to ephemeral—and a dynamic dimension, including flowing systems (rivers), standing waters (lakes and ponds), and systems with at times large seasonal fluctuations in water depth—with some being waterlogged and others flooded permanently, seasonally, intermittently, or even episodically. The term wetland is often used to define all inland aquatic systems, such as lakes, rivers, or lagoons. At other times it is used to describe a narrower group of habitats that represent a variety of shallow, vegetated systems, such as bogs, marshes, swamps, and floodplains. Extensive information on wetland definition and delineation is available (e.g. Finlayson and van der Valk 1995; Mitsch et al. 1994), but the failure to consider fully the different dimensions and definitions that have been used around the world has resulted in confusion and inaccurate analyses on the extent and condition of these systems (Finlayson and Spiers 1999). In this chapter, the terms "inland water systems" or "inland waters" are used wherever possible unless specific habitat types are unambiguously referred to in the source material.

The extent and distribution of inland waters is poorly and unevenly known at the global and regional scales due to differences in definitions as well as difficulties in delineating and mapping habitats with variable boundaries due to fluctuations in water levels (Finlayson et al. 1999). In many cases, comprehensive documentation at the regional or national levels also does not exist. The larger habitats, such as lakes and inland seas, have been mapped along with the major rivers, but for many parts of the world smaller wetlands are not well mapped or delineated. As a consequence, assessment of the extent of and change in inland water habitats at the continental level is compromised by the inconsistency and unreliability of the data. The most recent attempt to ascertain the extent and distribution of inland water systems (Lehner and Döll 2004) is shown in Figure 20.1 (in Appendix A). As with previous estimates, these data contain many inaccuracies and gaps. For example, intermittently inundated habitats are not included, and there are many inaccuracies because of problems of scale and resolution.

20.2 Services Derived from Inland Water Systems

With the exception of the provision of fresh water, comprehensive global analyses of services provided by inland waters have not been undertaken, nor has the link between the condition and trend of the biodiversity, including habitats, and the provision of ecosystem services been strongly made at this scale. As such, the knowledge base of the true value of inland water systems is poorly known (see, e.g., Finlayson et al. 1999; Tockner and Stanford 2002; Malmqyist and Rundle 2002). Assessments of inland waters have not always considered inland saline waters, which are particularly widespread and important in many arid regions of the world.

A generalized list of services provided by or derived from inland waters has been compiled from a number of sources. (See Table 20.1.) The value of these services has been estimated at

Table 20.1. Ecosystem Services Provided by or Derived from Inland Water Systems

Services	Comments and Examples
Provisioning	
Food	production of fish, wild game, fruits, grains, etc.
Freshwater[a]	storage and retention of water for domestic, industrial, and agricultural use
Fiber and fuel	production of logs, fuelwood, peat, fodder
Biochemical	extraction of materials from biota
Genetic materials	medicine, genes for resistance to plant pathogens, ornamental species, etc.
Biodiversity	species and gene pool
Regulating	
Climate regulation	greenhouse gases, temperature, precipitation, and other climatic processes; chemical composition of the atmosphere
Hydrological flows	groundwater recharge and discharge; storage of water for agriculture or industry
Pollution control and detoxification	retention, recovery, and removal of excess nutrients and pollutants
Erosion	retention of soils
Natural hazards	flood control, storm protection
Cultural	
Spiritual and inspirational	personal feelings and well-being
Recreational	opportunities for recreational activities
Aesthetic	appreciation of natural features
Educational	opportunities for formal and informal education and training
Supporting	
Soil formation	sediment retention and accumulation of organic matter
Nutrient cycling	storage, recycling, processing, and acquisition of nutrients
Pollination	support for pollinators

[a] See also Chapter 7 for commentary on how this is variously considered a provisioning or regulating service.

$2–5 trillion annually (Costanza et al. 1997; Postel and Carpenter 1997). This wide range represents major differences in methods, reliability, and accuracy of the economic data and differences in the definition and area of habitats being assessed. Despite ongoing discussion about methods and data quality, it is *well established* that these systems are highly valued and extremely important for people in many parts of the world. It is *speculated,* but not well documented globally, that the loss and degradation of inland water systems has resulted in an immense loss of services.

As Chapter 7 deals solely with the critical service of the provision of fresh water, this service is not considered further here. Other chapters that contain information on services provided by or derived from inland water systems include those on food (Chapter 8), nutrient cycling (Chapter 12), waste processing and detoxification (Chapter 15), regulation of natural hazards (Chapter 16), cultural and amenity services (Chapter 17), and cultivated systems (Chapter 26).

Table 20.2 contains a summary of estimates for the global average value of services derived from or provided by inland and coastal water systems (referred to generically as wetlands in the source documents). The figures presented are average global values based on sustainable use levels and taken from two synthesis studies—Schuyt and Brander (2004), calibrated for the year 2000, and Costanza et al. (1997), calibrated for 1994—that together cover more than 200 case studies. Most of the data are derived from Schuyt and Brander (2004), except for the aesthetic information service and climate regulation. The total economic value of 63 million hectares of wetland around the world would, according to this data, amount to about $200 billion a year (which is a conservative estimate, since for many services no economic data were available). Costanza et al. (1997) arrived at a figure of $940 billion, mainly due to higher estimates for several services (flood control at $4,539 per hectare per year, for example, water treatment at $4,177 per hectare, and water supply at $3,800 per hectare).

Table 20.2. Total Economic Value of Ecosystem Services Provided by Wetlands (Costanza et al. 1997; Schuyt and Brander 2004)

	Average Value *(dollars per hectare per year)*
Provisioning services *(products obtained from wetlands)*	**601**
Fishing	374
Hunting	123
Water supply	45
Raw materials (thatch, timber, fodder, fertilizer, etc.)	45
Fuelwood	14
Other (genetic, medicinal, and ornamental resources)	?
Cultural services *(nonmaterial benefits obtained from wetlands)*	**1,373**
Aesthetic information	881
Recreation and tourism	492
Other (e.g., artistic, spiritual, historic, or scientific information)	?
Regulating services *(benefits obtained from ecosystem processes)*	**1,086**
Flood control/water regulation	464
Water treatment	288
Nursery function	201
Climate regulation	133
Other (e.g., sediment control, biological control)	?
Supporting services *(ecosystem functions necessary to maintain all other services)*	**214**
Habitat/refugia for biodiversity	214
Other (e.g., primary products, soil formation, nutrient/biogeochemical cycling)	?
Total value	**3,274**

Despite such figures becoming available, the importance of services derived from inland waters (such as fresh water, fish, and groundwater recharge) is often taken for granted or treated as a common good, with the real value only being recognized after the services have been degraded or lost. This is demonstrated particularly well in semiarid and arid regions, with Lake Chad in western Africa being very illustrative, as it has a multiplicity of valuable services (see Table 20.3), which are mostly in decline. This situation is common globally, particularly where population pressures are high and services have been overexploited or inland water systems have been inappropriately managed.

In addition, while the value of particular services may be low in terms of global economic analyses, it can be extremely high locally. This is evident in the preliminary analyses undertaken in 10 inland water systems in the Zambezi in southern Africa, where multiple services—including subsistence agricultural crops, fish production, natural products, and livestock grazing—were estimated to be worth $123 million per year (Seyam et al. 2001). Such analyses (other examples in Lupi et al. 2002; Emerton et al. 1998) are fraught with assumptions, but they do illustrate the relative worth of the main services to local populations.

An analysis of global ecosystems has established with some confidence that for a standardized set of services, the capacity of inland water habitats (referred to as freshwater habitats in the source material) to produce these services is in decline and is as bad as or worse than the other systems considered (Revenga et al. 2000; WRI et al. 2000). (See Figure 20.2 in Appendix A.) This conclusion has been supported by global analyses of the condition of inland water systems, such as those undertaken for large lakes and inland seas (Beeton 2002), flowing waters (Malmqvist and Rundle 2002), floodplains (Tockner and Stanford 2002), temperate freshwater wetlands (Brinson and Ines Malvarez 2002), tropical wetlands (Junk 2002), and salt lakes (Williams 2002).

20.2.1 Hydrological Regulation

It is well recognized that some inland waters serve as important storage sites, accumulating water during wet periods and providing a reserve of water during dry periods by maintaining base flow in adjacent rivers (e.g., Revenga et al. 2000; Malmqvist and Rundle 2002). Similarly, it is increasingly known that some inland waters, such as lakes and marshes, attenuate floods by retaining water or storing it in the soil and therefore reducing the need for engineered flood control infrastructure (Abramovitz 1996). While it has been known for many years that aquatic vegetation attenuates surface flows, the considerable value of this service is not often widely and accurately assessed in economic terms. (See Chapter 16.) In contrast, figures on the cost of flood damage are readily available after this function has been lost or seriously eroded by unsustainable development; for example, the 1998 flash floods in China caused an estimated economic loss of $20 billion (Qu 1999).

While the damage caused by floods is often discussed, it must also be recognized that natural floods provide an essential service

Table 20.3. Change in Ecosystem Services Derived from Lake Chad (White et al. 2004)

Ecosystem Service	Services in Lake Chad	Change in Services	Trend
Provisioning services			
Food – plant crops	rice, maize, cowpeas, wheat, cotton, millet, groundnuts, cassava	increase in production of food crops	up
Food – aquatic plants	spirulina for commercial production	loss of commercial plant production	down
Food – fish	harvesting for local diet and for trade	less fish for food and for trade	down
Food – milk	milk from livestock	decrease in milk available from Kuri population	down
Food – meat	meat from cattle	decrease in meat available from Kuri population	down
Fuel – wood	timber and fuelwood from floodplain forests	recession of floodplain and drying out of habitat for floodplain forests	down
Genetic resources	laboratory for genetic studies on endemic livestock breeds	decrease in availability of genetic material	down
Biochemicals	mineral resources used as salt and in preparation of soap and medicines	less deposition of mineral-contributing production of trade goods	down
Fresh water – surface water	water for domestic and agricultural use	decrease in volume and surface area	down
Fresh water – groundwater	groundwater recharge provides water supply	decrease in groundwater recharge	down
Regulating services			
Climate regulation	precipitation and temperature control	decrease in precipitation	down
Water regulation	seasonal fluctuations replenish farmland and feeding areas for fish	less replenishing of farmland for crops and fish feeding areas	down
Erosion control	aquatic vegetation holds sediment	less erosion control	down
Water purification	suspended solids reduced as water spreads across floodplain	increase in deposition of suspended solids	down
Storm protection	holds storm water, provides flood control	less flood protection	down
Cultural services			
Cultural diversity	permanent residents and seasonal herders	loss of cultural diversity	down
Spiritual/religious values	locally grown spirulina used as a treatment to ward off sorcerers	less growth of algae used in traditional treatment	down
Knowledge systems	traditional village-based systems of fisheries management	breakdown of village systems without fish resource base	down
Cultural heritage values	historical cultural landmarks of ancient Sao people	possibly no change	stable
Recreation	habitat for game species, local hunting reserve	fewer game species	down
Supporting services			
Soil formation	retains sediment, adding to islands, banks, polders	less soil formation and island/bank-building	down
Nutrient formation	fertile soil from alluvial deposits	less nutrient cycling with seasonal water fluctuations	down
Primary production	abundant aquatic vegetation for wildlife	less aquatic vegetation; more grazing habitat for domestic livestock	mixed
Habitat	habitat for endemic cattle, rich avifauna, endemic fish, diverse mammals	less habitat for domestic and wild aquatic species	down

to millions of people. For example, the livelihoods of many people depend on floods to replenish the soil and nutrients of the floodplains used in flood-recession agriculture and for grazing and to clean and renew streams and sandbanks to permit fish passage for migration and the enhancement of fish production, as on the Pongolo floodplain in southern Africa (Heeg and Breen 1982). Floods also replenish sediment in coastal areas. Despite a lack of reliable quantitative evaluations, the importance of hydrological regulation by inland water systems is widely recognized around the world (Mitsch and Gosselink 2000).

20.2.2 Sediment Retention and Water Purification

Over the past few decades the valuable role that plants and substrates play in many inland waters by trapping sediments, nutrients, and pollutants has been *well established* (see Chapter 15) and is illustrated in many analyses (see reviews of the condition of inland water systems cited earlier). Wide-scale vegetation clearing has caused erosion to increase, filling many shallow water bodies with sediment and disrupting the transport of sediment to coastal areas. Excessive amounts of sedimentation due to land disturbance are a global problem and have severely degraded many coastal-marine habitats, especially coral reefs close to shore. (See Chapter 19.) It is speculated that soil retention in inland waters would have ameliorated the impacts of excess sedimentation on coastal systems.

In addition to retaining sediments, the vegetation in some inland water systems, such as lakes and swamps, can remove high levels of nutrients, especially phosphorus and nitrogen, commonly associated with agricultural runoff, which could otherwise result in eutrophication of receiving ground, surface, and coastal waters. (See Chapter 12.) For example, cypress swamps in Florida in the United States can remove 98% of the nitrogen and 97% of the phosphorus that would otherwise have entered the groundwater (Brown 1981), and vegetation along the edge of Lake Victoria, East Africa, was found to have a phosphorus retention of 60–92% (Arcadis Euroconsult 2001). Inland water systems can also export nutrients, and although the general conditions under which these systems retain or export nutrients are known (e.g., Richardson and Vepraskas 2001; Mitsch and Gosselink 2000), they are often not investigated sufficiently on a site-specific basis.

The capacity of many wetland plants to remove pollutants derived from chemical or industrial discharges and mining activities is *well established* and increasingly used as a passive treatment process. (See Chapters 10 and 15.) The floating water hyacinth (*Eichhornia crassipes*) and large emergent species (such as some *Typha* and *Phragmites* species), for example, have been used to treat effluents from mining areas that contain high concentrations of heavy metals such as cadmium, zinc, mercury, nickel, copper, and vanadium. In West Bengal, India, water hyacinth is used to remove heavy metals, while other aquatic plants remove grease and oil, enabling members of a fishing cooperative to harvest one ton of fish a day from ponds that receive 23 million liters of polluted water daily from both industrial and domestic sources (Pye-Smith 1995). In another example, the Nakivubo papyrus swamp in Uganda receives semi-treated effluent from the Kampala sewage works and highly polluted storm water from the city and its suburbs. It has been established that during the passage of the effluent through the swamp, sewage is absorbed and the concentrations of pollutants are considerably reduced, at an estimated value of $2,220–3,800 per hectare per year (Emerton et al. 1998). These examples are indicative of the extremely important role that these habitats can play in removing pollutants from wastewater effluents.

It is also *well established* that not all inland water systems can assimilate all types and amounts of waste. Excessive loads of domestic sewage or industrial effluent can degrade inland water systems, with a consequent loss of biota and services. (See Chapter 15.) The environmental problems associated with waste from mining operations are a good example of the limited waste-processing capacity of these ecosystems. Recent examples of this problem include the failures of engineered waste containment structures, as occurred in 1999 in southern Spain, where more than 5 million cubic meters of heavy metal-laden sludge flowed into the Guadiamar River and part of the Coto Doñana wetlands (Bartolome and Vega 2002), and the discharge in 2000 of 100,000 cubic meters of cyanide and heavy metal-contaminated wastewater from the Baia Mare mine in Romania, which affected the Tisza, Szamos, and Danube Rivers (WWF 2002). In both these cases, species and ecosystem services from wetlands were severely affected by the excessive and toxic waste loads (Bartolome and Vega 2002; WWF 2002).

20.2.3 Recharge/Discharge of Groundwater

The issues of groundwater supply, use, and quality have received far less attention around the world than surface waters, even in industrial countries. Our understanding of groundwater resources is more limited as sufficient data, such as covering groundwater discharge/recharge and aquifer properties, for global applications are only beginning to be synthesized (Foster and Chilton 2003; UNESCO-IHP 2004). While many wetlands exist because they overlie impermeable soils or rocks and there is, therefore, little or no interaction with groundwater, numerous wetlands are fed largely by groundwater, and recharge of the aquifer occurs during flooding periods. It is well known though that many groundwater resources are vulnerable to a variety of threats, including overuse and contamination. (See Chapter 7.)

The importance of groundwater for human well-being is *well established*; between 1.5 billion (UNEP 1996) and 3 billion people (UN/WWAP 2003) depend on groundwater supplies for drinking. It also serves as the source water for 40% of industrial use and 20% of irrigation (UN/WWAP 2003). Many people in rural areas depend entirely on groundwater.

Because of unsustainable withdrawals, parts of India, China, West Asia, the former Soviet Union, the western United States, and the Arabian Peninsula, among other regions, are experiencing declining water tables, limiting the amount of water that can be used and raising the costs of getting access to it (Postel 1997; UNEP 1999). Overpumping of groundwater can lead to land subsidence, as has been recorded in megacities such as Mexico City, Manila, Bangkok, and Beijing (Foster et al. 1998). In coastal areas, lowering water tables can cause the underground intrusion of saline water, rendering these freshwater sources unusable for human consumption. In 9 of 11 European countries, for example, especially along the Mediterranean coast, where groundwater over-exploitation is reported, saltwater intrusion has become a serious problem. The main cause is groundwater overabstraction for public water supply (EEA 2003).

A common outcome of groundwater overabstraction is dryland salinization, which renders the soil unusable for cropping (see Chapter 22), often exacerbated by irrigation practices, such as those that have affected about 40% of the dryland area in West Asia (Harahsheh and Tateishi 2000). Salinity and waterlogging have affected 8.5 million hectares or 64% of the total arable land in Iraq, while 20–30% of irrigated land has been abandoned due to salinization (Abul-Gasim and Babiker 1998). In Azerbaijan, some 1.2 million hectares (about a third of total irrigated area) has been affected by salinization, and much of it has been abandoned (State Committee on Ecology and Control of Natural Resources Utilization 1998).

The ability of inland waters to recharge groundwater has been *well established*. For example, in monetary terms a 223,000-hectare swamp in Florida has been valued at $25 million per year for its role in storing water and recharging the underlying aquifer (Reuman and Chiras 2003). And the Hadejia-Nguru wetlands in northern Nigeria, in addition to supporting fishing, agriculture, and forestry, play a major role in recharging aquifers that are used by local people for domestic water supplies—a service estimated as being worth $4.8 million per year (Hollis et al. 1993).

20.2.4 Climate Change Mitigation

Inland water systems play two critical but contrasting roles in mitigating the effects of climate change: the regulation of greenhouse gases (especially carbon dioxide) and the physical buffering of climate change impacts. Inland water systems have been identified as significant storehouses (sinks) of carbon as well as sources of carbon dioxide (such as boreal peatlands), as net sequesters of organic carbon in sediments, and as transporters of carbon to the sea. Although covering an estimated 3–4% of the world's land area, peatlands are estimated to hold 540 gigatons of carbon (Immirizy and Maltby 1992), representing about 1.5% of the total estimated global carbon storage and about 25–30% of that contained in terrestrial vegetation and soils (Joosten and Clarke 2002; Lévêque 2003). Many wetlands also sequester carbon from the atmosphere through photosynthesis and act as traps for carbon-rich sediments from watershed sources. It is likely that one of the most important roles of wetlands may be in the regulation of global climate change through sequestering and releasing a major proportion of fixed carbon in the biosphere (Mitsch and Wu 1995).

Inland waters also contribute to the regulation of local climates. Possibly the most widely publicized example is that of the Aral Sea, where a combination of desiccation and pollution have altered the local climate, with dire effects on human health (as described later in the chapter). Similarly, the burning and degradation of peatland in Southeast Asia have degraded the atmosphere and affected the health of a large but possibly indeterminate number of people if the long-term effects on livelihoods as a consequence of the land degradation are considered. Getting accurate measurements of such effects and the number of people actually affected by changes in local climates is likely to prove difficult in some instances due to an absence of data and the dispersed nature of some effects or the population affected.

20.2.5 Products from Inland Water Systems

Inland water systems are a major source of products that can be exploited for human use, including fruit, fish, shellfish, deer, crocodile and other meats, resins, timber for building, fuelwood, peat, reeds for thatching and weaving, and fodder for animals. Many of these products are exploited at subsistence, cottage industry, or the larger commercial scale in most parts of the world.

Arguably the most important product derived from inland waters in terms of human well-being on a global scale is fish and fishery products. An estimated 2 million tons of fish and other aquatic animals are consumed annually in the lower Mekong Basin alone, with 1.5 million tons originating from natural wetlands and 240,000 tons from reservoirs. The total value of the catch is about $1.2 billion (Sverdrup-Jensen 2002). In recent years, the production of fish from inland waters has become dominated by aquaculture operations, mainly carp in China for domestic consumption and salmon, tilapia, and perch mainly for export to other countries (Kura et al. 2004). (See Chapters 8, 19, and 26.) In fact, since 1970 aquaculture has become the fastest-growing food production sector in the world, increasing at an average rate of 9.2% per year—an outstanding rate compared to the 2.8% rate for land-based farmed meat products (FAO 2004). In parallel, consumption of freshwater fish has shown the greatest increase over recent years, especially in China, where per capita consumption of fish increased nearly tenfold between 1981 and 1997 (Delgado et al. 2003; Kura et al. 2004).

Inland fisheries are of particular importance in developing countries, as fish is often the only source of animal protein to which rural communities have access (Kura et al. 2004). A large proportion of the recorded inland fisheries catch comes from developing countries, and the actual catch is thought to be several times the official 2001 figure of 8.7 million tons, as much of the inland catch is undereported (FAO 1999; Kura et al. 2004). Indeed, FAO considers its data on freshwater harvests so uncertain that it declined to give a comprehensive analysis of inland trends in its latest report on the state of world fisheries and aquaculture (FAO 2004).

Most of the above-mentioned increase in freshwater fish consumption has occurred in Asia, Africa, and more moderately in South America. In 1999, China accounted for 25% of the annual catch, India 11%, and Bangladesh 8% (Fishstat 2003). In North America, Europe, and the former Soviet Union, landings of fish have declined, whereas in Oceania they have remained stable (FAO 1999). Despite this increase in landings, maintained in many regions by fishery enhancements, such as stocking and fish introductions, the greatest overall threat for the long-term sustainability of inland fishery resources is the loss of fishery habitat and the degradation of the terrestrial and aquatic environments (FAO 1999). Historical trends in commercial fisheries data for well-studied rivers show dramatic declines over the twentieth century, mainly from habitat degradation, invasive species, and overharvesting (Revenga et al. 2000).

The Great Lakes of North America, shared by the United States and Canada, illustrate the value of inland fishery in these countries. These lakes have supported one of the world's largest freshwater fisheries for more than 100 years, with the commercial and sport fishery now collectively valued at more than $4 billion annually (Great Lakes Information Network 2004). The fishery consists of a mix of native and introduced species, some of which are regularly restocked. The fishery declined due to the combined effects of overfishing, pollution, and the introduction of invasive species. Recent years have seen a major resurgence in Lake Erie's fish production as some populations have recovered, and in Lake Ontario as a new fishery has been developed. However, this has only occurred in response to considerable expenditure in support of fish stocking and administration, including facilitating cooperation between governmental agencies; the real overall cost of recovering the fishery may not be accurately known (Dochoda 1988).

