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Long-term environmental trends and the future of tropical wetlands

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SUMMARY

Tropical wetlands assume important functions in the landscape and contribute considerably to the welfare of large parts of the human population, but they are seriously threatened because they are considered free resources of land and water. This review summarizes long-term environmental trends for tropical wetlands and predicts their future to the time horizon 2025. Many tropical countries do not have the economic strength, scientific and technological capacity, and/or administrative infrastructure to adequately react to the challenges of increasing population pressure and globalization of the economy with respect to the sustainable use of the resources. Furthermore, political instability and armed conflicts affect large areas in several tropical countries, hindering wetland research and management. Detailed wetland inventories are missing in most countries, as are plans for a sustainable management of wetlands in the context of a long-term integrated watershed management. Despite large regional variability, a continental ranking shows, in decreasing order of wetland integrity, South America, Africa, Australia and Asia, while efforts to mitigate human impacts on wetlands are largest and most advanced in Australia. Analysis of demographic, political, economic and ecological trends indicates fairly stable conditions for wetlands in tropical Australia, slight deterioration of the large wetland areas in tropical South America excepting the Magdalena and Cauca River flood plains where human population is larger, rapidly increasing pressure and destruction on many African and Central American wetlands and serious threats for the remaining wetlands in tropical Asia, by the year of 2025. Policy deficiencies, deficient planning concepts, limited information and awareness and institutional weakness are the main administrative reasons for wetland degradation and must be overcome to improve wetland management and protection in future. Intensification of international cooperation and assistance is considered of fundamental importance for most tropical countries to solve problems related to wetland research, protection and sustainable management.

Keywords: tropical wetlands, watershed management, flood plain

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INTRODUCTION

Tropical wetlands have played an important role for humankind on all continents. The fertile flood plains of the Nile, Euphrates, Tigris and Indus Rivers were the economic basis for the high cultures of Egyptians, Sumerians and Harappas, 5000 to 4000 years ago (Hammerton 1972; Boulé 1994). Fairly predictable dry and wet seasons and connected inundations by the large rivers favoured the cultivation of paddy rice and other aquatic macrophytes, fish culture, the domestication of water buffaloes and ducks, and the breeding of flood-resistant crops, vegetables, fruit and domestic animals, and allowed the sustainable use of many tropical wetlands by a dense human population (Fernando 1980*a*,*b*). Amerindians colonized wetlands from the time of their arrival in South America about 12 000 years ago (Roosevelt 1999). They built complex systems of earth mounds, dykes, and channels for housing, agriculture, fishery and transport (Parsons & Bowen 1966; Denevan 1966; Meggers 1987). Population density in the Amazon River flood plain was about 10–20 times larger than in the neighbouring non-flooded upland (Denevan 1976). Rapid population increase in the entire tropical belt during the last century and a dramatic change in food production and management methods led to accelerated wetland reclamation and deviation of water. These reduced the wetland area, seriously threatening wetland integrity in most tropical countries.

Directories of wetlands are published for Asia (Scott 1989), South America (Scott & Carbonell 1986), Africa (Hughes *et al.* 1992) and Australia (Environment Australia 2001). An international wetland inventory has been given by Finlayson and van der Valk (1995) and updated in a review for the Ramsar Convention by Finlayson and Spiers (1999). These inventories form an important data basis, but are far from complete. The wetlands of Brazil are reported to cover an area of 680 794 km^2, and those of Argentina 59 423 km^2 (Davidson *et al.* 1999). However, about 20% of tropical South America (an area 2 to 3 times larger than officially indicated) are wetlands, albeit many of small size or little known (Junk 1993). In fact, all continents are covered by a network of small temporary and perennial wetlands along streams and in depressions that assume important functions in the landscape, mostly for water retention, as filters, sinks and sources for substances, and as habitats for specific plants, animals and humans. The relative importance of wetlands increases in the semi-arid and arid tropical belt, because these dispersed wetlands are of vital importance for specialized plants, animals and humans. In many semi-arid and arid countries, seasonal wetlands may remain without water for several years or decades, yet when water arrives, flora and fauna characteristic of wetlands soon reappear, as in many Australian dryland wetlands or in the 10 000 km^2 of the Makgadikgadi Pans of Botswana (Taylor *et al.* 1995).

In this review, I begin with the description of environmental forcing factors in wetland ecology. Then I will characterize long-term trends in demographic, political, economic and ecological development. Furthermore, I will discuss the future of wetlands in the tropical parts of Central and South America, Africa, Asia and Australia up to the time horizon of 2025. Finally, I will discuss general requirements to slow down wetland deterioration and improve wetland management and protection. I treat the tropics as not having strict geographical borders because some countries extend over different climatic zones but represent political units, as for instance, Argentina, India and Australia. In Africa, political conflicts often surpass climatic borders and involve several countries. Some large rivers like the Paraná/Paraguay, Mekong and Ganges and connected wetlands extend from the tropics to temperate regions and are also treated as one unit.

ENVIRONMENTAL FORCING FACTORS IN TROPICAL WETLANDS

The main environmental forcing factor in wetlands is hydrology. Most wetlands in the tropics are subjected to considerable water-level fluctuations according to the dry and rainy season and belong to the floodplain category (Junk *et al.* 1989). Flooding can occur by the rise of connected rivers, lakes and/or by rainwater. Permanent swamps are rare and often part of larger periodical wetlands. Organisms living in these wetlands not only tolerate, but also require these water-level fluctuations for the long-term survival of their populations, as terrestrial invertebrates (Adis & Junk 2002). Annual changes in water level modify the extent of the area covered by water and determine flood amplitude and duration. The hydrological regime requires adaptations of plants and animals to drought and floods, influences composition of plant and animal communities, and triggers biological processes on land and in water (Junk *et al.* 1989). Accelerated nutrient recycling and nutrient transfer between the terrestrial and aquatic phases, increases primary production by herbaceous plants (Junk 1997). Predictable water-level fluctuations lead to ecological determinism (Lewis *et al.* 2000). Large spawning migrations of fishes related to the onset of the rainy season are reported from all tropical river-floodplain systems (Lowe-McConnell 1987). Fish catches are positively correlated with the extent of flooding (Welcomme 1979). Major modifications of the natural hydrological regime by water deviation, dam and channel construction or drainage have dramatic impacts on these populations.

All wetlands have been affected by palaeoclimatic changes as testified by sediment cores, floral and faunal relicts, and present species composition. For instance, during the last glacial period, the surface of the Amazon River flood plain near Manaus was about 20 m lower and its total area considerably smaller than today, because of the lower sea-level stage (Müller *et al.* 1995). The Pantanal of Mato Grosso was mostly dry (Ab'Saber 1988) and wetland species were extinct or migrated to the lower Paraguay River flood plain. During the mid-Holocene, much of North Africa was covered with grasslands along with scattered lakes and wetlands (Carrington *et al.* 2001). In the arid and semi-arid belt, climatic changes had dramatic impacts on wetland size and species composition. Low precipitation led to low water levels or complete drying up of many East African lakes and seriously affected the connected wetlands about 14 000 years ago (Scholz & Rosendahl 1988).

In recent times, major changes in hydrology have also been occurring all over the tropics. The frequent and unpredictable occurrence of pluriannual wet and dry periods is characteristic of countries with a monsoonal climate like India, and the related water-level fluctuations are of fundamental importance for the maintenance of biodiversity in the wetlands (Gopal & Chauhan 2001). In South America, El Niño and La Niña and, in Africa, the Sahelian precipitation anomalies (Thompson 1996), seriously affect the water balance. Pluriannual dry and wet periods lead to dramatic changes in the area of Lake Chad and connected wetlands. In the early 1960s heavy rainfalls led to a considerable rise in the level of Lakes Victoria, Tanganjika and Naivasha and to high discharge rates of the Chari and Zaire Rivers (Bugenyi 2001). Extreme dry periods are stressful for wetland organisms because they strongly reduce the extent and affect the quality of wetland habitats (Dumont 1992). They also affect terrestrial communities by lack of water combined with increased fire stress. As a consequence, many tropical wetland species show a great morphological and physiological plasticity of response to periodic hydrological changes or react with large variations in population size.