Another critical product derived from wetlands is rice—the staple food for nearly 50% of the world's peoples, mainly in Asia (FAO 2003). The world per capita rice consumption in 1990 was 58 kilograms per year of milled rice. This represents 23% of the average world per capita caloric intake and 16% of the protein intake (International Rice Research Institute 1995). In Asia alone, more than 2 billion people obtain 60–70% of their calories from rice and its derived products (FAO 2003). Rice is also the most rapidly growing source of food in Africa and is of significant importance to food security in an increasing number of low-income food-deficit countries. It is estimated that by 2020, 4 billion people—more than half the world's population—will depend on rice as a staple of their diet (International Rice Research Institute 1999).

Peatlands in particular, as a diverse group of habitats, provide many useful products. Peat soil has been mined extensively for domestic and industrial fuel, particularly in Western Europe but also in South America, and peat mining for use in the horticulture industry is a multimillion-dollar industry in Europe (Finlayson and Moser 1991; Maltby et al. 1996; Joosten and Clarke 2002). Whereas peat mining can be destructive in terms of the biodiversity values of the affected areas, there is an increased emphasis on sustainable practices through improved planning, water regulation, and post-mining restoration (Joosten and Clarke 2002). Peatlands also provide foods in the form of berries and mushrooms, and sometimes timber, all of which can be locally important. The tropical peat swamp forests of Southeast Asia, for example, have been an important source of tropical hardwood and are also a source of products that contribute significantly to the economy of local communities, including fish, fruit, latex, and tannins (Rieley et al. 1996). In all regions of the world there are indigenous people whose livelihoods and cultures are sustained by peatlands.

20.2.6 Recreation and Tourism

It is extremely apparent that the aesthetics as well as the diversity of the animal and plant life of many inland water systems has attracted tourism. Many inland water sites are protected as National Parks, World Heritage Sites, or wetlands of international importance (that is, Ramsar sites) and are able to generate considerable income from tourist and recreational uses. In some locations tourism plays a major part in supporting rural economies, although there are often great disparities between access to and involvement in such activities. The negative effects of recreation and tourism are particularly noticeable when they introduce inequities and do not support and develop local economies, especially where the resources that support the recreation and tourism, such as wetlands, are degraded.

The income generated by recreation and tourism can be a significant component of local and national economies. Recreational fishing can generate considerable income: some 35–45 million people take part in recreational (both inland and marine) fishing in the United States, spending $24–37 billion each year on their hobby (Thomsen 1999; Ducks Unlimited 2002). In 2001, freshwater fishing (including the Great Lakes) alone generated more than $29 billion from retail sales and more than $82.1 billion in total economic output (including contributions to household income and taxation revenues) (American Sportfishing Association 2001). The total economic value of such activities extends far beyond the direct expenditure and includes, for example, contributions to local property markets and taxation revenues.

The value of recreation and tourism from inland water systems is widely recognized in many other parts of the world, but not necessarily as well quantified (Finlayson and Moser 1991). There are many inland waters with significant recreational value for which a monetary value cannot easily be given because visitors use the area without direct payment. Employing economic valuation techniques, such as willingness to pay and other methods (see Chapter 2), to investigate the value that users ascribe to a wetland is becoming the topic of increased research and documentation. The recreational value of the Norfolk Broads wetlands in the United Kingdom, for instance, was estimated at $57.3 million per year for people living relatively close to the Broads and $12.9 million per year for those living further away (Barbier et al. 1997).

In considering such analyses, the cost of repairing any degradation or providing facilities for visitors must also be taken into account. It is well known, for example, that overuse of popular fishing or camping spots around lakes or along rivers can lead to severe degradation and result in the demise of such activities and the loss of income-generation opportunities.

Although not strictly speaking a ''recreational'' function, the educational value of wetlands is closely related: there are many wetland education centers and programs around the world that involve the general public and schoolchildren in practical activities in their local wetland environments; these activities span the border between education and recreation. Approximately 160,000 people a year visit a 40-hectare wetland complex in the heart of London; created from a series of reservoirs, it offers 30 lakes and marshes, boardwalks, hides, and pathways as well as an exhibition center that educates visitors on the functions and values of inland water ecosystems, biodiversity issues, and other environmental matters in an essentially recreational setting (Peberdy 1999).

20.2.7 Cultural Value

Inland waters are closely associated with the development of human culture—notably, for example, in the Indus, Nile, and Tigris-Euphrates valleys (Finlayson and Moser 1991)—and many major cities are built near rivers. In some cultures inland waters may have deep religious significance for local people. In Tibet, for example, pre-Buddhist belief identified various lakes as sacred, making them objects of worship as well as ensuring their protection from pollution and other harm. As Buddhism took over, these beliefs remained, albeit in a modified form, and certain lakes in Tibet are still sacred to the people, with strict regulations on their exploitation (Dowman 1997).

Cranes have a near-sacred place in the earliest legends of the world and have featured prominently in art and folklore for millennia. For example, the Brolga (*Grus rubicunda*) figures prominently in some indigenous Australian folklore and culture, and in Northeast Asia cranes are revered as symbols of longevity and peace (Wetlands International 1999). At anything but a local scale, however, cultural values are a relatively poorly documented service of inland waters, despite the many instances where wetlands have significant religious, historical, archaeological, or other cultural values for local communities. (See Chapter 17.)

20.3 Condition of Inland Water Systems

The information base for assessing the condition of inland water systems globally is widely documented and summarized in many reports (e.g., Finlayson et al. 1992; Finlayson and Moser 1991; Moser et al. 1993, 1996; Whigham et al. 1993; Mitsch 1994; McComb and Davis 1998). But it is as widely documented that at a global or continental scale there are large gaps in information (Finlayson and Spiers 1999; Darras et al. 1999; Revenga et al. 2000; Brinson and Ines Malvare 2002; Junk 2002; Malmqvist and Rundle 2002; Williams 2002). The information in this section on the biodiversity of inland water systems is largely based on analyses undertaken by Revenga and Kura (2003), which made use of global and regional-scale datasets while identifying the inadequacy of many information sources and the difficulties of gaining access to others.

20.3.1 Extent and Change of Inland Water Systems

Estimates of the extent of wetlands at a global level vary from 530 million to 1,280 million hectares, but it is *well established* that this is a clear underestimate (Spiers 1999; Finlayson et al. 1999). Estimates of the global extent of wetlands are highly dependent on the definitions for wetlands used in each inventory, the type of source material available, the methodology used, and the objectives of the investigation. The 1999 *Global Review of Wetland Resources and Priorities for Wetland Inventory* estimated wetlands extent from national inventories as approximately 1,280 million hectares (Finlayson et al. 1999), which is considerably higher than previous estimates derived from remotely sensed information.

Nevertheless, the GRoWI figure is considered an underestimate, especially for the Neotropics. For example, Ellison (2004) contends that in central America the savannas should be classed as seasonal wetlands rather than grasslands; it is not known if this is the case in other savanna landscapes. Analyses of wetland inventory in Mexico (CNA-INUBAN 1999) and Brazil (Maltchik 2003) similarly illustrated the poor state of knowledge covering wetland classification and inventory. Another limitation of the data used in GRoWI is that for certain wetland types (such as intermittently flooded inland wetlands, peatlands, artificial wetlands, seagrasses, and coastal flats), data were incomplete or not readily accessible (Finlayson et al. 1999).

Even so, the data collated by Finlayson et al. (1999) suggest that the largest area of wetlands is in the Neotropics (32%), with large areas also in Europe and North America. But note that figures provided by Lehner and Döll (2004) (see Table 20.4) suggest that Asia may contain a greater and Europe a lesser area of wetlands. Table 20.4 presents the two best available estimates from

Table 20.4. Estimates of Inland (Non-marine) Wetland Area (Finlayson et al. 1999; Lehner and Döll 2004)

Region	1999 Global Review of Wetland Resources	2004 Global Lakes and Wetlands Database
	(million hectares)	
Africa	121–125	131
Asia	204	286
Europe	258	26
Neotropics	415	159
North America	242	287
Oceania	36	28
Total area	**~ 1,280**	**~ 917**

Note: Not all wetland types are equally represented in the underlying national inventory data. Some countries lack information on some types of wetlands.

wetlands extent: the GRoWI assessment (Finlayson et al. 1999) and the WWF/Kassel University Global Lakes and Wetlands Database (GLWD) (Lehner and Döll 2004).

Mapping exercises have been undertaken for inland waters, but the level of detail varies from region to region. The most recent global map, with a 1-minute resolution, was produced by combining various digital maps and data sources (Lehner and Döll 2004), but it still suffers from the problems of definition and scale outlined by Finlayson et al. (1999). Problems with the scale and resolution of data sources for inventory have been shown for northern Australia, where estimates of the area of inland water systems from 10 data sources varied from 0 to 98,700 square kilometers (Lowry and Finlayson 2004).

Inventories of major river systems, including data on drainage area, length, and flow volume are available, but there is considerable variability between estimates, based on the method and definitions used. Information on river flow volume and discharge, for example, varies considerably depending on the water balance model applied and the different time periods or locations for the measurement of discharge (see Revenga and Kura 2003).

Information on the estimated 5–15 million lakes across the globe is also highly variable and dispersed (WWDR 2003). Large lakes have been mapped reasonably well, but issues of scale also occur with smaller lakes being more difficult to map. Nevertheless, there is no single repository of comprehensive lake information, which makes assessment of these water bodies difficult and time-consuming. A high proportion of large lakes—those with a surface area over 500 square kilometers—are found in Russia and in North America, especially Canada, where glacial scouring created many depressions in which lakes have formed. Tectonic belts, such as the Rift Valley in East Africa and the Lake Baikal region in Siberia, are the sites of some of the largest and most "ancient" lakes, all of which have highly diverse species assemblages. Some of the largest lakes are saline, with the largest by far being the Caspian Sea (422,000 square kilometers). There are many saline lakes occurring on all continents and many islands; given the impermanence of many, it is difficult to derive accurate values for their number worldwide.

Reservoirs are also widespread; the number of dams in the world has increased from 5,000 in 1950 to more than 45,000 at present (WCD 2000). These reservoirs provide water for 30–40% of irrigated agriculture land and generate 19% of global electricity supplies (WCD 2000).

Peatlands are known to occur in at least 173 countries throughout most parts of the world, from Arctic systems through temperate to tropical regions (Joosten 1992). Their total area has been estimated as approximately 400 million hectare, of which the vast majority are in Canada (37%) and Russia (30%), which together with the United States account for over 80% of the global peatland resource. The largest area of tropical peatland is in Indonesia (6–7% of the global area). Peatlands are estimated to store 30% of Earth's surface soil carbon (Joosten and Clarke 2002). The global area of paddies has been estimated as 1.3 million square kilometers (130 million hectares) (Aselmann and Crutzen 1989), of which almost 90% is in Asia, but it is likely that this figure is now out of date. Information on other human-made wetlands is variable and even lacking for some countries.

Groundwater systems have received slightly increased attention in recent years. These systems vary in size, from the small-scale alluvial sediment along rivers to extensive aquifers such as the 1.2 million square kilometers of the Guarani aquifer located across parts of Argentina, Brazil, Paraguay, and Uruguay (Danielopol et al. 2003). Groundwater systems have many connections and interactions with surface waters, although many of these are not well understood. Some aquifers are better known for their biodiversity values, such as the karst systems of Slovenia that cover some 8,800 square kilometers and are increasingly known for their high species biodiversity (see Box 20.1), while others are not known at all.

The loss and degradation of inland waters have been reported in many parts of the world (Finlayson et al. 1992; Mitsch 1998; Moser et al. 1996), but there are few reliable estimates of the actual extent of this loss. Dugan (1993) speculated that on a global scale the loss of wetlands was about 50%, but he did not provide supporting evidence, and as reliable estimates of the extent of wetlands (and particularly of intermittently inundated wetlands in semiarid lands) are lacking, it is not possible to ascertain the extent of wetland loss reliably.

The information available on the distribution of inland waters is on the whole better for North America than for many other parts of the world. The overall area of wetlands in North America includes 2.72 million hectares in Mexico (CNA-IBUNAM 1999), 127–168 million hectares in Canada (Wiken et al. 1996; Moore and Wiken 1998; National Wetlands Working Group 1988; Warner and Rubec 1997), and 43 million hectares in the conterminous United States (Dahl 2000).

As with the information on the distribution of wetlands, data on their conditions and trends are on the whole better for the United States than that for many other parts of the world. The United States is one of the few countries that systematically monitors change in wetlands extent. From the mid-1970s to mid-1980s, wetland losses (excluding lakes and rivers) in that country amounted to about 116,000 hectares per year (Dahl and Johnson 1991). This rate of loss decreased by 80% to a loss of approximately 23,700 hectares a year from 1986 to 1997, with 98% of these losses being from forested and freshwater wetlands, mostly from conversion or drainage for urban development and agricultural purposes (Dahl 2000). As of 1997, an estimated 42.7 million hectares remains out of the 89 million hectares of wetlands present in the United States at the time of European colonization (Dahl 2000).

The overall decline in the rate of loss observed in the United States is attributed primarily to wetland policies and programs that promote restoration, creation, and enhancement of wetlands, as well as incentives that deter the draining of wetlands. Between

BOX 20.1

Biodiversity of Karsts in Slovenia (Information supplied by G. Beltram from multiple sources)

Approximately 8,800 square kilometers or 44% of the surface area of Slovenia is carbonate bed-rock, known as karst. It is very permeable and supports many caves and fissures. Over many centuries the karst areas have been greatly modified by humans, with eventual replacement of the deciduous forests by dry, rocky pastures and meadows, small arable fields, dry stone walls, and karst pools. Logging, grazing, forest fires, and strong winds have further degraded the karsts through soil erosion and exposed a stark and bare-stone landscape. In the last 50 years or so, further change has occurred as local people abandoned the agricultural land and as shrubs and trees invaded meadows and arable fields—changing the vegetation structure and cultural significance of these areas (Beltram and Skoberne 1998). Pollution and habitat destruction are also problematic.

The subterranean caves and fissures within the karst are important for biodiversity as well as human use. The subterranean fauna, particularly aquatic stygobiontic species, is very rich and includes about 800 endemic fauna taxa. Many species also have extremely small distributions. The fauna in the caves is varied, with many species not found elsewhere—for example, the cave vertebrate (*Proteus anguinus*), tubeworm (*Marifugia cavatica*), mollusk (*Kerkia kusceri*), cnidarian (*Velkovrhia enigmatica*), and water fleas (*Alona sketi* and *A. stochi*), as well as a number of stygobiontic snails (*Gastropoda*) and epizoic turbellearians (*Temnocephalida*). Additionally, the crustacean fauna, including amphipods, copepods, and isopods, is extremely rich.

The karst landscape has a strong cultural heritage dating back centuries. Significant settlements were constructed near natural springs, and natural and human-made pools were used for watering domestic animals. With the demise of agricultural activities, some caves have become popular tourist destinations. Groundwater from the karst is a very important source of domestic water supply for almost half of Slovenia's inhabitants, making recharge of this source a very important function of the landscape.

1986 and 1997, the country had a net gain of about 72,870 hectares of upland wetlands, mostly due to Federal protection and restoration programs and an increase in the area of lakes and reservoirs by 47,000 hectares due to creation of new impoundments and artificial lakes (Dahl 2000).

20.3.2 Status of Inland Water Species

Data on the condition and trends of freshwater species are for the most part poor at the global level, although some countries have reasonable inventories and indicators of change of inland water species (such as Australia, Canada, New Zealand, South Africa, and the United States) (Revenga and Kura 2003). This does not mean that data are not available; there are considerable data on freshwater species and populations, but they are not easily accessible. For example, there are many extensive records in museums and universities around the world, but these are often not centrally located or electronically archived.

Revenga and Kura (2003) assessed the level of knowledge of the distribution and condition of inland water biodiversity at the global level. Key conclusions from this assessment indicated that fish and waterbirds are by far the best studied groups of inland water species, although with considerable regional differences; that aquatic plants, insects, freshwater mollusks, and crustaceans are poorly known or assessed in most parts of the world, with very fragmentary information available; and that every group of organisms considered, including aquatic plants, invertebrate, and vertebrate animal species, contained examples of extinct, critically endangered, endangered, and vulnerable taxa.

Although small in global area compared with marine and terrestrial ecosystems, inland water systems are relatively species-rich (McAllister et al. 1997). (See Table 20.5.) Marine systems contain over six times as many known species as inland waters, but cover over two thirds of the globe, compared with inland water systems, which occupy less than 1% as much area. Over three quarters of known species are terrestrial, but these systems have similar relative species richness to inland water systems. Inland water systems also support a disproportionately large number of species of some taxonomic groups. For instance, some 40% of known species of fish inhabit inland waters (more than 10,000 species out of 25,000 species globally), and about 25–30% of all vertebrate species diversity is concentrated close to or in inland waters (Lévêque et al. in press). There are about 100,000 described species of freshwater fauna worldwide (Lévêque et al. in press). Half of these are insects (see Table 20.6), about 12,000 are crustaceans, 5,000 are mollusks, and some 20,000 are vertebrate species. It is anticipated that the number of aquatic animals will be far higher than current estimates as more species from inland waters are described every year—about 200 new fish species are described each year (Lundberg et al. 2000).

Because many inland wetlands are geographically isolated, levels of endemism of freshwater species are particularly high, especially in ancient lakes, such as the Great East African Lakes (Tanganyika, Malawi, and Victoria), Lake Baikal, Lake Biwa, and Lake Ohrid, which have been isolated for millions of years (Lévêque et al. in press).

The *IUCN Red List,* a widely used indicator for assessing the conservation status of plants and animals, does not comprehensively assess inland water species. For instance, only a very small proportion of the species in most freshwater taxa, such as aquatic plants, mollusks, crustaceans, and insects, have been assessed. However, among the taxa that have been comprehensively assessed, such as amphibians and birds, a high number of species are threatened with extinction (IUCN 2003), as described further later in this section.

Another global measure of the status of animal species is the Living Planet Index developed by WWF and UNEP-WCMC (Loh and Wackernagel 2004). The LPI provides a measure of the trends in more than 3,000 populations of 1,145 vertebrate species around the world. It is an aggregate of three separate indices of

Table 20.5. Relative Species Richness of Different Ecosystems (McAllister et al. 1997)

Ecosystems	Habitat Extent	Species Diversity	Relative Species Richness [b]
	(percent of world)	*(percent of known species)*[a]	
Freshwater	0.8	2.4	3.0
Marine	70.8	14.7	0.2
Terrestrial	28.4	77.5	2.7

[a] Does not add up to 100 because 5.3% of known symbiotic species are excluded.

[b] Calculated as the ratio between species diversity and habitat extent

Table 20.6. Current State of Knowledge of Global Species Richness of Inland Water Animal Groups (Lévêque et al. in press; Revenga and Kura 2003; IUCN et al. 2004)

Phylum	Described Species
	(number)
Porifera (sponges)	197
Cnidaria (hydra, freshwater jelly fish)	30
Nemertea (ribbon worms)	12
Plathelminthes (flatworms)	c. 500
Gastrotrichia	c. 250
Rotifers	1,817
Nematods (microscopic worms)	3,000
Annelids (segmented worms)	c. 1,000
Bryozoa (moss animals)	70—75
Mollusks (mussels, snails, slugs, etc.)	c. 6,000
Crustaceans (crabs, crayfish, etc.)	c. 12,000
Arachnids (spiders, etc.)	5,000
Insects	> 50,000
Vertebrates	
Fish	13,400
Amphibians	3,533
Reptiles	c. 250
Birds	c. 1,800
Mammals	c. 122

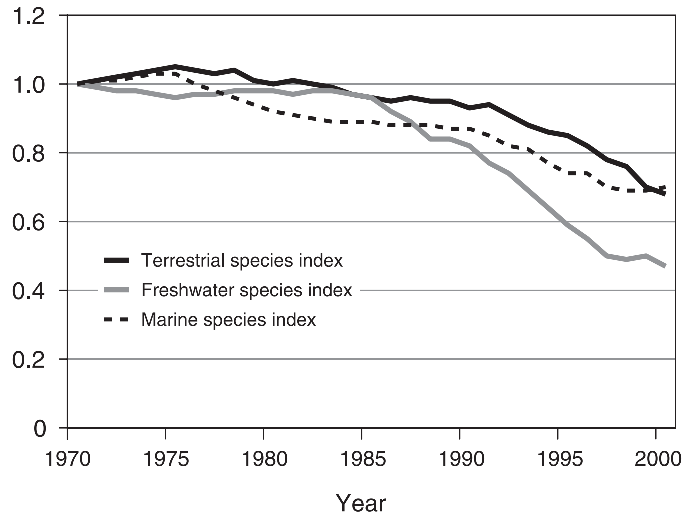

Figure 20.3. Living Planet Index for Terrestrial, Inland Water, and Marine Systems (Loh and Wacknernagel 2004)

change in freshwater, marine, and terrestrial species. The 2004 freshwater species population index, which took into account trend data for 269 temperate and 54 tropical freshwater species populations (93 of which were fish, 67 amphibians, 16 reptiles, 136 birds, and 11 mammals), shows that freshwater populations have declined consistently and at a faster rate than other species groups assessed, with an average decline of 50% between 1970 and 2000. Over the same period, both terrestrial and marine fauna decreased by 30%. (See Figure 20.3.) While the index has a bias in the available data toward North America and Europe, and particularly toward bird populations, data collection and collations have been undertaken each year to extend the veracity of this index, with initial indications of a continuing decline remaining constant (Loh and Wackernagel 2004).

20.3.2.1 Aquatic Plants and Fungi

The definition of aquatic plants has been and is still debated, but in general plants that tolerate or require flooding for a minimum duration of time are considered wetland plants. Aquatic macrophytes include angiosperms (flowering plants), macroalgae, pterophytes (pteridophytes, ferns), and bryophytes (mosses, hornworts, and liverworts). Gymnosperms (conifers, cycads, and their allies) do not have strictly aquatic representatives, but include a number of tree species that tolerate waterlogged soil, such as the bald cypress.

It is estimated that up to 2% (250 species) of pterophytes and 1% (2,500 species) of angiosperms are aquatic, but their geographic distribution, diversity patterns, or conservation status have not been summarized globally, although information exists for specific regions. Some families of aquatic angiosperms show highest diversity at tropical latitudes, while others show higher diversity in temperate regions, making it evident that the typical latitudinal gradient found in terrestrial species diversity does not apply. Locally, many macrophyte species may be threatened or lost, especially in lakes undergoing eutrophication; as an example, many isoetid species are widespread but increasingly threatened throughout their range (e.g. Nichols and Lathrop 1994). The maximum diversity of bryophytes is found in highly oceanic regions, where cool or temperate and consistently moist climate conditions persisted over geological time (Groombridge 1992). Bryophytes found in lowland aquatic environments, including pools and reservoirs, tend to have very restricted distribution and therefore are rare and threatened (Revenga and Kura 2003).

A relatively small fraction (over 600 species) of fungi are considered freshwater species, but recent studies indicate that there are many more freshwater fungi to be discovered in temperate and tropical regions; the total number estimated at between 1,000 and 10,000 (Palmer et al. 1997). Information on the conservation status of aquatic fungi is very limited.

20.3.2.2 Invertebrates

Information on aquatic invertebrate species diversity is fragmentary, with a few descriptive global overviews of particular taxa and some more detailed regional inventories. The conservation status of aquatic invertebrates has not been comprehensively assessed, except for regional assessments of certain taxonomic groups such as Odonata (dragonflies and damselflies; see Box 20.2) (Clausnitzer and Jodicke 2004), freshwater mollusks (mostly mussels), and freshwater crustaceans (Master et al. 1998; IUCN 2003). Assessments of the status of known mollusk species have been conducted for a limited number of taxa and regions, including the Mekong, which has a very diverse freshwater mollusk fauna (Dudgeon 2002a, 2002b, 2002c); Lake Biwa, Japan, which has 73% of the freshwater mussel species described in the country, of which 43% are endemic; and Lakes Baikal, Tanganyika, and Titicaca. (See Box 20.3.)

IUCN (2003) reports 130 freshwater species of aquatic insects, 275 species of freshwater crustacean, and 420 freshwater mollusks as globally threatened, although no comprehensive global assessment has been made of all the species in these groups. For the

BOX 20.2

Status of Odonata (Dragonflies and Damselflies)
(Clausnitzer and Jodicke 2004)

A recent global review of the threat status of dragonflies and damselflies in 22 regions covering most of the world (except for parts of Asia) found that there are many more dragonfly species now regarded as threatened than are listed in the *IUCN Red List,* which currently lists 130 species (*medium certainty*). It is important to note, however, that the criteria and categories used to assess conservation status are not harmonized across regions.

In Australia, for example, there are 4 species currently on the *Red List* as globally threatened but another 25 are considered to be in critical condition and an additional 30% of species are data-deficient in regional assessments. In North America, 25 species (6%) are of conservation concern; in the Neotropics, 25 species are considered globally threatened and a further 45 species are considered of high conservation priority, with many others being data-deficient. In eastern Africa, 90 species are considered appropriate for globally threatened status. And in southern Africa, although 2 species are currently recognized as globally threatened, a further 11 are now considered threatened in regional assessments. In Madagascar, 2 species are currently recognized as globally threatened, but because of high diversity and endemism, a large number—111 species, 64% of the fauna—are of conservation concern, although all species are data-deficient. In the Western Indian Ocean Islands, 3 species are recognized as globally threatened and 33 are now regarded as critical; in Sri Lanka, no species are currently on the *Red List,* although 47 species (all endemic) are regarded as threatened with extinction. Finally, in Europe 6 species are *Red-listed,* although two of these are now considered out of danger, and a further 22 species are of concern as their populations are declining. And in Turkey, Iran, and the Caucasus, there are 5 species on the *Red List* and 27 regarded as critical.

In most areas assessed, habitat loss and degradation of wetlands (and forests) were considered the major drivers of declines in Odonate species, often associated with overabstraction and pollution of water as well as the impacts of alien invasive species.

BOX 20.3

Endemism of Mollusks in Inland Waters

Twenty-seven areas of special importance for freshwater mollusk endemism worldwide have been identified, in three types of wetlands:

- ancient lakes: Baikal, Biwa, and Tanganyika, where 70%, 52%, and 64% of molluscan species are endemic respectively;
- lower river basins: 93% of the total freshwater mollusk species found in the Mobile Bay region of the Alabama-Tombigbee River basin in the United States are endemic; another notable center of endemism is found in the Lower 500 kilometers of the Mekong River basin, where 92% of molluscan species are endemic; and
- springs and underground aquifers (Australia, New Caledonia, the Balkans, western United States, Florida, and the Cuatro Cienegas basin in Mexico).

Inland Waters	Gastropods	Bivalves	Total
	%	%	%
Ancient lakes			
Baikal	78	52	73
Biwa	50	56	52
Sulawesi	c. 80	25	c. 76
Tanganyika	66	53	64
Malawi	57	11	46
Victoria	46	50	48
Ohrid	76		
Titicaca	63		
Major river basins			
Mobile Bay Basin	93	54	78
Lower Uruguay River and Rio de la Plata	48	21	37
Mekong River (lower 500 km)	92	13	73
Lower Congo basin	25	n/a	
Lower Zaire basin	25	n/a	

United States, one of the few countries to assess freshwater mollusks and crustaceans comprehensively, 50% of known crayfish species and two thirds of freshwater mollusks are at risk of extinction, and at least one in 10 freshwater mollusks are likely to have already gone extinct (Master et al. 1998).

20.3.2.3 Freshwater Fish

Most global and regional overviews of freshwater biodiversity include more information on fish than any other taxa (Cushing et al. 1995; Gopal et al. 2000; Groombridge and Jenkins 1998; Maitland and Crivelli 1996). A number of regional overviews of the status of freshwater fish are available, yet many of the existing overviews underestimate the number of species, as there are still many species to be described and assessed. There is, therefore, a high level of uncertainty about the status of fish in many inland waters. Estimates of the number of freshwater fish in Latin America vary from 5,000 to 8,000; in tropical Asia and Africa, there are an estimated 3,000 species on each continent (Revenga and Kura 2003), although these figures are almost certainly underestimates. The Mekong River alone is considered to have 1,200–1,700 species (WRI et al. 2003). (See Box 20.4.) North America is estimated to have more than 1,000 species, and Europe and Australia have several hundred species each (Revenga and Kura 2003).

With respect to their conservation status, estimates are that in the last few decades more than 20% of the world's 10,000 described freshwater fish species have become threatened or endangered or are listed as extinct (Moyle and Leidy 1992). The *IUCN Red List* (2004) classifies 648 freshwater ray-finned fish species as globally threatened. However, the coverage for freshwater fish is highly biased to particular regions for which more data are available, such as North and Central America or the African Rift Valley Lakes. For example, of the ray-finned fishes listed as threatened in the *IUCN Red List,* 122 are found in the United States and 85 in Mexico, partially reflecting the high level of knowledge in these two countries (IUCN 2003).

In the 20 countries for which assessments are most complete, an average of 17% of freshwater fish species are globally threatened. In addition, there are a few well-documented cases that show clearly this level of threat. The most widely known is the apparent disappearance of between 41 and 123 haplochromine cichlids in Lake Victoria (Harrison and Stiassny 1999), although taxonomic questions remain a problem in accurately assessing this group of fish. In Europe (including the former Soviet Union), BOX 20.4

Species Diversity of the Mekong River (Information supplied by A. Lopez; see Mattson et al. 2002)

The vertebrate fauna of the Mekong River basin is difficult to quantify due to the incomplete state of the inventory and taxonomic effort. Many published figures are considered to be underestimates. The Mekong River Commission (1997) estimated that in the Laotian, Vietnamese, Cambodian, and Thai part of the basin there were some 830 mammal species, 2,800 bird species, 1,500 fish species, 250 amphibians, and 650 reptiles.

Many of these species are threatened. For example, among the mammals this includes the fishing cat (*Prionailurus viverrinus*), the hairy-nosed otter (*Lutra sumatrana*), the smooth-coated otter (*Lutrogale perspicillata*), and the Oriental small-clawed otter (*Aonyx cinerea*). A high proportion of bird species are in decline (Dudgeon 2002), particularly those that rely on sandbars and large river stretches for breeding or feeding. These include the Plain Martin (*Riparia paludicola*) and the now extinct White-eyed River Martin (*Pseudochelidon sirintarae*). Two crocodile species occur, although the population of the estuarine crocodile (*Crocodylus porosus*) is likely very low. A number of aquatic and semi-aquatic turtles, snakes, and lizards occur, many of which are hunted for subsistence or sold for food and medicine in local markets. A substantial illegal market also exists for many wildlife products.

The fish fauna is considered to be diverse, although this has not been well documented. There are an estimated 700 freshwater fish species in Cambodia. The diversity at a family level seems to be high, with some 65 families in the Cambodian and 50 in the Laotian parts of the basin. Fish introductions have occurred with the Nile tilapia (*Oreochromis niloticus*) and mosquito fish (*Gambusia affinis*), now considered as pests. A number of large native species have declined—the giant catfish (*Pangasianodon gigas*), river catfish (*Pangasius sanitwongsei*), thicklip barb (*Probarbus* labeamajor), and the giant barb (*Catlocarpio siamensis*) are now rare (Mattson et al. 2003).

there are 67 threatened species of freshwater fish, including sturgeons, barbs, and other cyprinids (IUCN 2003).

20.3.2.4 Amphibians

Amphibians are found in many types of freshwater habitats—from ponds, streams, and wetlands to leaf litter, trees, underground, and vernal (temporary) pools. Although some amphibians thrive in cold or dry conditions, the group reaches its highest diversity and abundance in warm, humid climates.

The recent Global Amphibian Assessment (IUCN et al. 2004) lists 5,743 known species of frogs, toads, salamanders, and caecilians, of which 3,908 species depend on fresh water during some stage of their life cycle, while the rest do not require fresh water to breed or develop. The study also shows nearly one third (1,856 species) of the world's amphibian species are threatened with extinction, a large portion of which (964 species) are freshwater—a far greater level of threat than for birds (12% of all species) and mammals (23% of all species). In addition, at least 43% of all species are declining in population, indicating that the number of threatened species can be expected to rise in the future. In contrast, less than 1% of species show population increases.

The rate of decline in the conservation status of freshwater amphibians is far worse than that of terrestrial species. As amphibians are excellent indicators of the quality of the overall environment, this underpins the notion of the current declining condition of freshwater habitats around the world.

Species associated with flowing water were found to have a higher risk of extinction than those associated with still water. For species of known status (that is, excluding those that are data-deficient), as many as 42% are globally threatened and as many as 168 amphibian species may already be extinct—at least 34 amphibian species are known to be extinct, while another 134 species have not been found in recent years and are possibly extinct. Salamanders and newts have an even high level of threat (46% globally threatened or extinct) than frogs and toads (33%) and Caecilians (2%, although knowledge of these is poor, with only one third assessed).

The largest numbers of threatened species occur in Latin American countries such as Colombia (208 species), Mexico (191 species), and Ecuador (163 species). However, the highest levels of threat are in the Caribbean, where more than 80% of amphibians are threatened in the Dominican Republic, Cuba, and Jamaica, and 92% in Haiti (IUCN et al. 2004). The major threat to amphibians is habitat loss, but a newly recognized fungal disease is seriously affecting an increasing number of species. Those species dependent on flowing water (usually streams) have a much higher likelihood of being threatened than those that use still water (often temporary rain-fed pools or other small freshwater pools). (See Figure 20.4 in Appendix A.) Basins with the highest number of threatened freshwater amphibians include the Amazon, Yangtze, Niger, Parana, Mekong, Red and Pearl in China, Krishna in India, and Balsas and Usumacinta in Central America. All these basins have between 13 and 98 threatened freshwater species.

20.3.2.5 Reptiles

There are around 200 species of freshwater turtles throughout the warm temperate and tropical regions of the world; information on the distribution of these species is available through the World Turtle Database (emys.geo.orst.edu), which contains maps of all the known localities of every freshwater (and terrestrial) turtle species. Of the 200 species of freshwater turtles, 51% of the species of known status have been assessed as globally threatened, and the number of critically endangered freshwater turtles more than doubled in the four years preceding 2000 (van Dijk et al. 2000). Of 90 species of Asian freshwater turtles and tortoises, 74% are considered globally threatened, including 18 species that are critically endangered and one, the Yunnan box turtle, which is already extinct (van Dijk et al. 2000).

Crocodiles, alligators, caimans, and gharials are widespread throughout tropical and sub-tropical aquatic habitats. Of the 23 species of crocodilians, which inhabit a range of wetlands including marshes, swamps, rivers, lagoons, and estuaries, 4 are critically endangered, 3 are endangered, and 3 are vulnerable (IUCN 2003). The other species are at lower risk of extinction, but depleted or extirpated locally in some areas (Revenga and Kura 2003). The most critically endangered crocodilian is the Chinese alligator, which is restricted to the lower reaches of the Yangtze River; it is estimated that only 150 individuals remain in the wild (IUCN/SSC Crocodile Specialist Group 2002). The major threats to crocodilians are habitat degradation and overexploitation (Revenga and Kura 2003).

There are several species of freshwater snakes in the world. The wart or file snakes (*Acrochordidae*) are adapted to aquatic life, with two species occurring in freshwater habitats (Uetz and Etzold 1996); there is little information on their conservation status. In addition, there are many semi-aquatic snakes, with some being considered vulnerable (IUCN 2003).

20.3.2.6 Birds

Waterbirds (bird species that are ecologically dependent on wetlands), particularly migratory waterbirds, are relatively well studied, with time series data available for some populations in North America and Southern and Northwest Europe for up to 40 years. Global information on waterbird population status and trends is compiled and regularly updated (Wetlands International 2002).

Detailed information and review of status for waterbird species has been compiled in North America (Morrison et al. 2001; Brown et al. 2001; U.S. Fish and Wildlife Service 2004) and for the Western Palaearctic and Southwest Asia (e.g., Delany et al. 1999). For African-Eurasian waterbird populations, comprehensive analyses have been compiled for Anatidae (ducks, geese, and swans) (e.g., Scott and Rose 1996) and waders (Charadrii) (Stroud et al. 2004). In East Asia, Bamford et al. (in press) have collated and reviewed the current status and trends of waders, while information for Gruidae (cranes) and Anatidae is available from Miyabayashi and Mundkur (1999) and the Asia-Pacific Migratory Waterbird Conservation Committee (2001). Networks of both large and small wetlands along migratory flyways are of key importance as resting and feeding sites. In semiarid landscapes, many waterbirds migrate in response to periodic and regionalized flooding that produces a temporally dispersed array of habitats (Roshier et al. 2001). The wetlands in the Sahel region of Africa provide a good example. (See Box 20.5.)

In all regions, population sizes of waterbirds are better known than population trends. Trends have been estimated for half of all waterbird populations and almost three quarters of European populations, but for only one third of populations in the Neotropics, and many trends are yet to be statistically quantified. The status of sedentary populations is much less well known that that of migratory ones.

Many waterbird species are globally threatened (Davidson and Stroud 2004), and the status of both inland and marine/coastal birds is deteriorating faster than those in other habitats (*high certainty*). Of the 35 bird families whose species are wholly or predominantly coastal/marine or inland wetland-dependent, 20% of the 1,058 species for which assessment data exist are currently globally threatened or extinct. Of these, 42 species—half of which are island-endemic rails—are extinct and 41 species (4%) are critically endangered. There are globally threatened species in 60% of these families. The percentage of globally threatened waterbirds (including seabirds) is shown in Figure 20.5.

The status of birds continues to deteriorate in all parts of the world and across all major habitat types (*high certainty*). Waterbirds dependent on freshwater ecosystems, especially those using marine and coastal ecosystems, have deteriorated in status faster than the average for all threatened species (see Figure 20.6), but similarly to other migratory bird species.

Shorebirds are declining worldwide: of populations with a known trend, 48% are declining (Stroud et al. 2004). Other waterbirds have as bad or worse global status as shorebirds, including

BOX 20.5

Sahel Wetlands (Information supplied by J. Brouwer: www.iucn.org/themes/cem)

The Sahel area of Africa is an important area for migratory birds, situated between the Sahara desert to the north and the more humid savanna and forests to the south. It is semiarid, with 200–600 millimeters of rainfall per year, and comprises the wetlands of the Senegal River, the Inner Delta of the Niger in Mali, the Hadejia-Nguru wetlands in northern Nigeria, Waza-Logone in northern Cameroon, and Lake Chad, as well as thousands of smaller, isolated wetlands.

In Niger, an estimated 1.1 million waterbirds are present during January-February, with 750,000 on the smaller, isolated wetlands. As in other semiarid regions, the waterbirds depend on a network of wetlands that are variously wet and dry, spatially and temporally. The water chemistry and vegetation composition also varies between wetlands, providing a diversity of habitats that is essential for the many birds that migrate through the region.

The wetlands are also used extensively by local people, as they are highly productive and important for grazing, fishing, and market gardening. As the human population has increased, so has pressure on these wetlands—land use is becoming more intensified, and many wetlands are threatened with change, which in turn is likely to adversely affect the waterbird populations that depend on these.

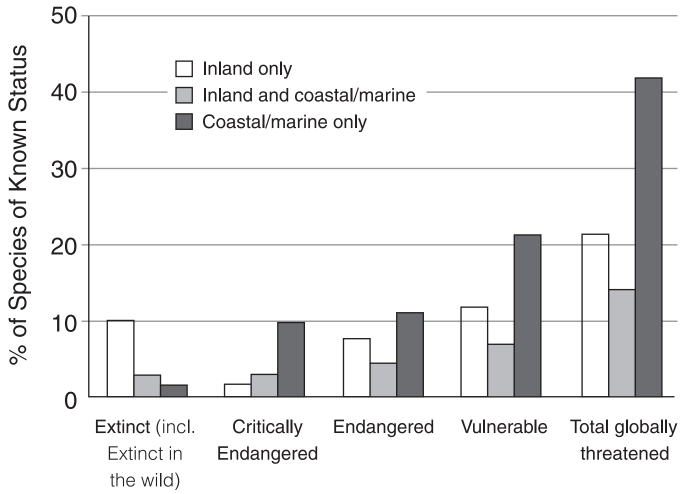

Figure 20.5. Percentage of Globally Threatened Waterbirds, Including Seabirds, in Different Threat Categories. Each waterbird family is allocated as either depending on only inland wetlands, depending on only coastal/marine systems, or depending on both inland and coastal/marine systems. (BirdLife International 2004)

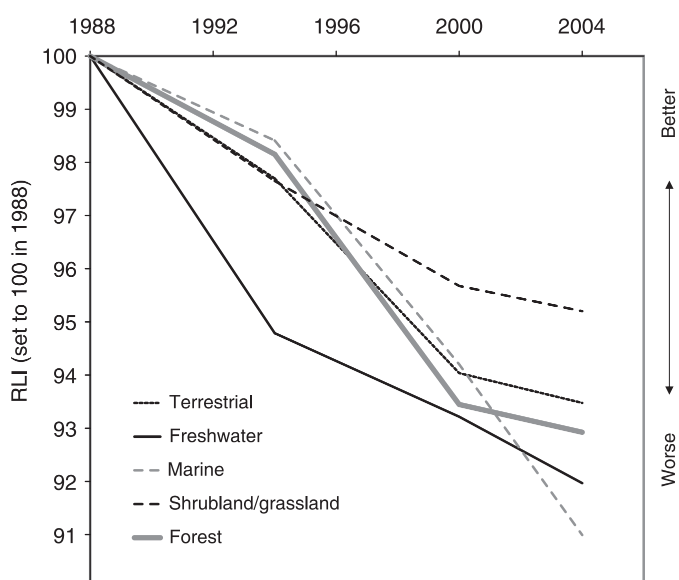

Figure 20.6. Red List Indices for Birds in Marine, Freshwater, and Terrestrial Ecosystems and for Birds in Forest and Shrubland/Grassland Habitats (Butchart et al. in press)

divers (67% of populations of known trend decreasing), cranes (47%), rails (50%), skimmers (60%), darters (71%), ibis and spoonbills (48%), storks (59%), and jacanas (50%). Only gulls (18%), flamingos (18%), and cormorants (20%) appear to have a relatively healthy status. A similar picture emerges for at least one region, Africa-Eurasia, where the status of some waterbird families is even worse than their global status. In this region, only grebes and gulls (9% decreasing) appear to have a relatively healthy status.

20.3.2.7 Mammals

Although most mammals depend on fresh water for their survival, and many feed in rivers and lakes or live in close proximity to freshwater ecosystems, as exemplified by many large mammals in Africa, only a few are considered aquatic or semi-aquatic mammals. Revenga and Kura (2003) provide an analysis of the status of aquatic and semi-aquatic mammals, including water otters, shrews, demans, tenrecs, marsh and swamp rabbits, aquatic rodents such as beavers, muskrats, nutria, and the capybara. Otters, seals (such as the Lake Baikal seal (*Phoca sibrica*)), manatees, river dolphins, and freshwater porpoises are among the most threatened mammals in the world. For example, of the five species of Asian freshwater cetaceans, four are threatened with extinction and one species, the Irrawaddy River dolphin, is data-deficient (IUCN 2003). Some 37% of inland water-dependent mammals are globally threatened, compared with 23% of all mammals (Revenga et al. in press). This includes otters (50% of species of known status threatened), seals (67% threatened), manatees (100% threatened), river dolphins and porpoises (100% threatened), and wetland-dependent antelopes (29% threatened) (Revenga et al. in press).

20.4 Drivers of Change in Inland Water Systems

Analyses over the past two decades have identified a suite of drivers of change in inland water systems (e.g. Ellison 2004; Revenga and Kura 2003; Beeton 2002; Brinson and Ines Malvarez 2002; Junk 2002; Malmqvist and Runndle 2002; Tockner and Stanford 2002; Finlayson et al. 1992; Finayson and Moser 1991; Moser et al. 1993, 1996; Whigham et al. 1993; Mitsch 1994; McComb and Davis 1998; Williams 2002). These reviews have focused mainly on biophysical pressures that are currently directly affecting adversely, or are likely to in the future, the ecological condition of inland water systems. The direct drivers of change in inland water systems are presented diagrammatically in Figure 20.7 (in Appendix A) (Ratner et al. 2004). The importance of also addressing the indirect drivers of wetland change has been increasingly recognized—for example, in Australia (Finlayson and Rea 1999) and most emphatically in the Mediterranean (Hollis 1992).

The direct drivers of wetland and riverine loss and degradation include changes in land use or cover due to vegetation clearance, drainage, and infilling; the spread of infrastructure whether for urban, tourism and recreation, aquaculture, agriculture, industrial, or even military purposes; the introduction and spread of invasive species; hydrologic modification to inland waters; overharvesting, particularly through fishing and hunting; pollution, salinization, and eutrophication; and, more recently, global climate change. These issues have been explored in many site-based analyses and comprehensive databases, and inventories for some exist or are being developed, while others are only now being assessed in a systematic manner (Kira 1997; Finlayson et al. 1999; Jorgensen et al. 2001; Revenga and Kura 2003).

In some cases many drivers operate together. For example, Finlayson et al. (1993) provide an analysis of the effects of multiple drivers on wetland habitats in the lower Volga, Russia, and further information on the multiple drivers and changes in the Caspian Sea is given in Box 20.6. Too often, though, these pressures are addressed in isolation and without an adequate information base; climate change is expected to exacerbate the problems. While the effect of such drivers on inland water systems is known with *medium*-to-*high certainty,* management responses are often undermined by an absence of sufficient information. The same drivers that affect surface waters, especially those associated with agricultural, urban, and industrial development, have also contributed to the degradation of groundwater systems (Danielopol et al. 2003).

20.4.1 Physical Change, Including Drainage, Clearing, and Infilling

Outside Western Europe and North America (including Mexico), there is very little systematic information available on the extent of loss of inland waters. The loss of wetlands worldwide has been speculated at 50% of those that existed in 1900 (Dugan 1993)—a figure that includes inland wetlands and possibly mangroves, but not large estuaries and marine wetlands. Although the accuracy of this figure has not been established due to an absence of reliable data (Finlayson et al. 1999), it is *well established* that much of the loss of wetlands has occurred in the northern temperate zone during the first half of the twentieth century.