Organisms with short life cycles can adjust quickly to extreme hydrological events, but long-lived organisms may require decades or centuries. The recent spread of the native flood-adapted tree *Vochysia divergens* in the Pantanal of Mato Grosso (Brazil) began after an intense pluriannual dry period in the early 1970s and is attributed to the pluriannual wet period in the area that then continued until 1998. The 1999 wild fires seriously affected the *Vochysia* communities and it is expected that a new pluriannual dry period will reduce them again to low-lying permanent wet habitats (C.N. da Cunha & W.J. Junk, unpublished data 2002). At the beginning of the 1970s, a four-year flood period killed shrubs and trees in low-lying areas of the central Amazonian flood plain. The eliminated species have still not been able to recolonize these areas (Junk & Piedade 1997). In the 1980s, a pluriannual Sahelian drought seriously affected the fishery in the central delta of the Niger River, fish catches declining from 90 000 t yr^{-1} to 45 000 t yr^{-1} because of poor rainfall (Lae 1994).

The amount and quality of dissolved and suspended solids determine primary and secondary production in wetlands.

Wetlands in semi-arid and arid regions are rich in nutrients and tend to eutrophication and salinization (Dumont 1992). They are vulnerable to additional nutrient input by agriculture and wastewater disposal and to water deviation. Many humid tropic wetlands have a low nutrient status, as shown for black and clear water flood plains in Amazonia (Furch & Junk 1997). Rich plant growth and wildlife in these systems are not indications of high fertility (Furch 2000) but of quick nutrient recycling and high nutrient-use efficiency (Fig. 1), and these systems are vulnerable to overexploitation of their plant and animal resources.

The wetlands are strongly influenced by their watersheds, from which they receive water and dissolved and suspended material, and with which they exchange organisms. They act as a periodic or permanent sink for inorganic sediments, nutrients and organic carbon, and also for toxic substances (Fig. 1). This makes them very vulnerable to inadequate management of the catchment area, for instance by large-scale agriculture, mining activities, industries and human settlements. River catchment areas are very large and connected wetlands can be seriously affected by inadequate resource management in distant areas, for instance by water deviation for irrigation or hydroelectric power plants in the headwaters, which modify the discharge pattern. Wetlands with small catchment areas, or those which depend exclusively on local rainwater supply, are less affected and can be easily protected.

The connectivity of wetlands with permanent water bodies is important for the exchange of water, dissolved and solid substances, and organisms. Flood plains are the most productive area of river-floodplain systems (Junk *et al.* 1989). A large number of tropical river fish (so-called 'white' fish) perform spawning and feeding migrations (Welcomme 1979). In large river systems like the Amazon they can cover several thousand kilometres. Reproduction and population development are seriously affected by interruption of migration routes or blocked access to the flood plains.

Wetlands in general and tropical wetlands in particular are hot spots for the development and maintenance of biodiversity (Gopal *et al.* 2000, 2001). About 20% of the Amazonian tree species occur in the floodplain forests of the large Amazonian rivers that occupy only about 5% of the total rainforest area. Most of them are flood plain specific. Many bird species live permanently or temporarily in wetlands. For large-distance migrants that nest in high latitudes, tropical and subtropical wetlands are essential for wintering (see Harris 1994; Shukla 1994; Petermann 1997). The carrying capacity of many African savannahs and Asian forests for ungulates depends to some extent on wetlands that store water, provide food and offer shelter against wild fires during the dry season (Belsare 1994; Thompson & Polet 2000).

Predictable hydrology with dry and rainy seasons in the tropics has allowed the development of flood-adapted management methods in contrast to the rather unpredictable flood conditions in temperate regions. Dinka and Nuer tribes use the Sudd swamps of the upper Nile for cattle farming and fishing on a seasonal basis. Efficient tribal management has been quantified for the Pongolo flood plain (Heed & Breen

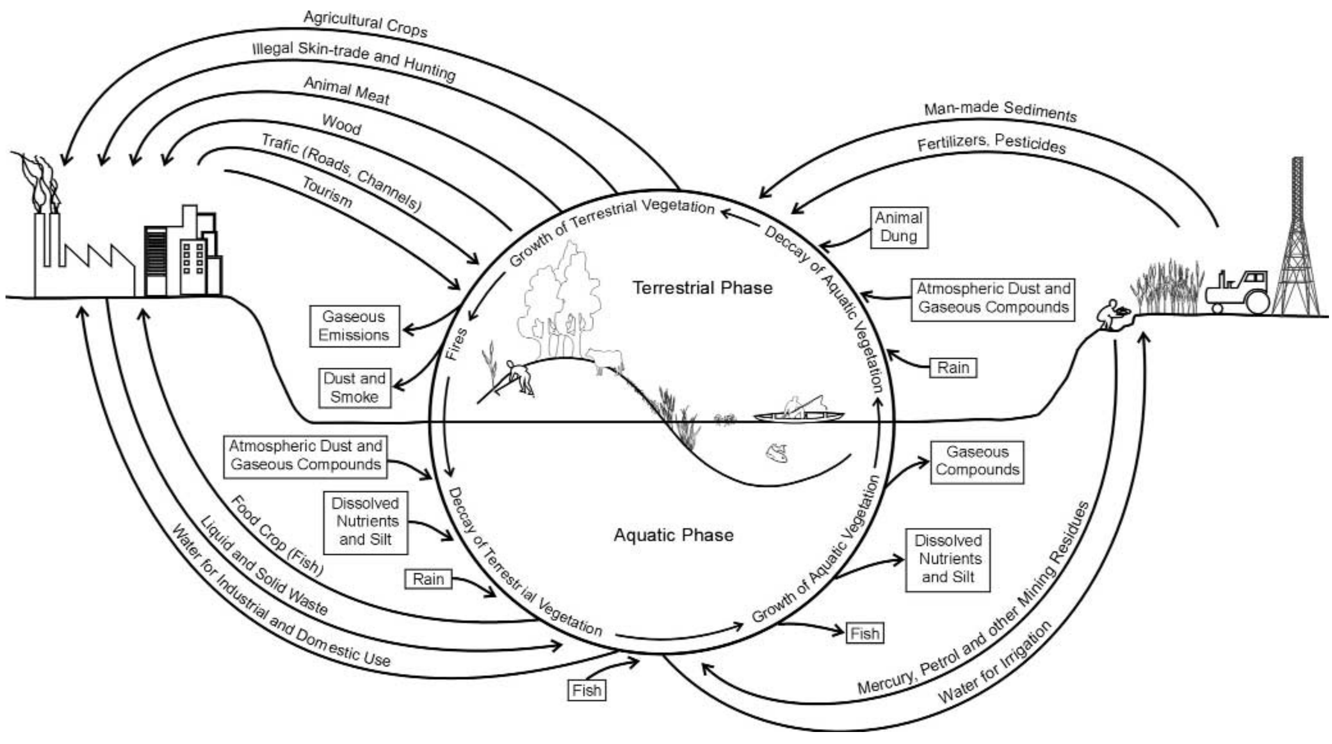

Figure 1 Diagram highlighting nutrient cycles and major human impacts on tropical wetlands.

1982). The Pantanal of Mato Grosso is one of the very few examples of the sustainable management of a tropical ecosystem over a period of centuries by European colonists.