BOX 20.6

Caspian Sea (Adapted from many sources, including www.grida.no/soe.cfin?country = caspian_*sea* and www.caspiamenvironment.org)

The Caspian Sea is the largest inland water body and is surrounded by Azerbaijan, Iran, Kazakhstan, Russia, and Turkmenistan. It is a major economic asset to the region, being rich in hydrocarbon deposits and many species of fish, crustaceans, and shrimp. Some waterbirds and the Caspian seal are also commercially hunted. The Volga River in the northwest provides about 80% of the annual 300 cubic kilometers of freshwater inflow. Evaporation is more than one meter per year, while salinity ranges from fresh to highly saline in the Kara Bogaz Gol, a small basin along the Turkmen coastline. The sea supports a diverse range of habitats and species, including many endemic aquatic taxa.

The sea is under great pressure from desertification and deforestation, river regulation, urbanization and industrial development, agricultural and aquacultural development, and pollution. The water is polluted and eutrophic and has been invaded by many non-native species. There are growing fears of further contamination from oil and gas developments. The comb jelly fish (*Mnemiopsos leidyi*) has invaded and spread throughout the Caspian more rapidly than it did in the Black Sea. (See Chapter 19.)

The value of the caviar industry has been greatly affected by an 80% decrease in sturgeon landings between 1985 and 1995. This has been caused by reduced access to breeding grounds due to the construction of large dams along the inflowing rivers, pollution, overfishing, and conversion of surrounding habitat to rice cultivation. Fluctuating sea levels over many decades have also resulted in major changes to the aquatic flora and vegetation of the Volga delta and riparian forests of the Samur delta. Mass mortalities of Caspian seals, one of only two freshwater species, have been reported, likely as a consequence of pollution by heavy metals and persistent organic pollutants.

The health and lifestyle of many people in the region have been adversely affected by changes to the sea and the surrounding landscape. This has included health effects of pollution as well as reduced access to resources and basic food commodities.

Since the 1950s, many tropical and sub-tropical wetlands, particularly swamp forests, have increasingly been lost or degraded. (See Box 20.7.) In South America, peatlands linked with the Andean paramos ecosystems, also called the high mountain water towers, are increasingly targeted for agriculture, including the practices of drainage and burning (Hofstede et al. 2003). A recent inventory of Patagonian peatlands (Blanco and Balze 2004) identified agriculture and forestry as the main causes of peatland disturbance, with peat mining (mainly for use in agriculture and horticulture) as a third, but increasing, threat.

It is highly certain that clearing or drainage for agricultural development is the principal cause for wetland loss worldwide. By 1985 it was estimated that 56–65% of available wetland had been drained for intensive agriculture in Europe and North America, 27% in Asia, 6% in South America and 2% in Africa—a total of 26% loss to agriculture worldwide (OECD 1996). In China, some of the most extensive peatland areas (> 5,000 square kilometers) occur at 3,500-meters elevation on the Tibetan Plateau, the source of the Yellow and Yangtze Rivers. Large networks of drainage canals were constructed there in the 1960s and 1970s to increase the area for livestock grazing, leading to a dramatic drop in peatland area and a subsequent degradation and loss of the peat, desertification, and loss of water retention capacity (UNDP/GEF/GOC 2003).

Conversion of peatlands for intensive agriculture has been a common feature in most parts of the world for many centuries, particularly in Europe, but also more recently in the highlands of the Andes, China, and parts of Africa. The most dramatic loss of peatlands to agriculture has been in some of the countries with a rich peatland heritage, such as Finland, the Netherlands, Estonia, Denmark, and the United Kingdom. The Netherlands (once one third peatland) lost virtually all (>99%) of its natural peatlands over the last two centuries (Brag et al. 2003; Joosten 1994).

Irrigated agriculture is the leading driver in water withdrawals worldwide, resulting in large changes in river flows (Revenga et al. 2000; see also Chapter 7)—flows that are essential in sustaining ecosystem services and species. The global extent of irrigated agricultural land has increased from 138 million hectares in 1961 to 271 million hectares in 2000, and it currently accounts for an estimated 40% of total food production even though it represents only 17% of global cropland area (Wiseman et al. 2003). (See Chapter 26.) Its negative impacts on inland waters tend to be disproportionate to the irrigated land area involved.

Well-documented examples include the biodiversity losses and human health impacts seen in the Aral Sea in Central Asia and the impacts of water diversions on the wetlands in the Murray-Darling Basin of Australia (Kingsford and Johnson 1998; Lemly et al. 2000). The important Turkish wetland bird–breeding site, Kus Cenneti, is currently being adversely affected by low flows due to diversions during the bird breeding season, which is also the main irrigation period (De Voogt et al. 2000). Numerous detrimental changes in the ecological condition of the Hadejia-Nguru wetland complex in Nigeria have also been associated with the Kano River Irrigation Project (Lemly et al. 2000).

The Aral Sea in Central Asia represents one of the most extreme cases in which water diversion for irrigated agriculture has caused severe and irreversible environmental degradation of an inland water system. (See Box 20.8 here and Figure 20.8 in Appendix A.) The volume of water in the Aral basin has been reduced by 75% since 1960, due mainly to large-scale upstream diversions of the Amu Darya and Syr Darya flow for irrigation of close to 7 million hectares of land (UNESCO 2000; Postel 1999). This loss of water, together with excessive chemical inputs from agricultural runoff, has caused a collapse in the fishing industry, a loss of species diversity and wildlife habitat, and an increase in human pulmonary and other diseases in the area resulting from the high toxicity of the salt concentrations in the exposed seabed (Postel 1999; WMO 1997).

There are many other well-documented examples where diversion of water for agriculture has caused a decline in the extent and degradation of inland water systems and their species richness. In the majority of the cases, the most affected people are the poor, who depend on freshwater resources (whether from wetlands, rivers, and lakes) not only for drinking water but as a source of food supply, especially animal protein, and of income from fisheries, reed harvesting, and so on. Lake Chad provides an example where major ecosystem change has occurred (see Figure 20.9 in Appendix A) as a consequence of both human-induced and natural changes, with subsequent loss of many species and ecosystem services as the lake shrank from about 25,000 square kilometers in surface area to one twentieth its size over 35 years at the end of the twentieth century. A drier climate and high agricultural demands for water in more recent years are the primary reasons for Lake Chad's degradation (Coe and Foley 2001).

BOX 20.7

Southeast Asian Peatlands

In Southeast Asia, most of the once-extensive tropical peat swamp forests have been heavily degraded, and large extents have been lost over the last four decades. The main cause of this has been logging for timber and pulp. This started with selective logging of forests, but it has increasingly been replaced by clear-felling. Over the last two decades, this has been exacerbated by the conversion of peat swamp forests to agriculture, particularly oil palm plantations. The peatlands of Malaysia and Indonesia are especially threatened by persistent changes. Drainage and forest clearing threatens their stability and makes them susceptible to fire. Attempts have been made to harness the deeper peat soils, often with a high rate of failure and resulting in one of the environmental disasters of the last century, with millions of hectares of peatlands burned and emitting large amounts of CO_2 into the atmosphere.

In 1997, during a drought linked with the El Niño-Southern Oscillation, land clearing and subsequent uncontrolled fires severely burned about 5 million hectares of forest and agricultural land on the Indonesian island of Borneo (Glover and Jessup 1999; Wooster and Strub 2002). The amount of carbon released into the atmosphere from these fires reached an estimated 0.8–2.6 billion tons (Page et al. 1997). BAPPENAS-ADB (1999) reported an estimated 156.3 million tons from the 1997/98 Indonesia peat fires, based on an estimate of only 750,000 hectares being burned. Revised estimates by Tacconi (2003) of the actual area burned brings the total to 442 million tones or 27% of global emissions from land use change in 1989–95. In economic terms (using $7 per ton), this would amount to over $3 billion. A noxious, yellow haze covered the region for several months, which had a serious economic and health impact—some 200,000 people were hospitalized with respiratory, heart, and eye and nose irritations. There are ongoing concerns for the health of the 70 million people in six countries affected by the haze.

Early economic assessments place the damage to timber, agriculture, and other benefits derived from the forests at $4.5 billion in addition to the actual cost of fighting the fires (Glover and Jessup 1999). The fires compound the loss of peatlands through clearing and failed attempts to cultivate large areas for rice, such as has occurred in large areas in Kalimantan (Rieley and Page 1997).

BOX 20.8

Aral Sea (Information supplied by Elena Kreuzberg-Mukhina, Nikolay Gorelkin, Alex Kreuzberg, Vladislav Talskykh, Elena Bykova, and Vyacheslav Aparin, and taken from Micklin 1993; Beeton 2002; UNEP 2002)

The degradation of the Aral Sea as a consequence of the expansion of the area under cotton and abstraction of water for large-scale irrigation is well known. The hydrological change has included the construction of at least nine water reservoirs and 24,000 kilometers of channels, with 40% of the annual water inflow of 80–100 cubic kilometers withdrawn for irrigation. The consequences for the Aral Sea have been enormous, and although estimates of the extent of change vary, the sea is now only about 20% of its former volume. The surface area has been reduced by a half or two thirds, the water level is some 16–22 meters lower, and the salinity has increased somewhere between three and twelve times. The shoreline has retreated 100–150 kilometers and exposed something like 45,000 square kilometers of former seabed, creating a salty desert and more than 100 million tons of salty dust.

The sea now has three separate entities: the Small Sea, with an area of 3,000 square kilometers, a volume of 20 cubic kilometers, and a salinity of 18–20 grams per liter; the eastern part of the Large Sea, with an area of 9,150 square kilometers, a volume of 29.5 cubic kilometers, and a salinity of 120 grams per liter; and the western part of the Large Sea, with an area of 4,950 square kilometers, a volume of 79.6 cubic kilometers, and a salinity of 80 grams per liter.

These changes have caused a collapse of the fishing industry, and many plant and animal species have been lost. Only a few of the former 34 fish species survive, with some becoming extinct, such as the Aral sturgeon, Aral trout, Chu sharpray, Tukestan dace, and Kessler's loach. Waterbirds have similarly been drastically affected, with a loss of breeding and stopover habitats for migratory species, such as those in the deltas of the Amu Darya and Syr Darya. This has seen a decline in habitat for breeding mute swan, Dalmatian and Great White pelican, and Pygmy cormorant, among others. New habitats have been created through the construction of irrigation areas, but these do not compensate adequately for the losses.

The local climate has been dramatically affected. For example, the average humidity has decreased from around 40% to 30%, leading to increased desertification, with subsequent loss of pasture productivity and impacts on human well-being. The latter is also associated with the pollution of the water and increased occurrence of dust storms. The consequences of the management decisions for the Sea have been drastic, but some at least were foreseen, and deliberate trade-offs were made in favor of economic outcomes. In 1995, the cost of making a net water saving of 12 cubic kilometers was estimated as $16 billion, but the prospects for funding were limited, and so it is likely that current conditions will prevail, with the continuing demise of the aquatic ecosystem and human well-being.

However, with the collapse of the agricultural industry in the region in recent years, the demand for water has decreased to some extent, and partly alleviated the situation. (For further information on the human well-being consequences of changes to the Aral Sea, see Chapter 5.)

20.4.2 Modification of Water Regimes

Water regimes of inland waters have been modified by humans for centuries, with the last 50 years in particular witnessing large-scale changes in many parts of the world, often associated with drainage and infilling activities as described earlier (Brinson and Ines Malvarez 2002; Junk 2002; Malmqvist and Rundle 2002; Tockner and Stanford 2002; see also reviews cited earlier). Modifications include construction of river embankments to improve navigation, drainage of wetlands for agriculture, construction of dams and irrigation channels, and the establishment of inter-basin connections and water transfers. (See Table 20.7 and Boxes 20.9 and 20.10; see also Chapter 7.) These changes have improved transportation, provided local flood control and hydropower, boosted fisheries, and increased agricultural output by making more land and irrigation water available. At the same time, physical changes in the hydrological cycle have resulted in the disconnection of rivers from their floodplains and wetlands, caused seasonal changes in water flows, increased the likelihood and severity of flooding (see Chapter 16), disrupted links with groundwater systems, and enabled saline water to intrude on freshwater systems in many coastal regions.

Further, these changes have also altered the flow velocity in rivers—transforming some to large lakes, such as the Kariba lake

Table 20.7. Alteration of Freshwater Systems Worldwide (Revenga and Kura 2003)

Alteration	Pre–1990	1900	1950–60	1985	1996–98
Waterways altered for navigation (km)	3,125	8,750	–	> 500,000	
Canals (km)	8,750	21,250	–	63,125	–
Large reservoirs[a]					
Number	41	581	1,105	2,768	2,836
Volume (sq. km.)	14	533	1,686	5,879	6,385
Large dams (>15 m high)	–	–	5,749	–	41,413
Installed hydro capacity (megawatts)	–	–	< 290,000	542,000	–660,000
Hydro capacity under construction (megawatts)	–	–	–	–	–126,000
Water withdrawals (cu. km. per year)	–	578	1,984	–3,200	–3,800
Wetlands drainage[b] (cu. km.)	–	–	–	160,000	–

– Data not available.

[a] Large reservoirs are those with a total volume of 0.1 cubic kilometers or more. This is only a subset of the world's reservoirs.

[b] Includes available information for drainage of natural bogs and low-lying grasslands as well as disposal of excess water from irrigated fields.

BOX 20.9

Danube River

Engineering structures have inexorably altered the Danube River, one of the major rivers of central and eastern Europe. Since 1950, hundreds of artificial lakes have been constructed along the Danube and its tributaries to provide storage and release of water for flood control, hydropower, navigation, irrigation, and domestic and industrial water supply. The construction of dikes and reservoirs has led to the loss of floodplain zones, with important loss of habitats and modification of the Danube's hydrological and sediment regimes.

Structures built along the first 1,000 kilometers of the river have formed an almost uninterrupted artificial waterway through a chain of 59 hydropower dams. The delta has also been changed with the construction of polders, canals, dikes, and fish farms, which along with eutrophication have led to major ecological changes in the river (IUCN 1992). These changes have altered the nature of the river and the delta, negatively affecting both services and the biodiversity, such as the extent of fisheries and a reduction or even loss in some places of the filtering capacity provided by reed beds and riparian vegetation. Further adverse change is expected with construction of the Bystroye navigation canal through the delta.

BOX 20.10

South American Wetlands and Rivers

The construction of hydroelectricity schemes poses a major threat to wetlands in South America. In Brazil, rapidly rising energy demands have stimulated ambitious plans to build dams on nearly all major rivers, except the main stream of the Amazon (Junk and Nunes de Mello 1987; World Energy Council 2003). However, many rivers have low gradients, and in such cases dams inundate large areas and provide little energy; for example, the Balbina reservoir on the Uatuma River in the Brazilian Amazon covers 2,300 square kilometers and produces $<$10 megawatts per square kilometer. There are likely to be significant socioeconomic trade-offs from the construction of these reservoirs to produce hydroelectricity (Fearnside 1989).

In Brazil, rapidly expanding agriculture, mainly for soybean production, has increased demand for inexpensive transport along the rivers. Waterways (*hidrovias*) have been constructed or are under construction (Brito 2001), which involves straightening sinuous stretches of the river channels, dragging, removing obstacles such as logs and rocky outcrops, and placing signals for ship traffic. Environmental impact analyses are lacking in most cases. In 2000, the Brazilian government stopped plans to construct a *hidrovia* through the Pantanal of Mato Grosso. This project would have threatened one of the largest wetlands in the world (Ponce 1995; Hamilton 1999). Plans have not yet been abandoned by private enterprises, however, and infrastructure construction is proceeding.

in southern Africa; creating a chain of connected deep reservoirs, such as those along the Volga River, Russia; leading to channelization, such as that along the Mississippi and Missouri Rivers in the United States; or significantly reducing flows to floodplains and downstream habitats, including deltas such as the Indus in Pakistan. Similarly, converting wetlands for agricultural purposes without completely destroying them, as with much of sub-Saharan agriculture or paddy (rice), still results in hydrological change.

Modifications to water regimes have drastically affected the migration patterns of birds and fish and the composition of riparian zones, opened up access to exotic species, and contributed to an overall loss of freshwater biodiversity and inland fishery resources (Revenga et al. 2000), as well as led to alterations to upstream and downstream habitats. Dams also affect the magnitude and timing of water flow and sediment transport of rivers, often for long distances downstream. The Aswan High Dam in Egypt, for example, has led to reduced sediment transport for more than 1,000 kilometers downstream (McAllister et al. 1997). A further example of the downstream effects of dams is illustrated in the Indus delta, where rapidly accelerating mangrove loss as a result of reduced freshwater flows has seriously jeopardized the livelihoods of 135,000 people who rely on mangrove products to a total economic value of $1.8 million a year for fuelwood and fodder, as well as a coastal and marine fisheries sector that generates domestic and export earnings of almost $125 million annually (Iftikhar 2002).

Other examples of large-scale drivers of change in inland water systems are those affecting the Dead Sea (ILEC and UNEP 2003) and the Mesopotamian marshlands in Iraq (Partow 2001; UNEP 2002). Lying in the heart of the Syrian-African rift valley at the southern outlet of the Jordan River, the Dead Sea—417 meters below sea level—is the world's saltiest large water body. It is severely threatened by excessive water withdrawals in the north and dams and industrial development in the south as a result of ever-increasing industry, agriculture, and tourism. The annual flow of the Jordan River was approximately 1,370 million cubic meters in the 1950s, while today the total river discharge to the Dead Sea is about 300 million cubic metes a year. As a result, the level of the lake is dropping by about one meter each year (ILEC and UNEP 2003).

The Mesopotamian marshlands have also been severely affected in recent decades. These covered an area of 15,000–20,000 square kilometers before being reduced by drainage and dam construction along the Tigris and Euphrates Rivers (Partow 2001). Now they cover less than 400 square kilometers. The capacity of dams along these rivers currently exceeds the annual discharge of both rivers, drastically reducing the supply of downstream floodwaters that were so important in delivering sediments and nutrients to the marshland. Further, in the early 1990s drainage schemes were used to divert large amounts of water from the marshlands—an event that was made easier by the upstream damming. (See Figure 20.10 in Appendix A.)

There are now more than 45,000 large dams (more than 15 meters high) (WCD 2000), 21,600 of which are in China. This represents a 700% increase in the water stored in river systems compared with natural river channels since 1950 (Vörösmarty et al. 1997). Water storage and sediment retention from dams have had enormous impacts on suspended sediment and carbon fluxes, as well as on the waste processing capacity of aquatic habitats (Vörösmarty et al. 1997). The construction of large dams has doubled or tripled the residence time of river water (Revenga et al. 2000), with enormous impacts on suspended sediment and carbon fluxes, waste processing, and aquatic habitat, and has resulted in fragmentation of the river channels. Revenga et al. (2000) found 37% of 227 river basins around the world were strongly affected by fragmentation and altered flows, 23% moderately affected, and 40% unaffected. (See Figure 20.11 in Appendix A.) Strongly or moderately fragmented systems are widely distributed globally. Small dams can also have major affects on the ecological condition of inland water systems (Oritz Rendan 2001), and many inland surface and groundwater systems have also been affected by modifications at smaller scales.

The extent of recent change is illustrated by figures collated for Asia and South America. In Asia, 78% of the total reservoir volume has been constructed in the last decade, and in South America almost 60% of all reservoirs have been built since the 1980s (Avakyan and Iakovleva 1998). The debate about the construction of dams is ongoing (WCD 2000)—weighing up, for example, the benefits against the potential adverse consequences of constructing further dams in the upper Mekong in China (Dudgeon 2003).

The effects of modification of flow regimes on fish migrations have been reviewed by Revenga and Kura (2003). The direct impacts of dams on diadromous fish species such as salmon are now *well established*. Indirect impacts of flow alteration, such as the reduction of floods and loss of lateral connections on floodplains, are also important. In many instances the construction of reservoirs has resulted in the disappearance of fish species adapted to river systems and the proliferation of species adapted to lakes, many of which were non-native. Examples include the decline of the sturgeon and the caviar industry in rivers such as the Volga in Russia (Finlayson et al. 1993). In West Africa, a sharp decline of *Mormyridae* (an elephant-nosed fish family of Osteoglossiformes) was observed in Lakes Kainji and Volta after the inundation of their preferred habitats as a result of dams (Lévêque 1997).

Cases of adverse impact on the structure of riparian vegetation and morphology from dams, embankments, and canals are also widely reported (Nilsson and Berggren 2000). In tropical Asia, change in flooding patterns due to river modification has affected riverine and wetland-dependent mammal populations, such as marshland deer and the Asian rhino in Thailand, India, and China, and diadromous fish stocks, such as sturgeons in China (Dudgeon 2000c). Similar cases have been reported by Pringle et al. (2000) for North and South America.

20.4.3 Invasive Species

The introduction of some non-native (alien) invasive species has contributed to species extinction in some freshwater systems (see Malmqvist and Rundle 2002; Tockner and Stanford 2002; see also reviews cited earlier). The problems caused by invasive species are very much a global concern (Mooney and Hobbs 2000). The spread of exotic species in inland waters is increasing with the spread of aquaculture, shipping, and global commerce. (See Boxes 20.11 and 20.12.) Examples include the pan-tropical weeds salvinia (*Salvinia molesta*) and water hyacinth (*Eichhornia crassipes*) that originated in South America but which are now widely distributed across the tropics. The cane toad (*Bufo marinus*), bullfrog (*Rana catesbeiana*), European domestic pig (*Sus scrofa*), carp (*Cyprinus carpio*), and zebra mussel (*Dreissena polymorpha*) are examples of animals that have become established outside of their native range and disrupted the inland water systems that they have invaded.

Species such as the water hyacinth, Canadian pondweed (*Elodea canadensis*), and mimosa (*Mimosa pigra*) have spread around the globe (Sculthorpe 1967; Gopal 1987; Walden et al. 2004) and remain largely unaffected by extensive and expensive control or management programs. Canadian pondweed illustrates the dilemma caused by invasive species. It is the first documented example of the explosive growth of an aquatic weed that originated in North America and in the late nineteenth century invaded the waterways of Europe. In becoming established, it grew rapidly, reproducing vegetatively, and reached maximum population densities within a period of a few months to four years. These population densities were maintained for up to five years and then declined to levels that were not considered a nuisance. The reasons for the rapid increase and subsequent decline were not determined, and this paradox still affects efforts to manage invasive species in inland waters.

Efforts to determine which of the many species that are introduced into new environments have not been fully successful have done little other than illustrate that only a small proportion of introduced species are likely to flourish and become serious problems (Williamson 1996; Manchester and Bullock 2000). While many species have features that enable them to take advantage of changed ecological conditions, there are likely as many factors that would limit establishment and growth.

Water hyacinth is an example of a widespread alien species that has caused considerable economic and ecological damage in inland water systems around the world (Gopal 1987). It is believed to be indigenous to the upper reaches of the Amazon basin, was spread in the mid-nineteenth century throughout much of the world for ornamental purposes, and now has a pan-tropical distribution. The plant spreads quickly to new rivers and lakes, clogging waterways and infrastructure, reducing light and oxygen in freshwater systems, and causing changes in water chemistry and species assemblages that affect fisheries. Water hyacinth control and eradication has become one of the top priorities for many environmental government agencies, with biological control being increasingly successful. (See Chapter 10.)

Many fish species have been spread beyond their native ranges, often as an important component of aquaculture (FAO

BOX 20.11

Invasive Species and European Rivers (Information supplied by H. Ketelaars)

For many centuries canals have been constructed between rivers and other water bodies in Europe, through which species actively migrated or were aided by shipping traffic, either in ballast water or outside on the hull of ships. The Volga-Baltic Waterway, reconstructed in 1964, connecting the Caspian basin with the Baltic region, is one example that has enabled translocation of many aquatic species, such as copepods, rotifers, the onychopod *Bythotrephes longimanus,* and several fish species to the Volga basin. The Main-Danube Canal, officially opened in 1992, is another that has allowed many Ponto-Caspian invertebrate species to reach the Rhine basin and from there to disperse to other basins, mainly in ballast water.

Intentional introductions of aquatic species have occurred mainly in the past two centuries. The North American amphipod *Gammarus tigrinus* was deliberately introduced in 1957 in the German rivers Werra and Weser because the local gammarid fauna had disappeared due to excessive chloride pollution. The mysid *Mysis relicta* has been introduced in many Scandinavian lakes to stimulate fish production. Three North American introduced crayfish species have established themselves in many European waters and introduced "crayfish plague" (*Aphanomyces astaci*), which has almost eliminated the native crayfish (*Astacus astacus*).

At least 76 non-European freshwater fish have been introduced into European fresh waters, with approximately 50 establishing self-sustained populations. When introductions between areas within Europe are also considered, the number of introduced species is more than 100. The numerically most important families are cyprinids and salmonids, of which grass carp (*Ctenopharyngodon idella*), silver carp (*Hypophthalmichthys molitrix*), rainbow trout (*Oncorhynchus mykiss*), and brook char (*Salvelinus fontinalis*) are now widely distributed in Europe. Only a few introductions have resulted in the spread of economically important species.

BOX 20.12

North America's Great Lakes and Invasive Species

Alien invasive species have threatened the Great Lakes ever since Europeans settled in the region. And since the 1800s, more than 140 exotic aquatic organisms of all types—including plants, fish, algae, and mollusks—have become established in the Great Lakes. The rate of introduction of exotic species has increased with human activity in the watershed. More than one third of the organisms have been introduced in the past 30 years, a surge coinciding with the opening of the St. Lawrence Seaway (Great Lakes Information Network 2004).

Approximately 10% of the Great Lakes' non-indigenous species have had significant impacts, both economic and ecological. For example, the sea lamprey has cost millions of dollars in losses to recreational and commercial fisheries and millions of dollars in control programs. Alewife fish littered beaches each spring and altered food webs, thereby increasing water turbidity before salmonids such as chinook salmon (themselves exotic) were stocked as predators and the foundation of a new recreational fishery.

Since 1991, the Great Lakes Panel on Aquatic Nuisance Species has worked to prevent and control the occurrence of aquatic alien invasive species in the Great Lakes, although efforts have not been totally successful.

1999). Introductions are usually done to enhance food production and recreational fisheries or to control pests such as mosquitoes and aquatic weeds. Introduced fish, for example, account for 96% of fish production in South America and 85% in Oceania (Garibaldi and Bartley 1998). The introduction of non-native fish, however, has had severe ecological costs. A survey of 31 studies of fish introductions in Europe, North America, Australia, and New Zealand found that in 77% of the cases, native fish populations were reduced or eliminated following the introduction of non-native fish. In 69% of cases, the decline followed the introduction of a single fish species, with salmonids responsible for the decline of native species in half of these (Ross 1991). The introduction of salmonids is attracting increased attention, as they have reduced the genetic diversity of wild stocks. In Canada and the United States, 68% of the recorded extinctions of 27 species and 13 sub-species of fish were due in part to the introduction of alien species (Miller et al. 1989). Similarly, in Mexico and Colombia, introduced fish pose a major risk to native fish and fisheries stock (Contreras-Balderas 2003; Alavrado and Gutiérrez 2002).

Fish introductions to tropical Asia and Latin America over the last 150 years have occurred mainly either to enhance food production (carps and tilapias, for instance) or for recreational purposes (piscivorous fish such as trout and bass for sport fishing) (Revenga and Kura 2003). The impacts of these species on the native fish fauna and ecosystems have not been well documented, although Fernando (1991) reports that introduced fish were not found to have caused severe damage to indigenous species except for some incidents in Latin America where piscivores were introduced.

In recent decades, tilapia species have been established and become a substantial contributor to inland fisheries in Mexico, the Dominican Republic, northeast Brazil, and Cuba (where as much as 90% of the fishery is tilapia species) (Fernando 1991). Although this has not resulted in the collapse of native fish stocks in most cases, it does indicate a significant shift in the composition and structure of biological communities in those systems.

In tropical Asia, herbivores and omnivores, such as Indian, Chinese, and common carps, account for the majority of introductions (Revenga and Kura 2003). Except in China, these temperate species of carps have not contributed much to fishery yield in the tropics. In comparison, tilapias have had a similar effect here as in Central America, boosting capture fishery in Sri Lanka and Thailand and aquaculture in Philippines, Taiwan, and Indonesia (Fernando 1991). In China, the world's largest producer of inland fisheries, carp contributes significantly to fisheries production. Although research on the impact of introduced species on the native aquatic ecosystems of China is limited, a few well-documented cases exist, such as Dianchi Lake in Yunnan Province, and Donghu Lake in Hunan Province, where it has been shown that indigenous and endemic fish species assemblages have significantly changed and many of their populations have declined (Xie et al. 2001).

Further information on invasive aquatic species can be found on the Global Invasive Species Program web site. Analyses of the economic costs of non-native invasive species are becoming more common, as shown by the fishery examples just mentioned, as are risk assessments of important species (e.g. Finlayson et al. 2000; van Dam et al. 2000, 2002a). The importance of alien invasive species in inland waters is likely to increase in response to global change (van Dam et al. 2002b).

20.4.4 Fisheries and Other Harvesting

Inland fisheries are a major source of protein for a large part of the world's population. People in Cambodia, for example, obtain roughly 60–80% of their total animal protein from the fishery resources of the Tonle Sap alone (MRC 1997). In some land-locked countries, this percentage is even higher; for example, in Malawi about 70–75% of the total animal protein for both urban and rural low-income families comes from inland fisheries (FAO 1996).

Global production of fish and fishery products from inland waters in 2002 amounted to 32.6 million tons (FAO 2004)—8.7 million tons from wild capture fisheries and the rest (23.9 million tons) from inland aquaculture. There is little dispute that major increases in the harvest of freshwater fish have occurred over the last two decades, mostly in the developing world, but as these statistics show, much of this increase is the product of aquaculture operations and enhancement efforts such as fish stocking and the introduction of non-native fish species in lakes and rivers.

Increased freshwater harvests, however, do not indicate healthy freshwater fish stocks or healthy aquatic ecosystems. In fact, FAO's last major assessment of inland fisheries (1999) reported that most inland capture fisheries that rely on natural reproduction of the stocks are overfished or are being fished at their biological limit and that the principal factors threatening inland capture fisheries are fish habitat loss and environmental degradation. In addition, one of the limitations in monitoring the state and condition of inland fish stocks is that the catch from inland fisheries is believed to be underreported by a factor of two or three, due to the large volume of harvest that is consumed locally, and remains unrecorded (FAO 1999). Asia and Africa are the two leading regions in inland capture fisheries, accounting for 90% of the catch in 2002 (FAO 2004). China alone accounts for at least one quarter of the inland catch, followed by India (9% of the catch), Bangladesh (8%), and Cambodia (4%) (FAO 2004).

Aquaculture continues to grow more rapidly than any other animal food-producing sector, at an average rate of 8.9% per year since 1970—a much higher rate than that for capture fisheries (1.2%) or terrestrial farmed meat products (2.8%) (FAO 2004). Most aquaculture production (58%) comes from the freshwater environment, the main producer by far being China. Between

1970 and 2000, inland water aquaculture production in China increased at an average annual rate of 11%, compared with 7% for the rest of the world (FAO 2004). However, many aquaculture operations, depending on their design and management, can and have contributed to habitat degradation, pollution, introduction of exotic species, and the spread of diseases through the introduction of pathogens (Naylor et al. 2000; see also Chapter 26).

Many other species of vertebrates are also harvested from inland waters, some in large numbers—such as turtles, waterbirds, crocodiles, and frogs. Overharvesting, whether for food, medicinal purposes, or recreation, has become a problem in many countries, and many species are locally or regionally threatened. For example, the increase in the harvesting and trade of freshwater turtles in South and Southeast Asia is causing severe declines in species populations, putting some of these species at risk of extinction (van Dijk et al. 2000). Because of the increase in trade, 11 proposals to list turtle species under Appendix II of CITES were accepted by consensus at the CITES Conference of the Parties in November 2002 (CITES 2002).

20.4.5 Water Pollution and Eutrophication

It is *well established* that nutrient concentrations have increased substantially in rivers throughout the world (Heathwaite et al. 1996; Revenga et al. 1998), resulting in eutrophication, harmful algal blooms, and high levels of nitrate in drinking water (Malmqvist and Rundle 2002). (See Chapters 7, 12, 15, and 19.) Many specific examples are available for inland water systems (e.g. Malmqvist and Rundle 2002; Tockner and Stanford 2002). For instance, the agricultural sector contributes an average of 50% of the total load of nitrogen and phosphorus to the Danube River in Europe, domestic sources contribute about 25%, and industry or atmospheric deposition 25%. Hazardous substances of particular concern are pesticides, ammonia, PCBs, polyaromatic hydrocarbons, and metals (IUCN 1992). (See also Chapter 15.) Industry and mining are responsible for most of the direct and indirect discharges of hazardous substances into the Danube and Volga Rivers in Europe, while transport is an important source of oil pollution (IUCN 1992; Popov 1992). Microbiological contamination by pathogenic bacteria, viruses, and protozoa is an important water quality problem in many regions of the world (see Chapters 7 and 15), and diffuse discharges from agriculture are important sources of micro-pollutants for both surface and groundwaters.

Jorgensen et al. (2001) notes that eutrophication is the most widespread problem in lakes and reservoirs and also one of the most difficult to abate. Cyanobacteria blooms have increased and are a major problem in inland and coastal waters worldwide. The problem of increased eutrophication from land-based activities is well shown for the Mississippi River in the United States, with problems along the length of the river and in the coastal zone—the so-called dead zone in the Gulf of Mexico.

It is *well established* that pollution from point sources such as mining has had devastating impacts on the biota of inland waters in many parts of the world. For example, the release of stored tailings (mine wastes) from the Aznalcollar mine some 50 kilometers from the Doñana National Park in Spain illustrated the problems that can occur to both ecological and socioeconomic activity of the areas downstream (Bartolome and Vega 2002). Following a spillage in 1998, an estimated 5.5 million cubic meters of acidic, metal-enriched water and 1.3–1.9 million tons of toxic tailings were spread over 4,600 hectares of downstream habitats—with fatal consequences for much of the biota in the affected area and a consequent disruption to the tourism industry. The cost of removing the tailings and contaminated soil reached about 3.8 billion euros.

In developing countries, an estimated 90% of wastewater is discharged directly to rivers and streams without any waste processing treatment, and in some locations both surface and groundwater have been so polluted that they are unfit even for industrial uses (WMO 1997). Threats of water quality degradation are usually most severe in areas where water is scarce due to the reduced capacity for waste dilution. These threats are exacerbated by industrial and agricultural practices that channel waste products into inland waters, including caves and other underground water.

Meybeck (2003) provides an overview of water pollution problems for inland waters. (See Table 20.8.) In industrial countries, fecal contamination has been largely eliminated, while new problems, particularly from agriculture run-off, are increasing everywhere. In other countries this is not the case, and fecal contamination is a major problem. In developing countries, urban and industrial pollution sources are increasing faster than related wastewater treatment.

Contamination by pesticides has increased rapidly since the 1970s, with many different substances being involved. In the Seine basin, in France, for example, more than 100 different active molecules are known to occur (Chevreuil et al 1998). The use of persistent chemicals is now increasingly regulated in Western Europe and North America. Records of PCBs and DDT in sedimentary archives peaked in the 1970s and are now markedly decreasing (Valette-Silver 1993). The persistence of these products can be high, however, and their degradation products can be more toxic than the parent molecule. (See Chapter 15.) Additionally, it is extremely difficult to assess and address the effects of multiple chemicals together in inland waters, both in the short and the long term.

Toxic substances are known to be a serious and increasing threat in developing countries as land use in watersheds changes. Chemical pollution from urban domestic and industrial sources and from pesticides is increasing in many key lake watersheds such as Lake Baikal and the African Great Lakes (Ntakimazi 1992;

Table 20.8. Major Water Quality Issues in Inland Water Systems at the Global Scale (Maybeck 2003)

Issue	Rivers	Lakes	Reservoirs	Groundwaters
Pathogens	•••	•	•	••
Suspended solids	••	na	•	na
Decomposable organic matter	•••	•	••	•
Eutrophication	•	••	•••	na
Nitrate	•	0	0	•••
Salinization	•	0	•	•••
Trace metallic elements	••	••	••	••
Organic micropollutants	•••	••	••	•••
Acidification	•	•	••	0

Key: ••• severe or global deterioration observed
•• important deterioration
• occasional or regional deterioration
0 rare deterioration
na not applicable

Hecky and Bugenyi 1992). Lake Baikal water, fish, and seals all contain measurable levels of organochlorine compounds (Kucklick et al. 1994). Concentrations of chlorinated organic compounds have declined in some North American Great Lakes fish species but remain high for all fish species in Lakes Michigan and Ontario (Rowan and Rasmussen 1992). There have also been recent discoveries of endocrine-disrupting toxics in pulp wastewater that have caused abnormal male sexual organs to develop in alligators, feminization of male fish and turtles, and masculinization of female fish (Mathiessen and Sumpter 1998; Mathiessen 2000). Further information on human health and toxic substances can be found in Chapter 14.

20.4.6 Climate Change

It is arguable whether or not climate change has already affected inland waters and their species, but it is anticipated (*medium certainty*) that it will directly or indirectly affect the biota and services provided by inland waters (van Dam et al. 2002b; Gitay et al. 2002). As climate change will increase the pressure on habitats that are already under severe pressure from other drivers just described and will interact in a synergistic manner, it is considered briefly here.

The certainty with which with which we can attribute cause and effect of climate change is undermined by the extent of our data and existing knowledge; in all but a few cases the data are inadequate. We are, however, highly confident that many inland waters are vulnerable to climate change. Particularly vulnerable are those at high latitudes and altitudes, such as Arctic and sub-Arctic bog communities, or alpine streams and lakes (Gitay et al. 2002; IDEAM 2002), as well as those that are isolated (Pittock et al. 2001) or are low-lying and adjacent to coastal wetlands (Bayliss et al. 1997). Groundwater systems will also suffer as climate change affects recharge of aquifers (Danielopol et al. 2003).

The major expected impacts to inland waters include warming of rivers, which in turn can affect chemical and biological processes, reduce the amount of ice cover, reduce the amount of dissolved oxygen in deep waters, alter the mixing regimes, and affect the growth rates, reproduction, and distribution of organisms and species (Gitay et al. 2002). It is *very certain* that sea level rise will affect a range of freshwater systems in low-lying coastal regions. For example, low-lying floodplains and associated swamps in tropical regions could be displaced by salt-water habitats due to the combined actions of sea level rise and larger tidal or storm surges (Bayliss et al. 1997; Eliot et al. 1999). Plant species not tolerant to increased salinity or inundation could be eliminated, while salt-tolerant mangrove species could expand from nearby coastal habitats. Changes in the vegetation will affect both resident and migratory animals, especially if these result in a major change in the availability of staging, feeding, or breeding grounds for particular species (Boyd and Madsen 1997; Zockler and Lysenko 2000).

The most apparent faunal changes will probably occur with migratory and nomadic bird species that use a network of wetland habitats across or within continents. The cross-continental migration of many birds is at risk of being disrupted due to changes in habitats (see references in Walther et al. 2002). Reduced rainfall and flooding across large areas of arid land will affect bird species that rely on a network of habitats that are alternately or even episodically wet and fresh or drier and saline (Roshier et al. 2001). Responses to these climate-induced changes will be affected by fragmentation of habitats or disruption or loss of migration corridors or even by changes to other biota, such as increased exposure to predators by wading birds (Butler and Vennesland 2000), as a consequence of adaptation to and mitigation of climate change (Gitay et al. 2002).

It is anticipated with *medium certainty* that fish species distribution will move toward the poles, with cold-water fish being further restricted in their range, and cool and warm-water fish expanding in range. Aquatic insects, on the other hand, will be less likely to be restricted, given that they have an aerial life stage. Less mobile aquatic species, such as some fish and mollusks, will be more at risk because is it thought that they will be unable to keep up with the rate of change in freshwater habitats (Gitay et al. 2002). Climate change may also affect the wetland carbon sink, although the direction of the effect is uncertain due to the number of climate-related contributing factors and the range of possible responses (Gitay et al. 2002). Any major change to the hydrology and vegetative community of a wetland will have the potential to affect the carbon sink. Vegetation changes associated with the water drawdown in northern latitudes, for example, result in increased primary production, biomass, and slower decomposition of litter, causing the net carbon accumulation rate to remain unchanged or even increase. Other aspects of climate change, such as longer and more frequent droughts and the thawing of permafrost, will have negative effects on the carbon balance in peatland.

The extent of change in inland waters as a consequence of climate change should not be addressed in isolation of other drivers of change, as many of the adverse effects of the above-mentioned drivers of change will be exacerbated by climate change (Gitay et al. 2002; van Dam et al. 2002). Further, the affects of climate change will be felt across many of the services delivered by inland waters; as an example, a sensitivity projection for Canada's river regions in response to climate change indicates that there will be an increase in flood and river erosion that will affect the use and value of rivers for recreation, conservation, fisheries, water supply, and transportation (Ashmore and Church 2001).

20.5 Trade-offs, Synergies, and Management Interventions for Inland Water Systems

Management of inland waters worldwide has been regularly based on decision-making mechanisms that have not included sufficient consideration of the wider implications or outcomes of specific actions or responses (see Finlayson et al. 1992; Finlayson and Moser 1991; Whigham et al. 1993; Mitsch 1994; Jaensch 1996; McComb and Davis 1998; Ali et al. 2002). The assessment and case studies provided in this chapter illustrate the outcomes of management decisions that have not considered the trade-offs between services provided by inland waters. These decisions have often resulted in the degradation of inland waters, and the loss or decline in the multiple services they provide, in favor of a smaller number of services, such as the supply of fresh water for drinking or irrigation or the supply of hydroelectricity or transport routes. The case studies cited earlier of the Aral and Caspian Seas illustrate the adverse effects that such sectorally based decisions can have. More multisectorally based responses and decisions are required if we are to reverse the loss and degradation of inland waters and the decline in the services that they deliver. Further information on management responses is provided in the MA *Policy Responses* volume in chapters on biodiversity (Chapter 5), nutrient management (Chapter 9) and freshwater (Chapter 7).

The past loss and degradation of inland waters and their services is increasingly being recognized through international conventions and treaties as having exceeded the value gained through such actions. In response, the Ramsar Wetlands Convention has provided leadership and worked collaboratively with other organizations, both informally and through formal agreements, such as the joint work plans agreed with the Convention on Biological Diversity, to develop more multisectoral approaches to stop and reverse the loss and degradation of wetlands. This includes working collaboratively to address the Millennium Development Goals (see MA *Policy Responses,* Chapter 19) and to reduce the rate of loss of biodiversity by 2010 (see Chapter 4 in this volume and MA *Policy Responses,* Chapter 5). Many other international collaborative efforts and initiatives are underway, some linked with and many others independent of the Ramsar Convention.

The Mediterranean wetland program (MedWet) is one collaborative, multisectoral initiative that is formally linked with the Ramsar Convention and has resulted in strident calls and actions to not only halt the loss and degradation of wetlands but to reverse their consequences. The program has evolved considerably since the initial declaration of intent was made in Grado, Italy, in February 1991 (Anon 1992). The declaration contained a recommendation that all supranational organizations, Mediterranean governments, NGOs, and concerned individuals adopt the following goal: to stop and reverse the loss and degradation of Mediterranean wetlands.

It further recommended a number of actions that should be included in a strategy to support this goal:

- identification of priority sites for wetland restoration and rehabilitation and the development and testing of techniques for their complete rehabilitation;
- evaluation of existing and proposed policies to determine how they affect wetlands;
- increased institutional capacity to conserve and effectively manage wetlands through vigorous education and training programs;
- integrated management of all activities concerning wetlands, their support systems, and the wider area surrounding them carried out by properly funded and well-staffed multidisciplinary bodies with active participation of representatives of government, local inhabitants, and the scientific and nongovernmental community;
- open consultation and free flow of information when managing wetlands; and
- adoption and enforcement of national and international legislation for better management.

The declaration was not received with enthusiasm by some key sectors; however, the individual recommendations have since been repeated or extended in many fora and with widespread acceptance, the most recent being in the Chilika Statement agreed at the Asian Wetland Symposium 2005, Bhubaneswar, India, in February 2005 (www.wetlands.org/news&/docs/AWS_Declaration.pdf).

In the early 1990s, the concept of replacing lost wetlands received increasing support (e.g., see Finlayson and Larsson 1991; Finlayson et al. 1992; Hollis et al. 1992), and more attention is now directed toward wetland restoration worldwide (see Eiseltova 1994; Eiseltova and Biggs 1995; Zalidis et al. 2002).

However, current rates of restoration are inadequate to offset the continued rate of wetland loss in many regions. Given this situation, the Ramsar Convention on Wetlands has proposed a series of guidelines to assist in reversing the loss of wetlands. These cover the current thinking and agreement on priority topics for management of inland waters, but due to political considerations many are not as prescriptive as requested by some parties, especially when dealing with indirect drivers of change, such as trade and population growth. The current guidance covers these topics:

- wise use of wetlands;
- national wetland policies;
- laws and institutions;
- river basin management;
- participatory management;
- wetland communication, education, and public awareness;
- designation of Ramsar sites;
- management of wetlands;
- international cooperation;
- wetland inventory;
- impact assessment;
- water allocation and management;
- coastal management; and
- peatlands.

One of the key barriers in developing management responses to prevent further loss and degradation of wetlands is the unwillingness to undertake effective actions. Sufficient knowledge is generally now available to know what actions are required to stop further loss and degradation and when these are most likely to be effective. (The general reviews cited at the start of section 20.3 provide guidance to a wealth of useful information.) There is also inadequate adoption and understanding of "ecosystem approaches" for managing inland waters, including the precautionary principle, as espoused by the Convention on Biological Diversity and the Convention on Wetlands (Ramsar Convention Secretariat 2004). The World Commission on Dams (WCD 2000) illustrated some of the contradictory issues faced in managing inland waters. Ongoing debate about the allocation of water for environmental outcomes in rivers and associated wetlands illustrates the trade-offs that have long been inherent features in water management, especially at a river basin scale. Further dialogue is required to ensure the delivery of water allocations from dams to support a wider range of services than has generally been the case.