Integrated studies exist on several tropical rivers and connected wetlands, as for instance, Nile River (Rzóska 1976), Kafue Flats (Ellenbroek 1987), Amazon River (Sioli 1984; Junk 1997; Junk *et al.* 2000), Pantanal of Poconé (Heckman 1998), Upper Paraná River (Vazzoler *et al.* 1997) and specific wetland organisms, for instance aquatic vegetation (Denny 1985; Gopal 1990) and fish and fisheries (Lowe-McConnell 1975, 1987; Welcomme 1979).

IDENTIFIED LONG-TERM DEMOGRAPHIC, POLITICAL, ECONOMIC AND ECOLOGICAL TRENDS

Long-term trends in wetland development vary from region to region according to the human demographic structure, economic development, and political system or leadership of the respective countries. In this general framework, there are many human activities that affect wetlands, such as fisheries, agriculture and animal ranching, modification of the hydrological regime, modification of the native flora and fauna, deterioration of water quality, climate changes, recreation and tourism.

Demographic development

All tropical countries suffer from high rates of population growth that increase human pressure on available resources of land and water. There are, however, considerable differences with respect to the current status and long-term trends including population density, demographic development, population distribution, purchase power and industrialization status, between tropical countries and regions within countries. Brazil has actually a mean population density of 20 people km^{-2}, a fairly high level of industrialization and an intermediate population growth that is steadily declining. About 20 million people live in the Brazilian Amazon basin (*c.* 5 million km^2 in area) but about 80% are in urban areas. In and around the large wetlands, population density varies between 0.5 and 5 people km^{-2}. Most Asian and some African countries have high population densities and growth rates, show little decline in population growth and depend strongly on agriculture in and around the wetlands (Tables 1 and 2). But here as well, regional differences are large; India has a mean annual population growth rate of about 1.69%, but the population growth rate of the Indian state of Kerala is only about half of that.

Economic and political development

Economic and political development are closely linked. In the long run, democracy and political stability are the basis for stable economic development. Most African and some Asian countries, suffer from non-democratic leadership and political instability. In many African and Asian countries conflicts with ethnic minorities create serious problems for national integrity and economic development or may do so in the future. In 2001, 13 out of 53 African countries (excluding the Middle East) were involved in armed conflicts, and 16 conflicts were reported from Asian countries. A heavy economic crisis and drug war affect some countries in Latin America (AKUF 2002). Predictions about future political development can hardly be made. Corruption and inefficient administration and management seriously hinder development in all types of government and are widely distributed in tropical countries.

The impacts of political and economic development on the environment in general, and on wetlands in particular, can differ. Politicians tend to argue that underdevelopment leads to poverty, which forces environmental destruction by inadequate and unproductive land use. For example, most Indian wetlands are threatened by land reclamation of low-income people who desperately need land for subsistence agriculture. Strong economic development leads to industrialization, efficient use of resources, welfare, decreasing population growth, and reduced pressure on the environment. Industrialized countries are used as examples of effective efforts in environmental protection and restoration. The USA has invested US$ 2 billion in efforts to restore the Everglades and the upper Missouri River flood plain. Within the IRMA (INTERREG Rhine-Meuse-Activities) programme, the European Union allocated 140 million Euro for the period up to 2001 to improve flood prevention along the rivers Rhine and Meuse. The governments bordering these rivers have increased the sum to about 420 million Euro including projects for protection and restoration of floodplain areas to reduce extreme flood peaks by up to 70 cm by 2020 (see URL http://www.ikse.org). Australia is making strenuous efforts in wetland protection.

However, an economic boom can also have negative impacts on the environment, because there is money available for large-scale development projects leading to wetland destruction and environmental side effects, which are often insufficiently analysed. Large and costly restoration projects in the USA, Europe and Australia are necessary because of heavy wetland destruction during economic boom periods of the 20th century. Population density in the Brazilian Amazon region is low, but the Brazilian economy is steadily growing and political stability is high. This allows the planning and implementation of large development projects, often based on inadequate environmental impact analyses, with heavy negative impacts on the environment (Laurance *et al.* 2001). The wetlands in the Congo River basin are safe from large development projects because population density and economic development are very low and political instability limits investment by national and foreign companies in large-scale development projects. However, in contrast to politically unstable non-democratic regimes, in democratic regimes, for instance Brazil, the constitution allows resistance from scientists, non-governmental organizations (NGOs), and the local

Table 1 Population development of some countries from tropical Asia, Africa, South America and Australia. Source: United Nations (2000). DRC = Democratic Republic of the Congo, URT = United Republic of Tanzania.

Country	*Population growth rate 1950–1955 (% yr⁻¹)*	*Population 1950 (million)*	*Population growth rate 1995–2000 (% yr⁻¹)*	*Population 2000 (million)*	*Predicted population growth rate 2020–2025 (% yr⁻¹)*	*Predicted population 2025 (million)*	*Predicted population growth rate 2045–2050 (% yr⁻¹)*	*Predicted population 2050 (million)*
Australia	2.26	8.22	1.15	19.14	0.67	23.52	0.41	26.50
Central America								
El Salvador	2.75	1.95	2.04	6.28	1.10	8.97	0.54	10.85
Guatemala	2.95	2.97	2.64	11.38	1.73	19.62	0.96	26.55
Mexico	2.94	27.74	1.63	98.87	0.82	130.19	0.24	146.65
South America								
Argentina	1.97	17.15	1.26	37.03	0.78	47.16	0.44	54.52
Bolivia	2.05	2.71	2.33	8.33	1.48	13.13	0.82	16.97
Brazil	3.06	53.97	1.33	170.41	0.78	218.98	0.32	247.24
Colombia	2.90	12.57	1.77	42.10	1.10	59.16	0.52	70.86
Paraguay	2.17	1.49	2.59	5.50	1.75	9.35	0.94	12.56
Venezuela	4.03	5.09	2.02	24.17	1.10	34.77	0.56	42.15
Asia								
Bangladesh	1.97	41.78	2.12	137.44	1.29	210.82	0.70	265.43
Cambodia	2.15	4.35	2.80	13.10	1.66	22.31	1.04	29.88
India	2.00	357.56	1.69	1008.94	0.92	1.351.80	0.41	1.572.05
Indonesia	1.67	79.54	1.41	212.09	0.82	272.91	0.35	311.33
Malaysia	2.72	6.11	2.09	22.22	1.13	31.33	0.54	37.85
Thailand	2.96	19.63	1.34	62.81	0.63	77.48	0.01	82.49
Africa								
Botswana	2.13	0.39	1.61	1.54	0.66	1.83	0.57	2.11
DRC	2.21	12.18	2.56	50.95	3.05	114.88	1.60	203.53
Kenya	2.67	6.26	2.32	30.67	1.01	44.90	0.74	55.37
Mali	2.11	3.52	2.68	11.35	2.81	23.46	1.76	41.72
Nigeria	2.24	29.79	2.74	113.86	1.93	202.96	1.09	278.79
Sudan	2.01	9.19	2.13	31.09	1.44	49.56	0.82	63.53
URT	2.45	7.89	2.58	35.12	1.92	60.39	1.04	82.74
Zambia	2.41	2.44	2.46	10.42	2.45	19.03	1.13	29.26

population to development projects. This democratic process may lead, in the long run, to the elaboration and implementation of roles that, in future, efficiently protect parts of Amazonian wetlands and the Pantanal, a social process that has not yet started in non-democratic regimes.