The extent of loss and degradation of wetlands, and trade-offs in services have resulted in an increasing number of large and small restoration projects, driven by legislation and public attitude, particularly in North America and Europe, and increasingly in Australia. The cost and complexity of large-scale restoration are shown by the plan for the restoration of the Everglades, USA (CERP 1999). A comprehensive plan containing more than 60 components has been prepared to restore, protect and preserve the water resources of central and southern Florida, including the Everglades wetlands. The plan has important environmental and economic benefits and is anticipated to cost US$7.8 billion over 30 years. The responses to the accidental release of tailings (mine wastes) from the Anzacollar mine site upstream of the Donana wetlands in Spain in 1998 also illustrate the complexity of large-scale restoration programmes involving both environmental and economic issues (Gallego Fernandez and Garcia Nove 2002; G. Schmidt personal communication). The removal of the waste, treatment of contaminated water, acquisition of contaminated land and rehabilitation cost the regional and central governments and the European Union some E208 million; the mining company spent a further E79 million and suffered an operational loss of E17 million; with another E81 million from the European Union being allocated for inter-related rehabilitation, including re-establishing some of the separately altered hydrological features of this important wetland.

In response to the complex nature of many management issues for inland waters, a good deal of effort has been invested in developing collaborative and integrated management structures that address common interests and differences between agencies or states over the services provided by shared inland water systems. (See Iza 2004 for an analysis of international agreements for the conservation of freshwater ecosystems.) In some instances, integrated and comprehensive strategies and action plans have been developed in support of active interventions, regionally and locally.

The Mediterranean wetland initiative, for example, is a successful mechanism for the conservation and wise use of wetlands throughout the Mediterranean region through local and regional actions and international cooperation (Papayannis 2002). More specific thematic initiatives or action plans cover the management of invasive species (e.g., Wittenberg and Cock 2001; McNeeley et al. 2001), the reintroduction and maintenance of biodiversity (e.g. Bibby et al. 1992), or the integration of development with conservation (e.g., Davies and Claridge 1993).

In some cases, specific technical methods suitable for local application have been developed (see Zalidis et al. 2002 for information on wetland restoration in the Mediterranean), with increasing recognition that integrated collation, collection, and use of data and information are essential aspects of an effective management mechanism, whether they are focused on local or regional issues. This recognition has resulted in the development of models that provide a basis for standardized inventory, risk assessment and evaluation, and monitoring, such as that proposed for an Asian wetland inventory, and integrated analyses incorporating community consultation and communication (Finlayson et al. 2002; Finlayson 2003; Ramsar Convention Secretariat 2004).

There has in recent years been increased interest in the development of mechanisms to encourage and support the capacity of local communities to contribute to the management of inland waters, particularly where local knowledge and experience can be constructively used (Ramsar Convention Secretariat 2004). Recognition of the beneficial outcomes that can occur when local people are involved in the management of inland waters and their services now underpins efforts by the Ramsar Convention to encourage best management practices. This concept is implicit in the guidance provided by the Convention covering policy and legal instruments, economic and social interactions, and technical tools (Ramsar Convention Secretariat 2004).

The challenge for the Convention and others is to ensure that such instruments and tools are used effectively and, as required, improved. This can be done within an adaptive management regime, noting that this necessitates active learning mechanisms, the involvement of key stakeholders, and the balancing of vested interests. All too often, however, the involvement of local communities has not occurred or has not been effective at resolving conflict between users and resource managers (Carbonell et al. 2001), or indeed, between competing users of sites listed as Wetlands of International Importance.

The Ramsar concepts of wise use and ecological character can be used to guide management interventions for wetlands (Ramsar Convention Secretariat 2004). Wise use of wetlands has been defined by the Convention as "their sustainable utilisation for the benefit of humankind in a way compatible with the maintenance of the natural properties of the ecosystem." "Sustainable utilisation" is in turn defined as "human use of a wetland so that it may yield the greatest continuous benefit to present generations while maintaining its potential to meet the needs and aspirations of future generations." "Ecological character" is defined under the Convention as "the sum of the biological, physical, and chemical components of the wetland ecosystem, and their interactions, which maintain the wetland and its products, functions, and attributes."

A suggested redefinition of this is under discussion, which would ensure that ecosystem services (referred to as products, functions, and attributes, in the definition above) are considered as central components of ecological character and not just dependent on the ecological components and processes. Such a definition could read "the combination of the ecosystem components, processes, and services that characterize the wetland." Wise use could similarly be redefined to reflect the emphasis on ecosystem services and human well-being. These redefinitions further emphasize the close match between the Ramsar concepts and the conceptual framework of the Millennium Ecosystem Assessment, with the latter being more explicit about the emphasis on ecosystem services and human well-being.

20.6 Inland Water Systems and Human Well-being

It is *well established* that the services provided by inland waters are vital for human well-being and poverty alleviation (Dugan 1990; Revenga and Kura 2003; Finlayson et al. 1992; Finlayson and Moser 1991; Whigham et al. 1993; Mitsch 1994; McComb and Davis 1998; Lundqvist and Gleick 2000). A list of the services provided by inland waters was provided at the start of this chapter in Table 20.1. The benefits of these services to human well-being, and hence the consequences of reduced availability and supply for human well-being, are discussed in more detail in individual chapters that cover services derived from inland water systems—in particular, fresh water (Chapter 7), food (Chapter 8), nutrient cycling (Chapter 12), waste processing and detoxification (Chapter 15), regulation of natural hazards (Chapter 16), and various cultural and amenity services (Chapter 17). An analysis of human well-being and its relationship to ecosystem services is provided in Chapter 5. This section provides a brief assessment of specific examples of the relationship between the degradation of inland waters and human well-being. (See Table 20.9.)

The ecosystem services of inland water systems provide a basis for human well-being for people who live in close proximity to the system as well as those who live much further away. As human well-being is strongly affected by the extent to which people are able to meet their most basic needs (water, food, shelter, and health) in a secure manner, the sustainable use of inland waters for ensuring human well-being is vital. (See Box 20.13, as well as Box 20.8 earlier in the chapter.) This is well illustrated by the infrastructure and trade networks that have been developed to supply, for example, drinking water, food, and energy from lakes and reservoirs that can be located far from densely populated urban areas. It is also *well established* that in both rural and urban areas the poor are likely to suffer most when the availability and quality of water and food is reduced, whether due to failures in the infrastructure and trade networks or the demise of the systems themselves. (See Chapters 6, 7, and 8.) The impacts on human well-being of degraded supporting and regulating services from inland waters is often not recognized as readily, but it can be as significant as changes to provisioning services—for example, a reduction in the capacity of a wetland to filter water or to detoxify wastes can have significant consequences for human health, even if food provision remains adequate.

It is also known with *high certainty* that maintenance of an adequate flow of good-quality water is needed to maintain the health of inland water systems as well as estuaries and deltas. The reverse is also true: healthy inland water systems generate and maintain adequate flows of good-quality water. As the supporting services of inland waters are the result of interactions among the ecological components within the system and those in the catchment, human well-being is inexorably linked to the maintenance of the ecological character of inland water systems. Because of

Table 20.9. Summary of Critical Changes in Inland Water Systems and Services and Their Impacts on Human Well-being (WWDR 2003)

Major Drivers of Change in Inland Waters	Major Impacts on Services Derived from Inland Waters	Function(s) at Risk	Major Impacts on Human Well-being	Vulnerable People or Places
Population and consumption growth	increases water abstraction and acquisition of cultivated land through inland water drainage; increases requirements for all other activities, with consequent risks	virtually all ecosystem functions, including habitat, production, and regulation functions	increased health risks reduced quality and quantity of water	urban communities
Infrastructure development (dams, dikes, levees, diversions, interbasin transfers, etc.)	loss of integrity alters timing and quantity of river flows, water temperature, nutrient and sediment transport, and thus delta replenishment; blocks fish migrations; increases mosquito breeding	water quantity and quality, habitats, floodplain fertility, fisheries, delta economies	increased agricultural productivity reduced food security reduced economic opportunities increased health risks	downstream communities
Land conversion	eliminates key components of aquatic environment; loss of functions, integrity, habitat, and biodiversity; alters runoff patterns; inhibits natural recharge; fills water bodies with silt	natural flood control, habitats for fisheries and waterfowl, recreation, water supply, water quantity and quality	reduced household security loss of productive land increased release of carbon dioxide into the atmosphere reduced recreational, cultural, historical, or religious values	
Overharvesting and exploitation	depletes living resources, ecosystem functions (leading to fire and drought), and biodiversity (groundwater depletion, fisheries collapse)	food production, water supply, water quality, and water quantity	reduced food security reduced economic opportunities (e.g., tourism) increased risk of natural disasters	communities living adjacent to and dependent on inland water resources
Introduction of exotic species	outcompetes native species, alters production and nutrient cycling, loss of biodiversity	food production, wildlife habitat, recreation	reduced food security (e.g., reduced genetic variety and resilience)	
Release of pollutants to land, air, or water	pollution of water bodies alters chemistry and ecology of rivers, lakes, and wetlands	water supply, habitat, water quality, food production	reduced quality of water reduced food security reduced household security	
Climate change	greenhouse gas emissions produce dramatic changes in runoff and rainfall patterns, loss of coastal areas to sea level rise, increased erosion of shorelines, degradation of water quality by rising temperatures, changes in water flow volume, increased salt-water intrusion, increased water demand for irrigation, increased flood damage, increased drought frequency	shoreline protection, water quality, dilution capacity, transport, flood control	reduced household security reduced quality and quantity of water reduced productive land	

the complexities of these interactions, management of supporting services is likely to be best served by a holistic river basin approach, within which the resource base is assessed and managed in an integrated manner (Hollis 1998; Ramsar Convention Secretariat 2004). Implementation of a river basin or ecosystem approach implies stakeholders' acceptance that there may need to be trade-offs between them for access to the services provided by the river and its associated habitats.

It is widely accepted that the loss and degradation of inland waters has reduced their natural ability to buffer or ameliorate the impacts of floods (see Chapter 16) and hence threaten the security of individuals and entire communities. For example, in Southern Africa in 1999 and 2000, devastating floods affected more than 150,000 families (Mpofu 2000); degradation of wetlands such as the Kafue in Zambia, damming of rivers, deforestation, and overgrazing led to a reduced absorption of excess water and magnified the impact of the floods (Chenje 2000; UNDHA 1994). The same applies to floodplains where increasing human habitation, drainage of wetlands, and river canalization have severely restricted the capacity to buffer floods in many places and increased people's vulnerability to flooding. (See Chapters 7 and 16.) In Central Europe in 2002, extreme flooding as a consequence of

BOX 20.13

Afghanistan (Adapted from UNEP 2003)

Three to four recent years of drought have compounded a state of widespread and serious resource degradation in Afghanistan, which has largely been brought about by two decades of conflict. These droughts have lowered water tables, dried up wetlands, denuded forests, eroded land, and depleted wildlife populations. With rainfall low and erratic in much of Afghanistan (and with large areas of desert or semi-desert), rivers, streams, and other inland waters are crucial for human needs, such as drinking water and agriculture, and for maintaining populations of wild plants and animals, many of which provide potential for economic opportunities.

Over 80% of Afghan people live in rural areas, yet many of their basic resources—water for irrigation, trees for food and fuel—have been lost in just a generation. In the Helmand River basin, 99% of the Sistan wetland dried up between 1998 and 2003. Without a stable source of water, much of the natural vegetation of inland water areas has been lost, and it has often been collected for fuel. This has contributed to soil erosion and significant movement of sand onto roads and into settlements and irrigated areas.

Up to 100 villages in the vicinity of the Sistan wetland have been submerged by windblown dust and sand, and many agricultural fields have also been affected. If the sedimentation continues, the risks are clear: as the storage capacity of the lakes, reservoirs, and irrigation networks is reduced, opportunities to store water will be lost, and at the same time vulnerability to both drought and flooding will increase. The construction of deep wells to meet immediate humanitarian needs, coupled with the collapse of traditional water management systems and decision-making structures at the community level, has resulted in many downstream users losing access to traditional supplies, leading to disputes over access to water resources.

unusually high rainfall was exacerbated by physical alterations along the rivers and changes in the water retention capacity of the riparian zone and upper catchment. Floods and droughts also typically affect the poorest people most severely, as they often live in vulnerable areas and have few financial resources for avoidance, mitigation, or adaptation. (See Chapters 6 and 16.) Few countries have been free of damaging floods during the last few decades (Kundzewicz and Schellnhuber 2004).

Although largely eliminated in wealthier nations, water-related diseases are among the most common causes of illness and mortality affecting the poor in developing countries. The extent of water pollution and its link with human health in many countries is well known. The World Health Organization has estimated that there are 4 billion cases of diarrhea each year in addition to millions of other cases of illness associated with a lack of access to clean water. (See Chapter 7.) Water-borne diseases that result in gastrointestinal illness (including diarrhea) are caused by consuming contaminated water. (See Chapter 14.)

Perhaps less recognized as a major influence on human well-being, but as potentially debilitating to people, are actions that degrade inland water systems and result in a reduction in water supply or encourage the spread and abundance of disease vectors. (See Chapters 5 and 14.) Schistosomiasis, for example, has been spread by the construction of dams and large lakes in many countries, and interference with the hydrology of wetlands has exacerbated the incidence of mosquito-borne diseases. In 2000, the estimated mortality due to water sanitation hygiene–associated diarrheas and some other water sanitation–associated diseases (schistosomiasis, trachoma, intestinal helminth infections) was 2,213,000. There were an estimated 1 million deaths due to malaria, and more than 2 billion people were infected with schistosomes and soil-transmitted helminths, of whom 300 million suffered serious illness. The majority of those affected by water-related mortality and morbidity are children under five (WWDR 2003). Since many illnesses are undiagnosed and unreported, the true extent of these diseases is unknown (Gleick 2002).

Water-related diseases that are exacerbated by the degradation of inland waters (see Chapter 14) include those caused by the ingestion of water contaminated by human or animal feces or urine containing pathogenic bacteria or viruses, such as cholera, typhoid, amoebic and bacillary dysentery, and other diarrheal diseases; diseases passed on by intermediate hosts such as aquatic snails or insects that breed in aquatic ecosystems, such as dracunculiasis, schistosomiasis, and other helminths as well as dengue, filariasis, malaria, onchocerciasis, trypanosomiasis, and yellow fever; and diseases that occur when there is insufficient clean water for washing and basic hygiene or when there is contact with contaminated water, such as scabies, trachoma, typhus, and flea-, lice-, and tick-borne diseases.

In addition to disease from inland waters, water-borne pollutants have a major effect on human health, often through their accumulation in the food chain. Many countries now experience problems with elevated levels of nitrates in groundwater from the large-scale use of organic and inorganic fertilizers. Excess nitrate in drinking water has been linked to methemoglobin anemia in infants, the so-called blue baby syndrome. Arsenicosis, the effect of arsenic poisoning when drinking arsenic-rich water over a long period, is also known and is a particularly severe problem in Bangladesh and Western Bengal, where some 35–77 million inhabitants are exposed to excessively high levels of arsenic in water drawn from wells (Bonvallot 2003). On the whole, though, it is still extremely difficult to quantify the cumulative effects of long-term exposure to a variety of chemicals at what seem like low concentrations. (See Chapter 15.)

There is increasing evidence from wildlife studies that humans are at risk from a number of chemicals that mimic or block the natural functioning of hormones, interfering with natural body processes, including normal sexual development. (See Chapter 15.) Chemicals such as PCBs, DDT, dioxins, and those from at least 80 pesticides are regarded as ''endocrine disrupters,'' which may interfere with human hormone functions, undermining disease resistance and reproductive health. Pharmaceuticals in the environment represent an emerging environmental issue, with many being only partially removed by conventional wastewater treatment and therefore being deposited into a variety of receiving waters. The presence of these compounds in inland waters is considered harmful for humans even though the extent of harm remains uncertain. It is certain, though, that the degradation of inland water systems reduces the potential of these systems to mitigate the effects of pollutants through detoxification and waste processing and results in an overall reduction in human well-being.

It is expected that continued degradation of inland water systems will result in further reduction in human health, especially for vulnerable people in developing countries where technological fixes and alternatives are not as readily available. The evidence that the degradation of inland waters results in a loss of services and reduction in human health is incontrovertible, and yet degradation continues at a global scale. Conserving and using sustainably the services derived from inland waters is an ongoing challenge for society, as is reducing the negative downstream consequences of inland waters degradation. Failure to reduce and reverse the loss and degradation of inland water systems will further undermine human well-being. The problem of continued loss and degradation is both environmental and social—it is *well established* that the loss and degradation of inland waters has and continues to reduce the ecosystem services available for people.

References

Abramovitz, J. N. 1996: Imperiled Waters, Impoverished Future: The Decline of Freshwater Ecosystems. Worldwatch Paper 128. Worldwatch Institute, Washington, DC, U.S.A.

Abul-Gasim, S. and M. Babiker, 1998: Iraq's Food security: the sand dunes fixation project. *Desertification Control Bulletin,* **33,** 2–10

Ali, A., Md Rawi, C.S., Mansor, M., Ramakrishna, S. & T. Mundkur, (eds) 2002: The Asian wetlands: bringing partnerships into good wetland practices, Proceedings of the Asian Wetland Symposium 2001 ''bringing partnerships into good wetland practices', Penang, Malaysia, August 2001, Penebit Universiti Sains Malaysia, Pulau Pinang, Malaysia

Alvarado, F. H and B.F. Gutiérrez, 2002: *Especies hidrobiológicas continentales introducidas y transplantadas y su distribución en Colombia.*. Ministerio del Ambiente de Colombia, Convención Ramsar, Corporación Autónoma Regional del Valle del Cauca. Bogotá. 176 p.

American Sportfishing Association. 2001: Economic impact of sportfishing in the US by type of fishing [online] Available at: www.asafishing.org/asa/statistics/economic_impact/economic_impact_table. html

Anon 1992: *A Strategy to Stop and Reverse Wetland Loss and Degradation in the Mediterranean Basin.* IWRB and Regione Friuli-Venezia Giulia, Trieste, Italy. 40p.

Arcadis Euroconsult, 2001: Buffering Capacity of Wetlands Study (BCWS): Final Report Vol. 1 Main Report. Lake Victoria Environmental Management Project (LVEMP), United Republic of Tanzania/World Bank.

Aselmann, I. and Crutzen, P.J. 1989: Global distribution of natural freshwater wetlands and rice paddies, and their Net Primary Productivity, seasonality and possible methane emissions. *Journal of Atmospheric Chemistry* **8,** 307–358

Ashmore, P. and Church, M. 2001: *The Impact of Climate Change on Rivers and River Processes in Canada.* Geological Survey of Canada Bulletin 555. Ottawa, Canada.

Asia-Pacific Migratory Waterbird Conservation Committee, 2001: Asia-Pacific Migratory Waterbird Strategy: 2001 – 2005. Wetlands International – Asia Pacific, Kuala Lumpur, Malaysia, 67 pp.

Avakyan, A.B. and V.B. Iakovleva, 1998: ''Status of Global Reservoirs: The Positioning the Late Twentieth Century. *Lakes & Reservoirs: Research and Management* **3**: 45–52.

BAPPENAS-ADB (National Development Planning Agency and Asian Development Bank), 1999: *Causes, Extent, Impact and Costs of 1997/1998 Fires and Drought.* Final report, Annex 1 and 2, Planning for Fire Prevention and Drought Management Project. Jakarta, Indonesia.

Barbier, E. B., M.C. Acreman, and D. Knowler, 1997: *Economic valuation of wetlands: A guide for policy makers and planners.* Ramsar Convention Bureau, Gland, Switzerland, 127 pp.

Bartolome, J. and I. Vega, 2002: *Mining in Donana: learned lessons.* WWF Spain, Madrid. 25 pp.

Bayliss, B., K. Brenman, I. Elliot, M. Finlayson, R. Hall, T. House, B. Pidgeon, D. Walden and P. Waterman,1997: *Vulnerability Assessment of Predicted Climate Change and Sea Level Rise in the Alligator Rivers Region, Northern Territory Australia.* Supervising Scientist Report 123, Supervising Scientist, Canberra, Australia 134 pp.

Beeton, A.M., 2002: Large freshwater lakes: present state, trends, and future. *Environmental Conservation* **29 (1)**: 21–38.

Beltram, G. and P. Skoberne, 1998: *Agricultural and Forestry Practices for Sustainable Use of Biological and Landscape Diversity in Slovenia.* In: M. Küttel and G. Thélin (eds.). Nature for East and Best, Congress, Basel 22–26 1997, Proceedings. SAEFL, Bern, Switzerland. pp. 91–102.

Bibby, C.J., N.J. Collar, M.J. Crosby, M.F. Heath, C. Imboden, T.H. Johnson, A.J. Long, 1992: *Environmental Conservation* 30(2): 104–130

Blanco, D.E., de la Balze, V.M. (eds) 2004: *Los Turbales de la Patagonia: Bases para su inventario y la conservacíon de su biodiversidad.* Publicacíon No. 19. Wetlands International. Buenos Aires, Argentina.

Bonvallot, V. 2003: . L'arsenic quotidien. Biofutur, **232,** 70–73.

Boyd, H. and J. Madsen, 1997: Impacts of global change on artic-breeding bird populations and migration. Pp. 201–217. In: Global change andArtic Terrestrial Ecosystems, W.C. Oechel, T. Callaghan, T. Gilmanov, J.I. Holten, B. Maxwell, U. Molau and B. Sveinbjoernsson (eds), Global Change and Arctic Terrestrial Ecosystems. *Ecological Studies* 124. Springer, New York. p. 201–217.

Brag, O., Lindsay, R., Risager, M., Silvius, M. and Zingstra, H. 2003: *Strategy and Action Plan for Mire and Peatland Conservation in Central Europe.* Wetlands International, Wageningen, The Netherlands.

Brinson, M.M. and A. Ines Malvarez, 2002: Temperate freshwater wetlands: types, status, and threats. *Environmental Conservation* 29 (2): 115–133.

Brito, M., 2001: Eixos amazônicos de integração e desenvolimento—obras e empreendimentos. In *Biodiversidade na Amazônia Brasileira,* ed. A. Verríssimo, A. Moreira, D. Sawyer, I. dos Santos, L.P. Pinto, pp. 321–326. Brasília, Brasil: Estação Liberdade & Instituto Socioambiental.

Brown, S., 1981: A comparison of the structure, primary productivity, and transpiration of cypress ecosystems in Florida. *Ecol. Monogr.* **51,** 403–27.

Brown, S., C. Hickey, B. Harrington and R. Gill, R. (eds), 2001: *United States Shorebird Conservation Plan,* 2nd Edition. Manomet Center for Conservation Sciences, Manomet, USA. [online] Available at www.manomet.org/USSCP/files.htm

Butchart, S.H.M., A.J. Stattersfield, L.A. Bennun, S.M. Shutes, H.R. Akçakaya, J.E.M. Baillie, S.N., Stuart, C. Hilton-Taylor and G.M. Mace, 2004. Measuring global trends in the status of biodiversity: Red List Indices for birds. Philosophical Transactions, LoS Biology, 2, 2294–2304.

Butler, R.W. and R.G. Vennesland, 2000: ''Integrating climate change and predation risk with wading bird conservation research in North America.'' *Waterbirds* **23(3),** 535–540.

Carbonell, M., N. Nathai-Gyan, and C.M. Finlayson, 2001: *Science and local communities: strengthening partnerships for effective wetland management.* Ducks Unlimited Inc, Memphis, USA. 93 pp.

CERP, 1999**.** Comprehensive Everglades Restoration Plan 1999. Available online at: http://www.evergladesplan.org/about/rest_plan.cfm

Chenje, M. (ed.), 2000: *State of the Environment Zambezi Basin 2000: Summary.* Maseru, Lusaka and Harare, SADC, IUCN, ZRA and SARDC.