Demand for water

Global water requirements have increased almost 10-fold during the 20th century (Biswas 1998). Half of the estimated 40 700 km^3 of annual run-off runs rapidly off the land in floods, and *c.* 20% is geographically too remote for human use. This leaves *c.* 31% accessible to controlled human use. About 54% of the accessible freshwater run-off globally is already appropriated for human use (Postel *et al.* 1996). Part of the annual run-off is stored for irrigation, hydropower generation, flood control and water supply in over 45 000 large reservoirs (dam height of >15 m and/or reservoir volume >3 million m^3). Large dam construction required the displacement of 40 to 80 million people, with dramatic negative social side effects. A considerable portion of large dams are falling short of physical and economic targets, negatively affecting rivers, watersheds and wetlands. After a peak in the 1970s, large dam construction decreased, but is continuing at a lower rate (World Commission on Dams 2000).

In the industrially developed countries of Europe and North America, the specific per caput urban water withdrawal rate is 500–800 l d^{-1}, in developing agricultural countries of Asia, Africa and Latin America, public water withdrawal is 50–100 l d^{-1} and, in individual regions with insufficient water resources, withdrawal is ≤ 10–40 l d^{-1} (Shiklomanov 1999).

More than 1×10^9 people currently lack access to clean drinking water (Jackson *et al.* 2001), but conservatively this

Table 2 Area, population density, purchasing power parity and composition by sector of some countries from tropical Asia, Africa, South America and Australia. Sources: CIA (2000); United Nations (2000). DRC = Democratic Republic of the Congo, URT = United Republic of Tanzania.

Country	*Land area (km^2)*	*Population 2000 (million)*	*Population density 2000 (km^{-2})*	*Purchasing power parity per caput ($ yr^{-1})*	*Composition by sector*			*Predicted population density 2025 (km^{-2})*	*Predicted population density 2050 (km^{-2})*	*Population increase 2000–2050 (% yr^{-1})*
					Agriculture (%)	*Industry (%)*	*Services (%)*			
Australia	7 617 930	19.14	2.5	22 200	3.0	26.0	71.0	3.1	3.5	38.5
Central America										
El Salvador	20 720	6.28	303.0	3100	12.0	22.0	66.0	433.0	524.0	72.9
Guatemala	108 430	11.38	105.0	3900	23.0	20.0	57.0	181.0	245.0	133.2
Mexico	1 923 040	98.87	51.0	8500	5.0	29.0	66.0	68.0	76.0	48.3
South America										
Argentina	2 736 690	37.03	13.5	10 000	7.0	29.0	64.0	17.1	19.9	47.2
Bolivia	1 084 390	8.33	7.7	3000	16.6	35.5	47.9	12.1	15.6	103.7
Brazil	8 456 510	170.41	20.1	6150	14.0	36.0	50.0	25.9	29.2	45.1
Colombia	1 038 700	42.10	40.5	6200	19.0	26.0	55.0	59.9	67.9	68.3
Paraguay	397 300	5.50	13.8	3650	28.0	21.0	51.0	23.5	26.7	128.6
Venezuela	882 050	24.17	27.4	8000	4.0	63.0	33.0	39.4	47.8	74.4
Asia										
Bangladesh	133 910	137.44	1026.0	1470	30.0	17.0	53.0	1574.0	1982.0	93.1
Cambodia	176 520	13.10	74.2	710	43.0	20.0	37.0	126.0	169.0	128.0
India	2 973 190	1008.94	339.0	1800	25.0	30.0	45.0	455.0	529.0	55.8
Indonesia	1 826 440	212.09	116.0	2800	21.0	35.0	44.0	149.0	170.0	46.8
Malaysia	328 550	22.22	67.6	10 700	12.0	46.0	42.0	95.3	115.0	70.4
Thailand	511 770	62.81	123.0	6400	12.0	39.0	49.0	151.0	161.0	131.3
Africa										
Botswana	585 370	1.54	2.6	3900	4.0	46.0	50.0	3.1	3.6	36.9
DRC	2 267 600	50.95	22.5	710	58.0	17.0	25.0	50.7	89.7	299.5
Kenya	569 250	30.67	53.9	1600	26.0	18.0	56.0	78.9	97.2	80.5
Mali	1 220 000	11.35	9.3	820	46.0	21.0	33.0	19.2	34.2	267.6
Nigeria	910 768	113.86	125.0	970	33.0	42.0	25.0	223.0	306.0	144.8
Sudan	2 376 000	31.09	13.1	940	41.0	17.0	42.0	20.9	26.7	104.3
URT	886 037	35.12	39.6	550	49.0	17.0	34.0	68.16	93.4	135.6
Zambia	740 724	10.42	14.1	880	20.6	30.6	48.8	25.7	39.5	180.8

number of people could rise by 50%–70% by the year 2025 (Postel *et al.* 1996; IUCN [World Conservation Union] 2000*a*). At the same time, accessible run-off is unlikely to increase more than 5–10% by reservoir construction (Postel *et al.* 1996; Postel 2000). This threat will severely affect many tropical countries because they suffer from high population increase, low economic performance, low political stability, and/or inefficient administration. This leads to fierce competition for water, inadequate exploitation, low water-use efficiency and environmental degradation. In semi-arid regions, storage and deviation of water from wetland tributaries are already major threats to wetland integrity, even in protected areas. Expansion of irrigation will cause further soil and water salinization (IUCN 2000*a*). Water has also been a cause of political tension between different countries, as for instance Syria and Israel, Syria and Iraq, India and Bangladesh, USA and Mexico, and all ten riparian states of the Nile River (Wolf 1998).

Water is considered a free resource that can be deviated for irrigation and domestic and industrial use. In fact, water is a public good on which rivers, flood plains and their biodiversity depend on (Kingsford 2000; Naiman *et al.* 1995), but little attention is given to this view. Wetlands and rivers providing water to wetlands will increasingly be used as reservoirs for water supply. The anticipated benefits of agricultural irrigation projects often do not compensate for environmental degradation, artificial water-shortage and increased poverty rates of local communities managing the wetlands by traditional methods, as shown for Mexican wetlands (Contreras-Balderas & Lozano-Vilano 1994).

Demand for hydroelectric energy

Increase in energy prices because of the declining worldwide stock of oil is bound to stimulate the exploitation of hydroelectric energy resources. In the long run, large dams will affect flood plains along with most large tropical rivers. In Asia, in 2000 more than 83 000 MW of additional hydroelectric generating capacity was under construction, particularly in China, India, Indonesia and Iran. In South America, Brazil generates over 93% of its electricity from hydropower, Paraguay *c.* 100%, Peru 74%, Venezuela 73%, Ecuador 68%, Colombia 68% and Chile 57%. In 2000, about 18 000 MW of generating capacity was under construction worldwide, with 2124 MW of that being in Central America. In Africa, most large dams are built for irrigation and water supply, but nevertheless hydropower contributes more than 80% of electricity production in 18 countries and over 50% in 25 countries. As of 2000, 2000 MW of generating capacity was under construction in Africa. In Australasia, *c.* 50% of the large dams were built for water supply. Hydropower contributes to more than 50% of the electricity supply in Fiji, New Zealand, Papua New Guinea and New Caledonia. At present, no new major dams are planned in Australia or New Zealand (World Commission on Dams 2000).

Dams interrupt hydrologic connectivity and affect down-river flood plains and estuaries in multiple ways, for instance by changing the flood pulse, modifying sediment transport, changing nutrient cycles and interrupting animal migration routes (Pringle 2001). Negative side effects of reservoirs can be reduced by the elaboration of plans to re-establish to some extent the natural flood regimes, which however negatively affect their capacity for hydroenergy generation.

Eutrophication and pollution

Wastewater treatment systems in most tropical countries (except Australia) are in a precarious state, despite the water shortage and the danger for public health. Globally, almost 3×10^9 people lack basic sanitation services (Jackson *et al.* 2001). In developing countries, about 90% of wastewater is discharged directly into rivers and streams without treatment (Johnson *et al.* 2001). Streams, rivers, lakes and wetlands near most tropical cities and in densely-populated areas are polluted and will continue to be so due to the rapid population increase counteracting the efforts to improve the wastewater treatment systems and reduce eutrophication and pollution by agrochemicals.

The need to increase the area for agriculture and to intensify production systems will increase the use of fertilizers and pesticides, which will in part be released to the aquifer, despite improved production methods. Semi-arid regions are suffering more than humid regions, where large amounts of water dilute pollutants, for instance along the Amazon, Zaire and Mekong Rivers.

Agriculture and animal ranching

Many tropical countries still depend heavily on agriculture, often on a subsistence basis (Table 2), and the greatest potential for expansion of food-producing land may be through the cultivation of wetland soils (International Rice Research Institute 1985). But this does not consider the multiple functions of wetlands in the landscape and for humans. The term 'sustainable development' is often used for short-term agricultural and economic programmes, but not for long-term ecological planning and is evidently connected more with individual benefits than the long-term welfare of the entire population (Hardin 1968).

Agriculture and animal ranching also affect wetlands indirectly by large-scale changes in vegetation cover of the catchments and related changes in hydrology and sediment input. Heavy deforestation and subsequent habitat modification are the main reasons for fish species decline in Madagascar. Export-oriented agro-industries are, or will become, major threats to South American wetlands, as shown for the savannah belt in Brazil (*cerrado*), the tropical deciduous forest and woodlands in Argentina (*chaco*), and the Amazon River flood plain. Smaller wetlands are being filled in to level the landscape for the highly mechanized agriculture. The destruction of streamside wetlands and sediment import via streams diminish habitat diversity and destroy ecological corridors in the landscape. The streams in connected wetlands deposit increasing sediment load, which results in severe environmental damage.

Global climate change

The mean increase in global surface air temperature predicted by the end of the 21st century may be 1.4–5.8°C, the larger temperature increase being in higher latitudes than in the tropics (IPCC [Intergovernmental Panel on Climate Change] 2001). The impact of a rise in temperature by the greenhouse effect on tropical vegetation has been little studied. For the Amazon lowland rainforest, some authors suggest the spread of *Podocarpus* species during the cooler glacial, and their disappearance during warm interglacial periods (Colinvaux *et al.* 2000). Similar changes may have happened for many aquatic and wetland communities.

As already discussed, palaeoclimatic studies show that tropical wetlands are very sensitive to changes in hydrology. A rise in temperature will increase evaporation rates and reduce water availability for the wetlands, mainly in semi-arid regions. Increased fire stress during low-water periods will heavily affect community structure and species diversity.

Climate models are not yet accurate enough to predict precipitation changes at a regional scale. By the second half of the 21st century, at low latitudes, both regional increases and decreases are expected over land areas, with larger year-to-year variations in precipitation and associated heavy droughts and floods. Since the mid-1970s, the amplitude and frequency of pluriannual extreme climatic events like El-Niño Southern Oscillation episodes has tended to increase (IPCC 2001). Their consequences will overlap with the diversified human-induced modifications of local wetland hydrology and strongly affect many tropical wetlands. A cycle of landscape degradation, desertification and rural displacement was set in motion in the Senegal River valley by the Sahel-wide drought that began in the 1970s, the consequences exacerbated by rural development policy that favoured large-scale, state-imposed irrigated rice production (Venema *et al.* 1997). However, up to the year 2025, impending changes in human population and economic development will affect wetlands to a much larger degree than will changes in climate (Vörösmarty *et al.* 2000).

Global mean sea level is projected to rise 0.09–0.88 m from the 1990 level by 2100 (IPCC 2001) and will considerably affect mangroves and coastal freshwater wetlands. By the 2080s, up to 22% of the world's coastal wetlands could be lost. When combined with other losses due to direct human action, this number could rise to 70% (Nicholls *et al.* 1999). For instance, some of the high-value coastal freshwater wetlands of Australia that are strictly protected by the Australian government could be replaced by saline wetlands (van Dam *et al.* 1999).

Fisheries

In most tropical countries, inland fisheries contribute substantially to the protein supply of the local population. Between 1961 and 1996, worldwide freshwater fish catches increased from 9 to 45 million tonnes, showing the greatest increase in developing countries. The recent local decrease in catches indicates that freshwater fish resources are exploited at, or above, sustainable levels (Abramovitz 1996).

Since yields are related to an intact environment, fishers should be interested in maintaining the ecological integrity of wetlands and could be important allies for the long-term maintenance of wetland habitats, forming a numerically large pressure group against other stakeholders. However, in most tropical countries, fishers have a low social and economic status.

There are negative impacts of fisheries on wetlands, by overexploitation of the stocks, hunting of endangered species (manatees, turtles, river otters, caimans), introduction of exotic species (for example, Nile perch *Lates niloticus* in Lake Victoria) and small-scale habitat destruction by fishing activities.

Unexplored resources still exist in some South American wetlands. The inland fishery potential of Amazonia is estimated at 900 000 t yr^{-1} (Bayley & Petrere 1989), of which one-third to one-half is actually used. About 45 000 people are directly or indirectly involved in the fishery sector in the State of Amazonas, Brazil, yet the political influence of the fishery sector on long-term development strategies for the Amazon River flood plain is small (Soares & Junk 2000).

Recreation and ecotourism

The importance of wetlands for the recreation of the local population is often underestimated, because people in the tropics often use wetlands differently from Europeans and North Americans. An intact wetland environment is part of their welfare and the basis for the maintenance of their lifestyle and culture.

In economic terms, ecotourism is increasing in importance and may ultimately play an important role in the maintenance of tropical wetlands. There is a considerable discussion about the negative effects of ecotourism on wildlife, the environment and local people. The Keoladeo National Park near Bharatpur, India, is an example of the multiple problems arising from the management of a wetland with a very rich wildlife in a densely populated area. Improved management and the inclusion of the local population in the decision-making process and sharing of benefits can resolve these problems (Pimbert & Gujja 1997). Prospering ecotourism may provide an economic alternative to other more threatening development schemes. Famous wetlands like the Okavango Delta in Botswana and the Pantanal of Mato Grosso in Brazil are beginning to use their potential for ecotourism, because the traditional use no longer provides an economic basis for the protection of the wetlands.

Invasion by exotic species

Invasion by exotic species is a serious threat for many wetlands. Neophytes disperse along river courses, because the frequent habitat disturbances by water-level fluctuations provide good living conditions for ruderal plants, as shown for the upper Amazon River flood plain (Seidenschwarz 1986). The introduction of the Nile perch led to severe reduction and partial extinction of the endemic cichlids in Lake Victoria and associated wetlands (Kaufman 1992; Schofield & Chapman 1999). The introduction of 27 exotic fish species threatens the fish fauna of Madagascar (Stiassny 1996). In 1993, the mussel *Limnoperna fortunei* was introduced, probably with ballast water by ships from Asia, to the Rio de la Plata. In 1995, it reached Santo Tome on the middle Paraná River (Darrigran & Ezcurra de Drago 2000) and was recorded in 2001 in the Pantanal of Mato Grosso, in the centre of South America (C.T. Callil, Federal University of Mato Grosso, personal communication 2002). Mussels may develop in large quantities on hard substrates and create serious problems in hydroelectric power plants and water treatment plants by clogging water pipes, but their environmental impact has yet to be studied. In northern Australian wetlands, the invasion of exotic plants and animals is well documented (see section on Australia). Despite increasing concerns about introductions of exotic species, the dispersal of species around the world will continue because of growing intercontinental trade and tourism.