Chevreuil, M., D. Thevenot, P. Scribe, M.Blanchard, Y. Duclos, M. Garmouna, et al. 1998: Micropollutants organiques: une boîte de Pandore. In *La Seine en son bassin,* M. Meybeck, G. de Marsily and E. Fustec (eds), Elsevier, Paris, France. p. 439–481.

Clausnitzer, V. and R. Jodicke, 2004: Guardians of the watershed: Global status of dragonflies: critical species, threat and conservation. *International Journal of Ordonatology* Vol **7 (2).** ISSN 1388-7890.

CNA-IBUNAM (Comisión Nacional del Agua-Instituto de Biología de la UNAM), 1999: Inventario de Cuerpos de Agua Continentales y Costeros, Vegetación. Comisión Nacional del Agua. Gerencia de Saneamiento y Calidad del Agua.

Coe, M.T. and Foley, J.A. 2001. Human and natural impacts on the water resources of the Lake Chad Basin. *Journal of Geophysical Research (Atmospheres)* **106,** 3349–3356.

Contreras-Balderas, S., 2003: *Las Presas del Noreste.* In: De la lanza-Espino G. y García-Calderón J.L. (Eds.) Lagos y Presas de México AGT Editor, Mexico. p. 484–499.

Costanza, R., R. d'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R.V. O'Neill, J. Paruelo, R.G. Raskin, P. Sutton, P. & M. van den Belt, 1997: The value of the world's ecosystem services and natural capital. *Nature* **387**: 253–260.

Cushing, C.E., K.W. Cummins, and G.W. Minshall, 1995: *Ecosystems of the World 22: Rivers and Stream Ecosystems.* Elsevier Science Publishers, Amsterdam, The Netherlands.

Dahl, T. E. and C. E. Johnson, 1991: *Status and Trends of Wetlands in the Conterminous United States, Mid-1970's to Mid-1980's.* Washington, DC: U.S. Department of the Interior, Fish and Wildlife Service.

Dahl, T.E., 2000: *Stats and trends of wetlands in the conterminous United States 1986–1997.* U.S. Department of the Interior, Fish and Wildlife Service, Washington, D.C. 82 pp.

Danielopol, D.L., Griebler, C., Gunatilaka, A. and Notenboom, J. 2003: Present state and future prospects for groundwater ecosystems. *Environmental Conservation* 30, 104–130.

Darras, S., M. Michou and C. Sarrat, 1999: *A first step towards identifying a global delineation of wetlands.* IGBP-DIS Working Paper # 19, Toulouse, France. 64 pp.

Davidson, N.C. and D.A. Stroud, D.A. 2004: African-Eurasian Flyways: current knowledge, population status, and future challenges. Proceedings of the Waterbirds around the World conference, Edinburgh, April 2004. Her Majesty's Stationary Office, London

Davies, J. and G.F. Claridge (eds), 1993: *Wetland benefits: the potential for wetlands to support and maintain development.* AWB Publication No 87, Kuala Lumpur, Malaysia, IWRB Special Publication No 21, Slimbridge, UK, and Wetlands of the Americas Publication No 11, Ottawa, Canada. 45 pp.

De Voogt, K., G. Kite, P. Droogers, and H. Murray-Rust. 2000. Modelling water allocation between a wetland and irrigated agriculture in the Gediz Basin, Turkey. *Water Resources Development,* **16,** 639–650.

Delany, S., C. Reyes, E. Hubert, S. Pihl, E. Rees, L. Haanstra and A. van Strien, 1999: Results from the International Waterbird Census in the Western Palearctic and Southwest Asia, 1995 and 1996.. Wetlands International Publication No. 54. Wageningen, The Netherlands. p. 1–178

Delgado, C.L., N. Wada, M.W. Rosegrant, S. Meijer and M. Ahmed, 2003: *Outlook for Fish to 2020: Meeting Global Demand.* International Food Policy Research Institute & WorldFish Centre, 28 pp.

Diaz-Carreras, Juan H., (n.d.): Comprehensive Everglades Restoration Plan [online] Available at: http://www.dep.state.fl.us/lands/conference/mateials/Diaz%20-%20Fixing%20Everg lades.pdf

Dochoda, M., 1988: Great Lakes Fishery Commission. [online] Available at: http://www.glfc.org/fishmgmt/fsecon.htm

Dowman, K., 1997: *The Sacred Life of Tibet.* Thorson (Harper Collins), London, 324 pp.

Ducks Unlimited, 2002: Recreation [online] Available at: www.ducks.org/conservation/improve_recreation.asp.

Dudgeon, D., 2000: "Large-scale hydrological changes in tropical Asia: prospects for riverine biodiversity." *BioScience* 50(**9**): 793–806.

Dudgeon, D., 2000a: Large-scale hydrological alterations in tropical Asia: prospects for riverine biodiversity. *BioScience* **50**: 793–806.

Dudgeon, D., 2000b: The ecology of tropical Asian rivers and streams in relation to biodiversity conservation. *Annual Review of Ecology & Systematics* **31**: 239–263.

Dudgeon, D. 2000c: Riverine wetlands and biodiversity conservation in tropical Asia. In: *Biodiversity in Wetlands: Assessment, Function and Conservation* B. Gopal, W.J. Junk & J.A. Davis (eds). Backhuys Publishers, The Hague: 35–60.

Dudgeon, D., 2003: The contribution of scientific information to the conservation and management of freshwater biodiversity in tropical Asia. *Hydrobiologia* **500** (Special Issue): 295–314.

Dugan, P. (ed.), 1993: *Wetlands in Danger.* World Conservation Atlas. (Oxford University Press: New York.)

Dugan, P.J. (ed.), 1990: *Wetland Conservation: A Review of Current Issues and Required Action.* IUCN, Gland, Switzerland, 94 pp.

Eiseltova, M., 1994: *Restoration of lake ecosystems.* IWRB Publication 32, Slimbridge, UK. 182 pp.

Eiseltova, M. and J. Biggs (eds), 1995: *Restoration of stream ecosystems—an integrated catchment approach.* IWRB Publication 37, Slimbridge, UK. 170 pp.

Eliot I, C.M. Finlayson and P. Waterman, 1999: Predicted climate change, sea level rise and wetland management in the Australian wet-dry tropics. *Wetlands Ecology and Management* **7,** 63–81.

Ellison, A.M., 2004: Wetlands of Central America. *Wetlands Ecology and Management* **12,** 3–55.

Emerton, L., P. Iyango, Luwum and A. Malinga, 1998: *The Present Economic Value of Nakivubo Urban Wetland, Uganda.* IUCN—The World Conservation Union, Eastern Africa Regional Office, Nairobi and National Wetlands Programme, Wetlands Inspectorate Division, Ministry of Water, Land and Environment, Kampala, 30 pp.

European Environment Agency 2003: Europe's water: An indicator-based assessment. Topic report No 1/2003, p. 93 and p. 97

FAO (Food and Agriculture Organization of the United Nations), 1996: Malawi Fishery Country Profile. FAO Fisheries Department [online] Available at: http://www.fao.org/fi/fcp/malawie.htm.

FAO, 1999: Inland Water Resources and Aquaculture Service, Fishery Resources Division, *Review of the State of World Fishery Resources: Inland Fisheries, 1999.* FAO Fisheries Circular, No. 942.

FAO, 2003: *Rice and Us.* [online] International Year of Rice 2004 Fact Sheet. Available at http://www.fao.org/rice2004/en/rice-us.htm

FAO, 2004: The State of the World Fisheries and Aquaculture 2004. FAO Fisheries Department, Rome, Italy.

Fernando, C.H., 1991: Impacts of fish introductions in tropical Asia and America. *Canadian Journal of Fisheries and Aquatic Sciences* 48 (Suppl. 1): 24–32.

Finlayson C.M. & M. Moser (eds), 1991: *Wetlands: A global perspective.* Facts on File, Oxford.

Finlayson C.M., T. Hollis and T. Davis (eds), 1992: *Managing Mediterranean wetlands and their birds.* Proceedings of an IWRB International Symposium, Grado, Italy, February 1991. IWRB Special Publication No 20, Slimbridge, UK. 285 pp.

Finlayson C.M. & A.G. van der Valk, 1995: *Classification and inventory of the world's wetlands*: Advances in Vegetation Science 16, Kluwer Academic Press, Dordrecht, The Netherlands.

Finlayson C.M. & N. Rea, 1999: Reasons for the loss and degradation of Australian wetlands. *Wetlands Ecology & Management* **7,** 1–11.

Finlayson C.M. & A.G. Spiers (eds), 1999: *Global Review of Wetland Resources and Priorities for Wetland Inventory.* Supervising Scientist Report 144 & Wetlands International Publication 53, Supervising Scientist, Canberra, 520 pp.

Finlayson C.M., N.C. Davidson, A.G. Spiers and N.J. Stevenson, 1999: Global wetland inventory—Status and priorities. *Marine and Freshwater Research* 50, 717–727.

Finlayson, M., van Dam, R., Walden, D. and Storrs, M. 2000: Risk Assessment for Managing the Tropical Weed, *Mimosa pigra.* In *Assessment and management of alien species that threaten ecosystems, habitats and species.* Abstracts of keynote addresses and posters presented at the sixth meeting of the Subsidiary Body on Scientific, Technical and Technological Advice, held in Montreal, Canada, from 12 to 16 March 2001. Montreal ,CBD Technical Paper no. 1. p. 17–20.

Finlayson C.M., G.W. Begg, J. Howes, J. Davies, K. Tagi and J. Lowry, 2002: *A manual for an inventory of Asian wetlands (version 1.0).* Wetlands International Global Series 10, Wetlands International, Kuala Lumpur, Malaysia. 72 pp.

Finlayson C.M., 2003: *Integrated inventory, assessment and monitoring of tropical wetlands. Environmental Monitoring of Tropical and Subtropical Wetlands,* Proceedings of a Conference, Maun, Botswana, 4–8 December 2002. Okavango Report Series No 1, HOORC, Maun, Botswana. Pp 16–44.

Finlayson, C.M., Y.S. Chuikow, R.C. Prentice and W. Fischer, 1993: *Biogeography of the lower Volga, Russia: an overview.* IWRB Special Publication No. 28, Slimbride, UK. 16 pp.

Finlayson, C.M. and T. Larsson (eds), 1991: *Wetland Management and Restoration,* Proceedings of a workshop, Sweden, 12–15 September 1990, Swedish Environmental Protection Agency Report 3992, pp. 17–23.

Foster, S., A. Lawrence, and B. Morris. 1998. Groundwater in Urban Development: Assessing Management Needs and Formulating Policy Strategies. World Bank Technical Paper No. 390. The World Bank, Washington, DC, U.S.A

Gallego Fernandez, J.B. and F. Garcia Nove, 2002: Restoration of tidal marshes in Guadalquivir river estuary, south-west Spain. In: *Restoration of Mediterranean Wetlands,* G.C. Zalidis, T.L. Crissman and P.A. Gerakis (eds), Hellenic Ministry of the Environment, Physical Planning and Public Works, Athens, and Greek Biotope/Wetland Centre, Thermi, Greece. pp. 213–228.

Garibaldi, L. and D. M. Bartley, 1998: The database on introductions of aquatic species (DIAS). Food and Agriculture Organization of the United Nations (FAO) Aquaculture Newsletter (FAN), no. 20. Available on the Web at http://www.fao.org/fi/statist/fisoft/dias/index.htm.

Gitay, H., Suarez, A., Watson, R., Ansimov, O., Chapin, F.S., Victor Cruz, R., Finlayson, M. et al 2002. Climate change and biodiversity. IPCC Technical Paper V, Intergovernmental Panel on Climate Change, Geneva, Switzerland. 77 pp.

Gleick, 2002: *Dirty Water: Estimated Deaths from Water-Related Diseases 2000–2020.* Pacific Institute for Studies in Development, Environment, and Security [online] Available at www.pacinst.org, page 12/12

Glover, D. and T. Jessup (eds), 1999: *Indonesia's fires and haze: the cost of catastrophe.* Institute of South East Asian Studies, Singapore and IDRC, Ottawa, Canada. 160 pp.

Gopal, B., 1987: *Water Hyacinth.* Aquatic Plant Studies 1, Amsterdam and New York: Elsevier Science.

Gopal, B., W.J. Junk, and J.A. Davis (eds), 2000: *Biodiversity in wetlands: assessment, function, and conservation,* volume 1. Leiden, The Netherlands: Backhuys Publishers.

Great Lakes Information Network, 2004: Fish and fisheries of the Great Lakes region—overview. [online] Available at http://www.great-lakes.net/envt/flora-fauna/wildlife/fish.html#over

Groombridge, B., 1992: Global Biodiversity: Status of the Earth's Living Resources. Chapman and Hall, London, U.K.

Groombridge, B. and M. Jenkins, 1998: *Freshwater Biodiversity: a preliminary global assessment.* World Conservation Monitoring Centre—World Conservation Press, Cambridge, UK. vii + 104 pp + 14 Maps.

Hamilton, S.K., 1999: Potential effects of a major navigation project (Paraguay-Paraná Hidrovia) on inundation in the Pantanal floodplains. *Regulated Rivers: Research and Management,* **15,** 289–299.

Harahsheh, H. and R. Tateishi, 2000: *Environmental GIS Database and Desertification Mapping of West Asia.* Paper presented at the Workshop of the Asian Region Thematic Programme Network on Desertification Monitoring and Assessment, Tokyo, 28–30 June 2000.

Harrison, I. J. and M. J. Stiassny, 1999: The Quiet Crisis: A Preliminary Listing of the Freshwater Fishes of the World that Are Extinct or 'Missing in Action'. In *Extinctions in Near Time* R.D.E. MacPhee (ed.), Kluwer/Plenum Publishers, New York, U.S.A. 271–331.

Heathwaite, A.L., Johnes, P.J. and Peters, N. 1996: Trends in nutrients. *Hydrological Processes* 10, 263–293.

Hecky, R. and Bugenyi, F. 1992: Hydrology and chemistry of the African Great Lakes and water quality issues: problems and solutions. *Mitteilungen Internationale Vereinigung für Limnologie* 23, 45–54.

Heeg, J. and C.M. Breen (eds) 1982: *Man and the Pongolo floodplain*. Pretoria, South Africa: South African National Scientific Programs Report 56, CSIR, Pretoria, South Africa.

Hofstede, R. Segarra, P. and Mena V. 2003: *Los Páramos del Mundo*. Proyecto Atlas Mundial de los Páramos. Global Peatland Initiative/NC-IUCN/Eco-Ciencia. Quito, Peru.

Hollis G.E., J. Patterson, T. Papayannis and C.M. Finlayson, 1992: Sustaining wetlands: Policies, programs and partnerships. In: *Managing Mediterranean wetlands and their birds,* C.M. Finlayson, G.E. Hollis and Davis, T.J. (eds), IWRB Special Publication No. 20, Slimbridge, UK, pp. 281–285.

Hollis, G.E. 1992: The causes of wetland loss and degradation in the Mediterranean. In: *Managing Mediterranean wetlands and their birds,* C.M. Finlayson, G.E. Hollis and Davis, T.J. (eds), IWRB Special Publication No. 20, Slimbridge, UK, pp. 83–90.

Hollis, G.E., W.M. Adams and M. Aminu-Kano (eds), 1993: *The Hadejia-Nguru Wetlands—Environment, Economy and Sustainable Development of a Sahelian Floodplain Wetland*. IUCN, Gland, Switzerland, 244 pp.

Hollis, G.E. 1998: Future wetlands in a world short of water. In: *Wetlands for the future,* AJ McComb & JA Davis (eds), Gleneagles Publishing, Adelaide, 5–18.

IDEAM (Instituto de Hidrología, Metereología y Estudioa Ambientales), 2002: Páramos y ecosistemas alto andinos de Colombia en condición hotspot and global climatic tensor. Ministerio del Media Ambiente, Programa de las Naciones Unidas para el Desarrollo, Bogota, Colombia. 387 pp.

Iftikhar, U., 2002: Valuing the economic costs of environmental degradation due to sea intrusion in the Indus Delta', in IUCN, Sea Intrusion in the Coastal and Riverine Tracts of the Indus Delta—A Case Study. IUCN—The World Conservation Union Pakistan Country Office, Karachi.

ILEC and UNEP (International Lake Environment Committee Foundation and United Nations Environment Programme), 2003: *World Lake Vision: A Call to Action*. 39 pp. ISBN 4–9901546–0–6.

Immirzi, C.P. and E. Maltby, 1992: The global status of peatlands and their role in carbon cycling. In: *Wetlands and climate change. Feasibility investigation of giving credit for conserving wetlands as carbon sinks*. Patterson, J. 1999 (ed), Wetlands International Special Publication 1, p 35.

International Rice Research Institute, 1995: *World Rice Statistics 1993–94,* International Rice Research Institute, Manila, Philippines, p. xv.

International Rice Research Institute, 1999: *The Facts of Rice: Population, Poverty, and Food Security in Asia*. International Rice Research Institute Annual Report 1998–1999.

IUCN (World Conservation Union), 1992: *Environmental Status Reports: Volume 4—Conservation Status of the Danube Delta*. Gland, Switzerland. 107 pp.

IUCN, 2003: *2003 IUCN Red List of Threatened Species*. [online] Available at: http://www.redlist.org

IUCN, Conservation International, and NatureServe 2004. Global Amphibian Assessment. www.globalamphibians.org

Iza, A., 2004. International Water Governance: Conservation of Freshwater Ecosystems. Volume 1 International Agreements—Compilation and Analysis. IUCN, Gland Switzerland and Cambridge, U.K. 324 pp.

Jaensch, R. (ed), 1996: Wetland Conservation in the Pacific Islands Region, Proceedings of the Regional Workshop on Wetland Protection and Sustainable Use in Oceania, June 1994, Port Moresby. Wetlands International-Asia Pacific, Canberra.

Joosten, H. (compiler) 1992. *Estimated peatland per country.* Global Peatland Initiative, Wageningen, The Netherlands.

Joosten, H. 1994: Turning the tides: experiences and perspectives of mire conservation in the Netherlands. In: *Mires and Man: Mire Conservation in a Densily Populated Country- The Swiss Experience,* A. Grünig (ed.), 300–310, Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf, Switzerland.

Joosten, H. and D. Clarke. 2002: *Wise Use of Mires and Peatlands—Background and Principles Including a Framework for Decision-making*. International Mire Conservation Group and International Peat Society. NHBS, Totnes, Devon.

Jorgensen, S.E., R. de Bernardi, T. Ballatore, and V. Muhandiki, 2001: *Lake Watch 25: changes in the world's lakes*. Draft report. International Lake Environment Committee, Kusatsu, Japan.

Junk, W.J. & J.A.S. Nunes de Mello, 1987: Impactos ecológicos das represas hidreétricas na bacia amazônica brasileira. *Tübinger Geographische Studiern,* **95,** 367–385.

Junk, W., 2002: Long-term environmental trends and the future of tropical wetlands. *Environmental Conservation* 29 (4): 414–435

Kaufman, L., 1992: "Catastrophic Change in Species-Rich Freshwater Ecosystems: The Lessons from Lake Victoria." *Bioscience* 42 (11): 846–858.

Kingsford, R.T., and W. Johnson. 1998. Impact of water diversions on colonially-nesting waterbirds in the Macquarie Marshes of arid Australia. *Colonial Waterbirds* **21,**159–170.

Kira, T., 1997: Survey of the state of world lakes. In: *Guidelines for lake management, volume 8: the world's lakes in crisis,* Chapter 7, Jørgensen, S.E. and S. Matsui (eds), Kusatsu, Japan: International Lake Environment Committee and United Nations Environment Programme.

Kucklick, J., Bidleman, T., McConnell, L., Walla, M. & Ivanov, G. 1994: Organochlorines in water and biota of Lake Baikal, Siberia. *Environmental Science & Technology* 28: 31–7.

Kundzewicz, Z. W, and H.J. Schellnhuber, 2004: Floods in the IPCC perspective, *Natural Hazards* **31**: 111–128.

Kura, Y., C. Revenga, E. Hoshino and G. Mock 2004. Fishing for Answers. World Resources Institute, Washington D.C., USA. 138 p.

Lehner, B. and P. Döll, 2004: Development and validation of a global database of lakes, reservoirs and wetlands. *Journal of Hydrology* **296/1–4**:1–22.

Lemly, A.D., R.T. Kingsford, J.R. Thompson. 2000. Irrigated agriculture and wildlife conservation: conflict on a global scale. *Environmental Management*. **25,** 485–512.

Lévêque, C. 1997: *Biodiversity dynamics and conservation: the freshwater fish of tropical Africa*. Cambridge, UK: Cambridge University Press.

Lévêque, C. 2003. Ecology: From Ecosystem to Biosphere. Science Publishers Inc. Plymouth, U.K. 472 p.

Lévêque, C., Balian,E.V., Martens, K (in press): An assessment of animal species diversity in continental water systems. *Hydrobiologia*.

Loh, J, and M. Wackernagel (eds), 2004: *The Living Planet Report 2004*. World Wide Fund for Nature. Gland, Switzerland.

Lowry, J. and C.M. Finlayson 2004. A review of spatial data sets for wetland inventory in northern Australia. Supervising Scientist Report 178, Supervising Scientist, Darwin, Australia. 18 p.

Lundberg, J.G., M. Kottelat, G.R. Smith, M.L.J. Stiassny, and A. C. Gill, 2000: So many fishes, so little time: an overview of recent ichthyological discovery in continental waters. *Annals of the Missouri Botanical Garden* **87**: 26–62.

Lundqvist, J. and P. Gleick, 2000: Comprehensive Assessment of the Freshwater Resources of the World: Sustaining our Waters into the 21st Century, Stockholm Environment Institute.

Lupi, F., M.D. Kaplowitz and J.P. Hoehn, 2002: The economic equivalency of drained and restored wetlands in Michigan. *American Journal of Agricultural Economics* **84,** 2355–1361.

Maitland, P.S. and A.J. Crivelli, 1996: *Conservation of Freshwater Fish,* MedWet–Tour du Valat, Arles (France), 94 pp.

Malmqvist, B. and S. Rundle, 2002: Threats to the running water ecosystems of the world. *Environmental Conservation* 29 (2): 134–153.

Maltby, E., C.P. Immirzi and R.J. Safford (eds) 1996: Tropical Lowland Peatlands of Southeast Asia. IUCN, Gland, Switzerland.

Maltchik, L., 2003: Three new wetlands inventories in Brazil. In: *Interciancia* Vol: **28 (7)**: 421–423.

Manchester, S.J. & J.M. Bullock, 2000: The impacts of non-native species on UK biodiveristy and the effectiveness of control. *Journal of Applied Ecology* 37: 845–864.

Master, L. L., S. R. Flack, and B. A. Stein (eds), 1998: Rivers of Life: Critical Watersheds for Protecting Freshwater Biodiversity. The Nature Conservancy, Arlington, Virginia, U.S.A.

Mathiessen, P. 2000: Is endocrine disruption an significant ecological issue? *Ecotoxicology* 9, 21–24.

Mathiessen, P.and J.P. Sumpter, 1998: Effects of estrogenic substances in the aquatic environment. In *Fish Ecotoxicology,* T. Braunbeck, D. Hinton and B. Streit (eds), Basel, Switzerland: Birkhauser Verlag. p. 319–335.