Development in research

Basic and applied research provide the scientific basis for sustainable management and protection of wetlands. Some tropical countries such as Australia, India and Brazil have high-level research institutions, however most tropical countries do not have the necessary scientific infrastructure, staff and funding, and teaching is seriously deficient. Africa spends only 0.3% of gross national product on research, in comparison to a world average of 2.6% (Salam 1991) and the number of scientists and engineers per million people is only 297 in comparison to 2200 for the developed world. Tropical limnology is heavily under-represented in comparison to that of temperate regions (Gopal & Wetzel 1995; Wetzel & Gopal 1999, 2001). This points to the need to intensify bilateral and multilateral cooperation between rich temperate and poor tropical countries in research projects and the training of local scientists. Globalization will favour scientific cooperation and the large scientific associations will become increasingly involved in initiating cooperation.

Environmental protection

Many tropical countries have protected large wetland areas, however increasing multiple pressures affect the protected wetlands at the species, community and ecosystem levels. For instance, despite a government ban on hunting wildlife, crocodile populations in Liberia are severely depleted, and severe environmental destruction also diminishes these populations. Mangrove ecosystems near human population centres are being destroyed. Although 40% of Liberia is forested, all rainforest will be gone by the year 2024 if current trends continue (Kofron 2002). Detailed cost-benefit analyses are required, attributing realistic economic values not only to direct benefits deriving from wetlands, but also to non-use attributes such as maintenance of wildlife, biodiversity, water quality (protection against salinization, eutrophication and pesticides) and water storage (Whitehead & Blomquist 1991; Stevens *et al.* 1995).

International conventions support national efforts in wetland protection. The Convention on Wetlands of 1971, commonly known as the Ramsar Convention, is an international treaty dedicated to the conservation and wise use of wetlands by national actions and international cooperation (see URL http://www.ramsar.org). The Ramsar Convention has become supported by other conventions such as the Convention on International Trade in Endangered Species (CITES) (URL http://www.cites.org), the Convention on Migratory Species (CMS) (URL http://www.wcmc.org.uk/cms), and the Convention on Biological Diversity (CBD) (URL http://www.biodiv.org).

Funding for the management and protection of protected areas is often unavailable and requires outside financial support. The international community is increasingly involved through organizations such as the United Nations Educational, Scientific and Cultural Organization (UNESCO) (URL http://www.unesco.org), World Wide Fund for Nature (WWF) (URL http://www.wwf.org), IUCN (URL http://www.iucn.org), The Nature Conservancy (TNC) (URL http://www.tnc.org), Conservation International (CI) (URL http://www.conservation.org), Wetlands International (URL http://www.wetlands.org), and many others playing roles in tropical environmental protection. In some countries, like Australia, Brazil and India, national NGOs already take a leading role in local activities. Restrictions on cooperation are set in some tropical countries by political leadership and instability.

In recent years, the discussion about the maintenance of biodiversity has strongly influenced the discussion about the protection of wetlands. Moss (2000) recommended concentrating on the protection of ecosystem functions, because they are the basis for biodiversity. Dudgeon (2003) recommended linking protection measures with the protection of 'flagship species' that focus conservation action and media attention, because ecosystem functions can hardly be observed by the public. A combination of both approaches seems to be best suited for conservation purposes in the complex field of environmental protection, public opinion, cultural background, economic interests of different stakeholders and governmental politics. The formulation of a coordinated policy for biodiversity protection is missing in most tropical countries (Pullin *et al.* 1999).

Protection of minorities and traditional management

Local populations have managed many tropical wetlands sustainably for centuries or even millennia. Theoretically, this long tradition should be an advantage for wetland protection in the tropics. Furthermore, cultural integrity is a fundamental human right. However, a rapidly growing population and globally-changing economic requirements have led to changes in political and economic strategies, new land-use systems, new development priorities, and the decline of traditional practices.

Changes are part of development and inevitable even in traditionally managed systems when the growth of human population surpasses the capacity of the wetland to sustain it. The situation is exemplified by Dal Lake and associated wetlands in Kashmir, India, which during the last decades, have been reduced in area from 25 km^2 to 11.65 km^2 by land reclamation. Expensive and politically difficult measures are being taken by the local authorities to control the number of people living on houseboats on the lake, to stop land reclamation and to diminish sediment import by the tributaries. However, in addition, a complete management plan for the catchment area, including the establishment of an efficient sewage treatment system, would be necessary to stop long-term degradation of the lake and wetland system (Anon. 1999).

Modern societies should be able to avoid abrupt changes, particularly when the impacts of the changes have not been sufficiently analysed. In many tropical countries, changes are taking place at a far faster rate than the development of sound databases and the planning capacity of the respective governments. The result is that traditional management methods are replaced by modern unsustainable management methods at the costs of the local human population and the integrity of the respective ecosystems (Gopal 1991). The fisheries in the wetlands of North East Nigeria (Neiland *et al.* 2000) and the Sahel region (FAO [Food and Agricultural Organization of the United Nations] 1991) demonstrate the conflicts between traditional and modern management. Plant and animal communities of many wetlands in India would completely change if management by the local population were prohibited. After the total ban on traditional grazing and the removal of biomass from Keoladeo National Park in Bharatpur, serious conflicts with the local population started and negative effects on the vegetation cover and populations of some important bird species were observed (Shukla & Dubey 1996; Middleton 1998; Chauhan & Gopal 2001).

POTENTIAL FUTURE STATES OF TROPICAL WETLANDS IN 2025

Central and South America

South America is characterized by large river systems (Fig. 2). Wetlands are subjected to relatively regular seasonal water-level fluctuations. In most areas, the water availability is sufficient for economic development and the maintenance of wetlands. Only 2–4% of the water resources are used (Shiklomanov 1999); 979 large dams have been constructed, mostly for hydropower generation and water supply (World Commission on Dams 2000). There are no data on wetland losses, but most wetlands, streams and rivers are strongly modified, eutrophicated and otherwise polluted in densely colonized areas, and there is little hope that the situation will improve in the near future. The wetland inventory is incomplete and even misleading (Naranjo 1995).

All South American countries are in the privileged position of having large, fairly pristine wetlands in remote areas (Junk 1993). Human pressure is increasing but most of these wetlands are still of little importance in the respective national economies and population densities are low except in the Magdalena and Cauca River basins. This provides the unique opportunity to choose between different options for sustainable development in the Amazon River basin (Junk *et al.* 2000). However, many governments care little about long-term development planning. Wetland classification in South America is at a preliminary stage. There is growing concern in some local populations for maintaining traditional lifestyles and environmental protection. Basic wetland research is advancing in several countries, including Brazil, Columbia, Argentina and Venezuela. Development in Brazil is of specific importance because of its political and economic leadership in South America.

Central American wetlands are of smaller size and therefore more vulnerable, and suffer increasing pressure from agriculture, industrial and urban development, pollution and overexploitation of natural resources. Relatively high popu-

Figure 2 Major wetlands of tropical and subtropical South America (according to Junk 1993).

lation densities and growth rates in some Central American countries will increase pressure on the wetlands, because the mountainous regions set limits to land reclamation for agriculture. El Salvador and Guatemala already have high population densities (Tables 1 and 2). The low freshwater resources of Mexico will increase pressure on the small wetland areas of the country (Olmsted 1993).

Orinoco River basin

The flood plain of the Orinoco River and the flooded savannahs of the Venezuelan llanos are little disturbed by low-density cattle ranching and fishing. Low human population density and low population growth have led to some impact on species abundances by poaching, but not on the ecosystem as a whole. There are no planned major development projects, but considering the general trend to large-scale agro-industries in the Brazilian cerrado belt and in the Argentinian chaco, these activities may start in the future.

Magdalena and Cauca River basins

The development of Colombia originated in the valleys of the Magdalena and Cauca Rivers (Fig. 2), and *c.* 70% of the human population is concentrated in the area. Domestic and industrial wastes and residues from mining activities pollute the rivers. Deforestation in the catchment area led to heavy erosion and increased sediment load. The sediments are in part deposited in the flood plain and modify the hydrology in floodplain lakes by closing former connection channels. Agriculture, cattle ranching and fisheries use the flood plain. There are about 30 000 fishers in the catchment. Fish production has decreased from 70 000 $t\,yr^{-1}$ in the 1970s to 10 000 $t\,yr^{-1}$ in 2000 (Roldan & Ruiz 2001). Dyke construction for land reclamation for agriculture and cattle ranching reduces the area of the aquatic-terrestrial transition zone. The government has established a programme for the protection and rational use of freshwater wetlands (Ministerio del Medio Ambiente 2001).

Amazon River basin

Most of the large wetlands of the Amazon River basin are still in a fairly pristine state, including the periodically flooded savannahs of Roraima and Rupununi, the Bananal at the Araguaia River and the Llanos dos Mojos in Bolivia (Fig. 2; Junk 1993). The fringing flood plains along the Amazon River and its large tributaries are currently affected by the large-scale destruction of the floodplain forest for timber extraction and pasture establishment for cattle and water buffalo ranching (Junk *et al.* 2000). Some of the tributaries, like the Tapajos and Madeira Rivers (Fig. 2), suffer from mercury pollution because of gold mining in the headwaters. Some black water rivers, like the Negro River, have very high natural mercury levels because of mercury-rich soils in the catchment area. In recent years, gold mining activities have decreased in many areas, but a total of about 5000 t of mercury has been released into the environment (Nogueira & Junk 2000).

Ongoing deforestation and large-scale agro-industrial projects will seriously affect stream-side wetlands and minor interfluvial wetlands. The Brazilian government's *Avança Brazil* project plans to invest a total of about US$ 40 billion over the years 2000–2007 in the Amazon basin. Scientists have criticized the government for not considering, or seriously underestimating, the negative side effects on the environment, including degradation of 25–42% of the Amazon rainforest by the year 2020 (Laurance *et al.* 2001).

Major impacts on wetlands will arise from the construction of reservoirs for hydroelectric power generation. There may be 63 possible sites for hydroelectric power plants on all major tributaries of the Amazon River (Junk & Nunes de Mello 1987). If all reservoirs in Amazonia were to be built, a total area of about 100 000 km^2 would be flooded. The Tocantins/Araguaia River (Fig. 2) would be transformed into a sequence of 27 reservoirs (Junk & Nunes de Mello 1987). Nobody should blame countries like Brazil for wanting to make use of its enormous hydroelectric energy potential. However, not all sites listed by engineers are ecologically or economically suitable; the Balbina Dam on the Uatumã River near Manaus has inundated 2300 km^2 of rainforest, produces very little energy ($<0.1\,MW\,km^{-2}$) and has many negative side effects (Fearnside 1989).

Currently, about 7.9% of the Amazon basin area is under full protection. Many protected areas include large wetland areas, for instance the National Park of Bananal Island on the Araguaia River, the Ecological Station of the Anavilhanas at the Negro River near Manaus, the Sustainable Development Reserve of Mamirauá in the Amazon River flood plain and the Jaú National Park on the Jaú River in Brazil. Wetland-including protected areas are also the Manu Biosphere Reserve and the National Park Pacaya-Samiria in Peru, the National Parks La Paya and Amacayacu in Colombia, and the Beni River Biosphere Reserve and the National Reserves of Noel Kempff Mercado and Rios Blanco y Negro in Bolivia. However, many protected areas suffer from insufficient funding for adequate management and protection (Centre for Applied Biodiversity Science/Conservation International 2000).

Paraná–Paraguay River basin

The upper Parana River in Brazil (Fig. 2) has been drastically modified by the construction of several reservoirs for flood control and hydroelectric power generation. There are only minor parts of the former flood plain left in nearly natural condition (Vazzoler *et al.* 1997). The Paraguay River has so far been little altered by humans, its upper course meanders through the Pantanal, a wetland of about 170 000 km^2 of which about 150 000 km^2 belong to Brazil, 15 000 km^2 to Bolivia and 5000 km^2 to Paraguay. The Brazilian government officially cancelled the *Hidrovia* project (Ponce 1995; Hamilton 1999; Gottgens *et al.* 2001), which was intended to rectify and deepen the upper Paraguay River channel inside the Pantanal of Mato Grosso for shipping. However, private companies are continuing to build the infrastructure for the implementation of the hidrovia, which would seriously affect one of the world's largest and most beautiful wetlands.

In recent years, there has been rising economic pressure to increase cattle production, which in turn has led to increasing deforestation of the Pantanal to expand pasture area (Da Silva 2000). Large-scale soybean plantations in the catchment of the Pantanal have led to increased soil erosion and sediment deposition in the Pantanal. The construction of a reservoir for hydroelectric power generation at the Manso River, a major tributary of the Cuiabá River, affects the floodplain area below the dam. Its long-term impact is unknown. The fact that UNESCO declared the Pantanal a Biosphere Reserve in 2000, will give NGOs strong support in defending the protection of the area.

Along the middle course of the Paraguay River (Fig. 2) there is the Paraguaian and Argentinian chaco region that is partly flooded during the rainy season. The lower Parana River is accompanied by an extensive fringing flood plain. The whole area was, until now, little used and had low-density cattle ranching and fishing. There is rising pressure on wetlands by large-scale agro-industrial projects. In 2000, the Argentinian Government withdrew from plans to build a dam for hydroelectric power generation across the middle Paraguay River.

Africa

Water resources are unevenly distributed in Africa. In the dry northern part, 95% of the renewable water resources are withdrawn (Shiklomanov 1999). Over 1269 large dams exist in Africa, most of them built for irrigation and water supply (World Commission on Dams 2000). In moist Central Africa, water withdrawal is negligible. There are 99 large African wetlands, of which 43 are flood plains or have floodplain elements (Howard-Williams & Thompson 1985). Most of the larger wetlands of southern Africa have been described (Denny 1985; Burgis & Symoes 1987; Hughes *et al.* 1992; Whigham *et al.* 1993). However, wetland inventories are deficient in most southern African countries and complete inventories are needed for management purposes (Taylor *et al.* 1995).

Nearly all African rivers are accompanied by large fringing flood plains in their lower courses, and several rivers have large internal deltas. Welcomme (1985) summarized the ecology and inland fisheries. Major wetlands in Africa (from north to south) are the Nile delta, Nile flood plain, Sudd (upper Nile River), Senegal delta, Senegal Middle Valley, Niger internal delta, Niger fringing plains, Niger delta, Volta River, Hadejia-Jama-are flood plain, Benue River flood plain, flood plain of the Chari and Logone River system, Zaire River flood plain, Tana delta, flood plains in the Kamulondo Upemba depression (Lualaba River), Kifakula depression (Lualaba River), Barotse plain, Kafue flats, Bangweulu, Shire River (Elephant and Ndinde marshes in Mali) and Okavango delta (Fig. 3).

The adaptation of local communities to changing hydrological conditions is shown by the multifunctional nature of resource use in African flood plains. Dinka and Nuer tribes combine cattle farming with fishing in the Sudd swamps (Dumont 1992). The Hadejia–Nguru wetlands in Nigeria are used for flood rice farming, fisheries, farming of flood recession crops and grazing animals (Thompson & Polet 2000). However, water competition for irrigation, domestic and industrial uses has led to the construction of reservoirs and to reduced flooding in the down-river areas. Increasing numbers of livestock in some wetlands compete significantly with game animals and modify plant cover.