Mattson, N.S., K. Buakhamvongsa, N. Sukamasavin, T. Nguyen and V. Ouk. 2002: Cambodia Mekong giant fish species: on their management and biology. MRC Technical Paper No.3. Mekong River Commission, Phnom Penh. 29 p.

McAllister, D.E., A.L. Hamilton and B. Harvey, 1997: Global freshwater biodiversity:striving for the integrity of freshwater ecosystems. *Sea Wind—Bulletin of Ocean Voice International* **11(3)**: 1–140.

McComb, A. J., and J.A. Davis (eds), 1998: *Wetlands for the Future.* (Gleneagles Publishing, Adelaide.)

McNeely, J.A., H.A. Mooney, L.E. Neville, P.J. Schei, and J.K. Waage (eds.), 2001: *Global strategy on invasive alien species.* IUCN, Cambridge, U.K., in collaboration with the Global Invasive Species Programme. 48 pp.

Meybeck, M. 2003: Global analysis of river systems: from Earth system controls to Anthropocene syndromes. Philosophical Transactions of the Royal Society London, B. **358,** 1935–1955.

MRC (Mekong River Commission), 1997: *Greater Mekong Sub-Region State of the Environment Report.* Bangkok, Thailand: Mekong River Commission and United Nations Environment Programme.

Miller, R. R., J. D. Williams and J. E. Williams, 1989: Extinctions of North American Fishes During the Past Century. *Fisheries* 14 (6): 22–38.

Mitsch, W. J., R.H. Mitsch, and R.E. Turner (eds), 1994: Wetlands of the Old and New Worlds: ecology and management. In: *Global Wetlands: Old World and New World,* W. J. Mitsch (ed.) pp.3–56, Elsevier, Amsterdam.

Mitsch, J. and X. Wu, 1995: Wetlands and global change. In: *Advances in Soil Science, Soil Management and Greenhouse Effect ,* Lal, R., J. Kimble, E. Levine, B.A. Stewart (eds.), CRC Lewis Publishers, Boca Raton, FL, pp. 205–230.

Mitsch, W.J., 1998: Protecting the world's wetlands: threats and opportunities in the 21st century. In: *Wetlands for the Future,* A.J. McComb and J.A. Davis (ed.), Contributions from INTECOL's V International Wetlands Conference, Perth, Australia, Gleneagles Press, Adelaide, SA, Australia, pp. 19–31.

Mitsch, W.J. (ed.) 1994: Global Wetlands: Old World and New. Elsevier, Amsterdam, The Netherlands. 967 pp.

Mitsch, W. J. and J.G. Gosselink, 2000: Wetlands. 3rd edn. John Wiley, New York, U.S.A. 920 pp.

Miyabayashi, Y. and T. Mundkur, 1999: *Atlas of key sites for Anatidae in the East Asian Flyway.* Wetlands International—Japan, Tokyo and Wetlands International—Asia Pacific, Kuala Lumpur, Malaysia. 148 pp.

Mooney, H.A. and R.J. Hobbs (eds), 2000: *Invasive species in a changing world.* Island Press, Washington D.C. 457 pp.

Moore, H. and E. Wiken, 1998: *Wetland Conservation Analysis.* Canadian Council on Ecological Areas (CCEA) Technical Report. Ottawa, Ontario.16 pgs.

Morrison, R.I.A.G., Y. Aubry, R. Butler, G.W. Beyersbergen, G.M. Donaldson, C.L. Grotto-Trevor, P.W. Hicklin, V.H. Johnson and R.K. Ross, 2001: Declines in North America shorebird populations. *Wader Study Group Bulletin* **94**: 34–38.

Moser, M., R.C. Prentice and J. van Vessem (eds), 1993: *Waterfowl and wetland conservation in the 1990s: A global perspective.* Proceedings of an IWRB Symposium, St Petersburg Beach, Florida, USA, 12–19 November 1992. IWRB Special Publication No 26, Slimbridge, UK.

Moser, M., C. Prentice and S. Frazier, 1996: A global overview of wetland loss and degradation. In: *Papers, Technical Session B, Vol. 10/12B, Proceedings of the 6th Meeting of the Conference of Contracting Parties, Brisbane, Australia, 19.27 March 1996.* pp. 21–31, Ramsar Convention Bureau: Gland, Switzerland.

Moyle, P.B. and R.A. Leidy, 1992: Loss of Biodiversity in Aquatic Ecosystems: Evidence from Fish Faunas. In: *Conservation Biology: The Theory and Practice of Nature Conservation, Preservation and Management,* P.L. Fiedler and S.K. Jain (eds.), New York. New York: Chapman and Hall. pp. 127–169

Mpofu, B., 2000: *Assessment of Seed Requirements in Southern African Countries Ravaged by Floods and Drought 1999/2000.* SADC Food Security Programme, Food, Agriculture and Natural Resources. [online] Available at http://www.sadc-fanr.org.zw/sssd/mozcalrep.htm

National Wetlands Working Group (NWWG), 1988: *Wetlands of Canada. Ecological Land Classification Series, No.24.* Canada Committee on Ecological Land Classification; Sustainable Development Branch, Environment Canada. ISBN No. 0–921317–13–1. Polyscience Publications. Montreal, Quebec 452 pgs.

Naylor, R.L., R.J. Goldburg, J.H. Primavera, N.Kautsky, M.C.M. Beveridge, J. Clay, C. Folke, J. Lubchenco, H. Mooney and M. Troell., 2000: "Effect of Aquaculture on World World Fish Supplies." *Nature* 405: 1017–1024.

Nichols, S. and R.C. Lathrop, 1994: Cultural impacts on macrophytes in the Yahara lakes since the late 1800s. *Aquatic Botany* **47**: 225–247.

Nilsson, C. and K. Berggren, 2000: Alterations of riparian ecosystems caused by river regulation. *BioScience* **50(9)**: 783–792.

Ntakimazi, G. 1992: Conservation of the resources of the African Great Lakes: why? An overview. *Mitteilungen Internationale Vereinigung für Limnologie* 23, 5–9.

OECD (Organisation for Economic Co-operation and Development), 1996: *Guidelines for aid agencies for improved conservation and sustainable use of tropical and subtropical wetlands.* Paris, France.

Ogutu-Ohwayo, R. 1999: The Nile perch in Lake Victoria: the balance between benefits and negative impacts of aliens. In *Invasive species and biodiversity management,* O.T. Sandlund, P.J. Schei and A. Viken (eds.). Kluwer Academic Publishers, Dordrecht, The Netherlands. P. 43–67.

Ortiz G., 2001: *Administración del Agua. Aplicación de Instrumentos de Política Hidráulica*: En Escenarios Alternativos. Instituto Mexicano de Tecnología del Agua, México; 227 p.

Page, S.E., F. Siegert, J. O'Reiley, H-D von Boehem, A. Jaya and S. Limin, 1997: The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature* **420,** 61–65.

Palmer, M. A., A.P. Covich, B.J. Finlay, J. Gilbert, K.D. Hyde, R.K. Johnson, T. Kairesalo, S. Lake, C.R. Lovell, R.J. Naiman, C. Ricci, F. Sabater, and D. Strayer, 1997: Biodiversity and ecosystem processes in freshwater sediments. *Ambio* **26(8)**: 571–577.

Papayannis, T., 2002: *Regional action for wetlands: the Mediterranean experience,* MedWet/Tour du Valat, Arles (France), 96 p.

Partow, H., 2001: *The Mesopotamian Marshlands: demise of an ecosystem.* UNEP, Nairobi, Kenya. 46 pp.

Peberdy, Kevin, 1999: *The Wetland Centre—A Showcase.* Proceedings of the *"WATERFOWL" INFORMATION NETWORK* International Conference, The Royal Veterinary College, London, 16 & 17 September 1999.

Pittock, B., D. Wratt *et al.,* 2001: Chapter 12. Australia and New Zealand. In: *Climate Change 2001: Impacts, Adaptations, and Vulnerability.* Contribution of Working Group II to the Thirds Assessment Report of the International Panel on Climate Change. McCarthy, J.J., Canziani, O.F., Leary, N.A., Dokken, D.J., White, K.S. (eds). pp. 591–640. Cambridge University Publication Press.

Ponce, V.M., 1995: *Impacto Hidrológico e Ambiental da Hidrovia Paraná-Paraguai no Pantanal Matogrossense—Um Estudo de Referência.* San Diego, California, USA: San Diego State University.

Popov, V.1992: Agricultural landse and water pollution in the lower Volga. In Wetland Conservation and Management in the Lower Volga, Russia, Finlayson, C.M. (ed.), 18–22, IWRB Special Publication No 18, Slimbridge, UK.

Postel, S. and S. Carpenter, 1997: Freshwater Ecosystem Services In: *Nature's Services: Societal Dependence on Natural Ecosystems.* Island Press, Washington DC. pp. 195–214.

Postel S., 1997: *Last Oasis: Facing Water Scarcity,* 1997. W.W. Norton & Company, New York.

Postel, S., 1999: *Pillar of Sand: Can the Irrigation Miracle Last?* New York, W.W. Norton & Company, 313 pp.

Pringle, C.M., M.C. Freeman and B. J. Freeman, 2000: Regional effects of hydrologic alterations on riverine macrobiota in the New World: tropical-temperate comparisons. *BioScience* 50(9): 807–823.

Pye-Smith, C., 1995: Salvation from Sewage in Calcutta Marshes. *People & the Planet,* **4(1),** 20–22.

Qu, G., 1999: Environmental Protection Knowledge (China's Red Flag Publishing House, Beijing), p. 354 (in Chinese). In: *China's Forest Policy for the 21st Century*: P. Zhang, G. Shao, G. Zhao, D.C. Le Master, G.R. Parker, J.B. Dunning, Jr., and Q. Li, *Science* Vol. **288,** 2135–2136.

Rabuor, C.O. and J.J. Polovina, 1995: An analysis of the multigear, multispecies fishey in the Kenyan waters of Lake Victoria. *NAGE, the ICLARM Quarterly. April, 1995*: 34–37.

Ramsar Convention Secretariat, 2004: Ramsar Handbooks for the Wise Use of Wetlands. 2nd Edition. Ramsar Convention Secretariat, Gland, Switzerland.

Ratner, B.D., Dong Thanh Ha, Mam Kosal, Ayut Nissapa, Somphanh Chanphengxay 2004. Undervalued and Overlooked: Sustaining Rural Livelihoods through better Governance of Wetlands. Studies and Review Series, World Fish Centre, Penang, Malaysia.

Reuman, S.C. & D.D. Chiras, 2003: *The Population Explosion* in *The 2003 World Book Encyclopedia.* Published by World Book Inc. 22 volume set with 14,000 pages.

Revenga, C. and Y. Kura, 2003: *Status and Trends of Biodiversity of Inland Water Ecosystems.* Secretariat of the Convention on Biological Diversity, Montreal, Technical Series no. 11. 120 pp.

Revenga, C., J. Brunner, N. Henninger, K. Kassem and R. Payne, 2000: *Pilot Analysis of Global Ecosystems: Freshwater Systems,* World Resources Institute, Washington D.C. 83 pp

Revenga, C., S. Murray, J. Abramovitz, and A. Hammond, 1998: *Watersheds of the World: Ecological Value and Vulnerability.* World Resources Institute, Washington, DC, 200 pp.

Revenga, C., I. Campbell, R. Abell, P. de Villiers and M. Bryer, in press: Prospects for Monitoring Freshwater Ecosystems towards the 2010 targets. In *Beyond extinction rates: monitoring wild nature for the 2010 target,* Philosophical Transactions, Biological Sciences, the Royal Society, London, U.K.

Richardson, J. L. and M. J. Vepraskas (eds), 2001: Wetland Soils: Genesis, Hydrology, Landscapes, and Classification. Lewis Publishers, Boca Raton, Florida, U.S.A.

Rieley, J.O., A.A. Ahmad-Shah and M.A. Brady. 1996: The nature and extent of tropical peat swamps. In: *Tropical Lowland Peatlands of Southeast Asia*. Maltby, E., Immirzi, C.P. & Safford, R.J. (eds) IUCN, Gland, Switzerland.

Rieley, J.O. and S.E. Page (eds) 1997. Biodiversity and Sustainability of Tropical Peatlands. Samara Publishing Ltd, Cardigan, U.K.

Roshier, D.A., P.H. Whetton, R.J. Allan, and A.I. Robertson, 2001: ''Distribution and persistence of temporary wetland habitats in arid Australia in relation to climate''. *Austral Ecology,* **26,** 371–384.

Ross, S. T., 1991: Mechanisms Structuring Stream Fish Assemblages: Are There Lessons From Introduced Species? *Environmental Biology of Fishes* 30: 359–368.

Rowan, D. & Rasmussen, J. 1992: Why don't Great Lakes fish reflect environmental concentrations of organic contaminants?—an analysis of between lake variability in the ecological partitioning of PCBs and DDT. *Journal of Great Lakes Research* 18, 724–41.

Schuyt, K. and L. Brander 2004: The economic value of the World's wetlands. WWF Living Waters: Conserving the Source of Life. Gland, Switzerland. 31 pp.

Scott, D.A. and P.M. Rose, 1996: Atlas of Anatidae Populations in Africa and Western Eurasia. Wetlands International Publication No. 41. Wetlands International, Wageningen, The Netherlands.

Sculthorpe, C.D., 1967: *The biology of aquatic vascular plants*. Edward Arnold, London.

Seyam, I.M., A.Y. Hoekstra, G.S. Ngabirano and H.H.G. Savenije, 2001: The value of freshwater wetlands in the Zambezi basin. Value of Water Research Report Series No. 7 IHE Delft, The Netherlands.

Spiers, A.G., 1999: Review of international/continental wetland resources. In: *Global Review of Wetland Resources and Priorities for Inventory.* C. M. Finlayson and A. G. Spiers (eds) Supervising Scientist Report No. 144, 63.104. Canberra, Australia.

State Committee on Ecology and Control of Natural Resources Utilization 1998: National Environmental Action Plan, Azerbaijan Republic. Baku, Azerbaijan.

Stroud, D.A., N.C. Davidson, R. West, D.A. Scott, L. Hanstra, O. Thorup, B. Ganter and S. Delany (compilers) 2004: Status of migratory wader populations in Africa and Western Eurasia in the 1990s. *International Wader Studies* **15**: 1–259

Sverdrup-Jensen, S., 2002: *Fisheries in the Lower Mekong Basin: Status and perspectives*. MRC Technical Paper No. 6, Mekong River Commission, Phnom Penh. 103 pp. ISSN: 1683–148.

Thomsen, J.B., 1999: Looking for hotspots. World Conservation, 2, 6–7. [online] Available at: www.iucn.org/bookstore/bulletin/1999/wc2/content/hotspots.pdf.

Tockner, K. and J.A. Stanford, 2002: Riverine flood plains: present state and future trends. *Environmental Conservation* 29 (3): 308–330.

Uetz, P. and T. Etzold, 1996: The EMBL/EBI Reptile Database, *Herpetological Review* **27 (4)**

UNDHA (United Nations Department of Humanitarian Affairs), 1994: *First African Sub-Regional Workshop on Natural Disaster Reduction,* Gaborone, 28 November to 2 December 1994. Gaborone.

UNDP/GEF/GOC (United Nations Development Programme, Global Environment Facility, and Government of China), 2003: Management Plan for Ruoergai National Nature Reserve. UNDP/GEF/GOC Wetland Biodiversity Conservation and Sustainable Use in China, January 2003.

UNEP (United Nations Environment Programme), 1996: *Groundwater: A Threatened Resource*. UNEP Environment Library No. 15, Nairobi, Kenya.

UNEP, 1999: *GEO-2000*. United Nations Environment Programme. London and New York, Earthscan.

UNEP, 2002: *Vital Water Graphics—An Overview of the State of the World's Fresh and Marine Waters*. UNEP, Nairobi, Kenya. ISBN: 92–807–2236–0.

UNEP, 2003: *Post-Conflict Environmental Assessment: Afghanistan.* Report by the United Nations Environmental Programme. ISBN 92–1–158617–8

UNESCO (United Nations Educational, Scientific, and Cultural Organization), 2000: *Water Related Vision for the Aral Sea Basin for the Year 2025.* Paris, France: UNESCO.

U.S. Fish and Wildlife Service, 2004: *Waterfowl population status 2004.* Department of the Interior, Washington, D.C. 54 pp.

Valette-Silver, N. N. J. 1993: The use of sediment cores to reconstruct historical trends in contamination of estuarine and coastal sediments. Estuaries **16,** 577–588.

van Dam, R.A., Walden, D.J. and Begg, G.W. 2002a: A preliminary risk assessment of cane toads in Kakadu National Park. Supervising Scientist Report 164, Supervising Scientist, Darwin, Australia.

van Dam, R., Walden, D., Begg, G. and Finlayson., M 2000**:** Ecological Risk Assessment of the Cane Toad, Bufo marinus, in Karadu National Park, Australia. In *Assessment and management of alien species that threaten ecosystems, habitats and species*. Abstracts of keynote addresses and posters presented at the sixth meeting of the Subsidiary Body on Scientific, Technical and Technological Advice, held in Montreal, Canada, from 12 to 16 March 2001. Montreal ,CBD Technical Paper no. 1. p. 21–24.

van Dam, R., H. Gitay, M. Finlayson, N.J. Davidson and B. Orlando, 2002b: *Climate Change and Wetlands: Impacts, Adaptation and Mitigation*. Background document (DOC.SC26/COP8–4) prepared by for the 26th Meeting of the Standing Committee of the Convention on Wetlands (Ramsar Convention) held in Gland, Switzerland, 3–7 December 2002.

van Dijk, P.P., B. L. Stuart, and A. G.J. Rhodin, 2000: Asian Turtle Trade: Proceedings of a Workshop on Conservation and Trade of Freshwater Turtles and Tortoises in Asia Chelonian Research Monographs, No. 2, Chelonian Research Foundation in association with WCS, TRAFFIC,WWF, Kadoorie Farm and Botanic Gardens US Fish and Wildlife Service. Chelonian Research Foundation Lunenburg, Massachusetts, U.S.A. 164pp.

Vörösmarty, C.J., K.P. Sharma, B.M. Fekete, A.H. Copeland, J. Holden, J. Marble, and J.A. Lough, 1997: The Storage and Aging of Continental Runoff in Large Reservoir Systems of the World. *Ambio* **26(4)**: 210–219.

Walden, D., R. van Dam, M. Finlayson, M. Storrs, J. Lowry and D. Kriticos 2004: *A risk assessment of the tropical wetland weed* Mimosa pigra *in northern Australia*. Supervising Scientist Report 177, Supervising Scientist, Darwin NT.

Walther, G.R., E. Post, P. Convey, A. Menzel, C. Parmesan, T.J.C. Beebeef, J.M. Fromentine, O. Hoegh-Guldberg and F. Bairlein, 2002: Ecological responses to recent climate change. *Nature* **416,** 388–395.

Warner, B. G. and Rubec, C.D.A. (eds) 1997: *The Canadian Wetland Classification System,* Second Edition. National Wetlands Working Group. Wetlands Research Centre, University of Waterloo. Waterloo, Ontario. 68 pp.

Wetlands International, 1999: *Atlas of Key Sites for Cranes in the North east Asian Flyway.* Simba Chan (ed).

Wetlands International, 2002: *Waterbird Population Estimates. 3rd Edition*. Consultation Draft available on-line at: http://www.wetlands.agro.nl.

Whigham, D.F., RE Goode and J. Kvet (eds) 1993: *Wetland Ecology and Management—Case Studies,* Kluwer Academic Publishers, Dordrecht, The Netherlands.

White, R.P., C. Revenga, J. Nackoney and E. Hoshino 2004: *Wetlands , drylands, and ecosystem services*. Report Prepared by World Resources Institute for the Millennium Ecosystem Assessment, 43 p.

Wiken, Ed B., D. Gauthier, I. Marshall, K. Lawton, and H. Hirvonen, 1996: *A perspective on Canada's ecosystems. An overview of terrestrial and marine ecozones*. Canadian Council on Ecological Areas. Occasional paper 14.

Williams, W.D., 2002: Environmental threats to salt lakes and the likely status of inland saline Ecosystems in 2025. *Environmental Conservation* 29 (2): 154–167

Williamson, M., 1996: *Biological invasions*. London: Champan & Hall.

Wiseman, R., D. Taylor and H. Zingstra (eds) 2003: Proceedings of the workshop on agriculture, wetlands and water resources: 17th Global Biodiversity Forum, Valencia, Spain. November 2002. National Institute of Ecology and International Scientific Publications, New Delhi, India. 122 p.

Witte, F., T. Goldschmidt, J. Wanink, M. van Oijen, K. Goudswaard, E. Witte-Mass and N. Bouton, 1992: The Destruction of an Endemic Species Flock: Quantitative Data on the Decline of the Haplochromine Cichlids of Lake Victoria. *Environmental Biology of Fishes* 34:1–28.

Wittenberg, R. and M.J.W. Cock (eds), 2001: *Invasive alien species: a toolkit of best prevention and management practices*. CAB International, Wallingford, UK. 228 pp.

Wooster, M.J. and N. Strub, 2002: Study of the 1997 Borneo fires: quantitative analysis using global area coverage (GAC) satellite data. *Global Biogeochemical Cycles* **16.**

WCD (World Commission on Dams), 2000: *Dams and Development: A new Framework for Decision-making.* The Report of the World Commission on Dams. London, U.K.: Earthscan Publications Ltd.

World Energy Council, 2003: *The Hydroelectric Power Option in Brazil Environmental, Technological and Economic Aspects.* London, U.K. URL: www.world-energy.org

WMO (World Meteorological Organization), 1997: *Comprehensive Assessment of the Freshwater Resources of the World.* Stockholm, Sweden: WMO and Stockholm Environment Institute.

WRI (World Resources Institute), United Nations Development Programme, United Nations Environment Programme, and World Bank, 2000. *World Resources 2000–2001: People and Ecosystems: The Fraying Web of Life.* World Resources Institute, Washington DC.

WWDR (World Water Development Report) 2003: *Water for People, Water for Life.* United Nations World Water Assessment Programme. UNESCO/Berhahn Boks, Paris, France, 575 pp. Available at www.unesco.org/water/wwap/wwdr/index.shtmlcheck publisher – web

WWF (World Wide Fund for Nature), 2002: *The Ecological Effects of Mining Spills in the Tisza River System in 2000.* WWF International Danube-Carpathian Programme, Vienna, Austria.

Xie, Y., Z. Li, W.P. Gregg and D. Li, 2001: Invasive species in China—an overview. *Biodiversity and Conservation* 10: 1317–1341.

Zalidis, G.C., T.L. Crissman and P.A. Gerakis (eds), 2002: *Restoration of Mediterranean Wetlands,* Hellenic Ministry of the Environment, Physical Planning and Public Works, Athens, and Greek Biotope/Wetland Centre, Thermi, Greece. Pp. 213–228.

Zockler, C. and I. Lysenko, 2000. *Water Birds on the Edge. First circumpolar assessment of climate change impact on Arctic breeding water birds.* WCMC Biodiversity Series No. 11, World Conservation Monitoring Centre—World Conservation Press, Cambridge, U.K.