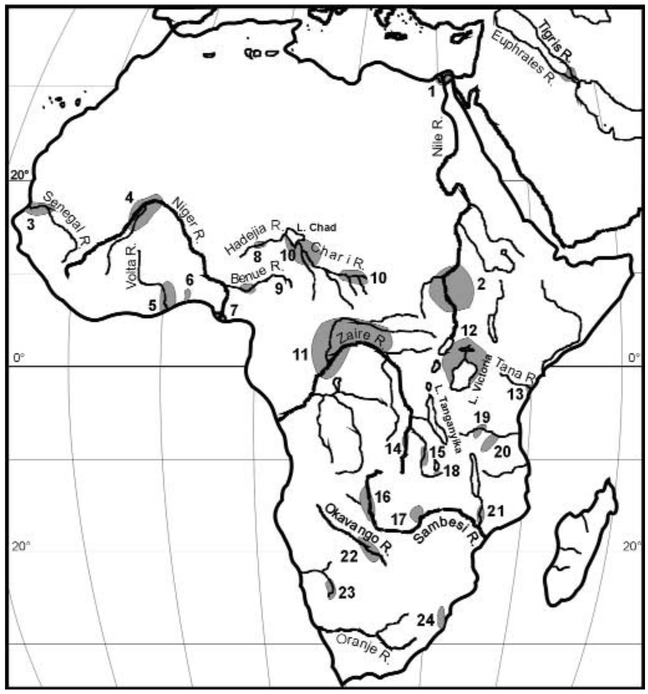

Figure 3 Major wetlands of tropical and subtropical Africa: 1. Nile Delta, 2. Sudd (upper Nile River), 3. Senegal Delta, 4. Niger Internal Delta, 5. Volta River, 6. Oueme, 7. Niger Delta, 8. Hadejia Jama-are flood plain, 9. Benue flood plain, 10. Chari and Logone flood plain, 11. Zaire River flood plain, 12. Lake Victoria wetlands, 13 Tana Delta, 14. Kamulondo Upemba Depression (Lualaba River), 15. Kifakula Depression (Luapula River), 16. Barotse Plain, 17. Kafue Flats, 18. Bangweulu, 19. Ruaha, 20. Rufigi, 21. Shire River (Elephant and Ndinde marshes in Mali), 22. Okavango, 23. Cuene/Ovambo, 24. Phongolo (modified from Welcomme 1985, with permission).

The Nile delta, the fringing flood plains along the Nile River, the Logone flood plain and the flood plain of the Benue River (Cameroon), the Hadejia–Nguru wetlands (northern Nigeria), the Phongolo flood plain (South Africa) and the Senegal delta (Senegal) are examples of serious wetland disturbance by large-scale irrigation schemes (Stanley & Warne 1998; Lemly *et al.* 2000; Thompson & Polet 2000). Even Ramsar sites have been severely affected by water allocation for irrigation purposes far upriver. The change in extent, timing, shape and frequency of the floods are major disturbance factors in the flood plains below the reservoirs. Only for the Phongolo flood plain has an artificial flood regime been established to reduce the negative impacts of the reservoirs, but effects on the system including fishery stocks are not yet fully understood (Merron *et al.* 1993).

A cost-benefit analysis of the dam construction for irrigation schemes in the Hadejia Jama-are River basin in northern Nigeria (Fig. 3) showed that the benefits of increased agricultural production did not compensate for the losses of benefits from the intact floodplain system (Barbier & Thompson 1998). The Okavango River is viewed as a potential water source for the development of the semi-desert nations of Namibia and Botswana. Dredging and excavation of the lower Boro River to increase surface outflow to meet human needs has already led to significant encroachment of terrestrial plant species onto the flood plain in the region of the dredged channel (Ellery & McCarthy 1998). Water deviation would result in major environmental threats to the integrity of the Okavango delta with its unique flora and fauna, which actually helps sustain about 130 000 people of several ethnic groups and earns over US$ 250 million in revenues per year (Rothert 1999).

Wetlands in the Lake Victoria basin suffer from problems similar to the large African river flood plains. Major threats are the use of papyrus swamps for agriculture, pollution, conversion of wetlands into settlement areas, increased sedimentation rates as a result of agricultural activities, and hydrological changes due to road construction and excessive water extraction (Kassenga 1997; Kairu 2001; Chapman *et al.* 2001).

Little information is available about the large forested wetlands of the Zaire River basin (Fig. 3). The unstable political situation of the country and the non-existent scientific community and infrastructure have led to an information gap. It appears the wetlands are still intact, with the exception of threats at the species level by poaching and at community level by logging, and that this situation will continue in the near future.

Population density is lower in most African countries than in Asia, but most African countries have high population growth rates and depend largely on agriculture. Water availability is sufficient only in the moist equatorial belt. Without well-adapted management plans for entire watersheds, the water supply will become a limiting factor for development in semi-arid areas. By 2025, total water abstraction will have risen by 54% to 337 $km^3\ yr^{-1}$, agricultural use accounting for 54% of this (IUCN 2000*a*). Conflicts of interests already arise over water resources management in the Sahelian zone and will also arise or become aggravated in the future in the semi-arid zone in the south of the Zaire River basin. Political tensions may arise between countries that share watersheds of large rivers, like the Nile and Okavango Rivers. Despite the great importance of hydrological data, the number of monitoring stations for water flow and water quality in Africa declined by 90% between 1990 and 2000 (Vörösmarty *et al.* 2001).

Tropical Asia

Tropical Asia is the most populous and most disturbed region on earth (Hannah *et al.* 1994) with the highest annual relative deforestation rate of about 2% (Laurance 1999). The monsoonal climate leads to pronounced dry and wet seasons. In east Asia, the monsoonal climate is characterized by strong and rather unpredictable interannual variations in rainfall (Gopal & Krishnamurthy 1993; Osborne *et al.* 1993). This has led, for centuries, to tank and reservoir building to guarantee water supply. India has already built more than 4000 large dams and is one of the most active countries in the world in dam construction and planning (World Commission on Dams 2000).

Major wetlands exist in India along the River Ganges, Bramaputra, Krishna, Godavari and Indus, in Myanmar along the Irawaddy, in Thailand along the Chao Phrya, and in Kambodscha along the Mekong. Marshy flooded areas and fringing flood plains also occur in Sumatra, Borneo (Mahakam, Barito and Kapuas Rivers) and New Guinea (Fly and Sepik River) (Figs. 4 and 5). Despite their importance, information about total wetland area is insufficient and classification of wetlands is incomplete. For instance, Gopal and Sah (1995) proposed a classification of Indian wetlands based on hydrology, salinity and plant cover, but there are considerable differences in the literature with respect to the area covered by wetlands. Gopal (1997) indicated a total area of about 18 Mha for inland aquatic ecosystems, excluding paddy rice. Garg *et al.* (1998) estimated from satellite images a total wetland area excluding paddy rice, rivers and canals of about 7.6 Mha, out of which 3.6 Mha are inland and 4 Mha are coastal wetlands. But such estimates are subject to a large margin of error, because the large annual and inter-annual water-level fluctuations are insufficiently considered.

Natural wetlands play an important role for subsistence of large segments of the population. The tradition in the sustainable management of wetlands is longest and most diversified in tropical Asia and countries like India have a large number of man-made wetlands that possess impressive biodiversity and have important ecological functions in the landscape. Local communities have managed some man-made wetlands sustainably for centuries, and there is often no sharp transition between man-made and natural wetlands.

The flow regime of the rivers has been altered and additional measures to increase flood control efficiency are being planned. Twelve dams are planned for the Mekong River and will severely affect the connected flood plains, including the high productive fishery in Tonle Sap (Fig. 5), the largest lake in South-east Asia (Dudgeon 2000). The strong decrease or local extinction of large grazing wetland mammals, such as the Indian rhinoceros (*Rhinoceros unicornis*) and swamp deer (*Cervus duvauceli, C. eldi, C schomburgki*), points to large-scale habitat degradation by draining, settlement and conversion of flood plains into cropland, mainly rice. Some of the rivers are heavily polluted. Despite its religious significance, the Ganges River is one of the

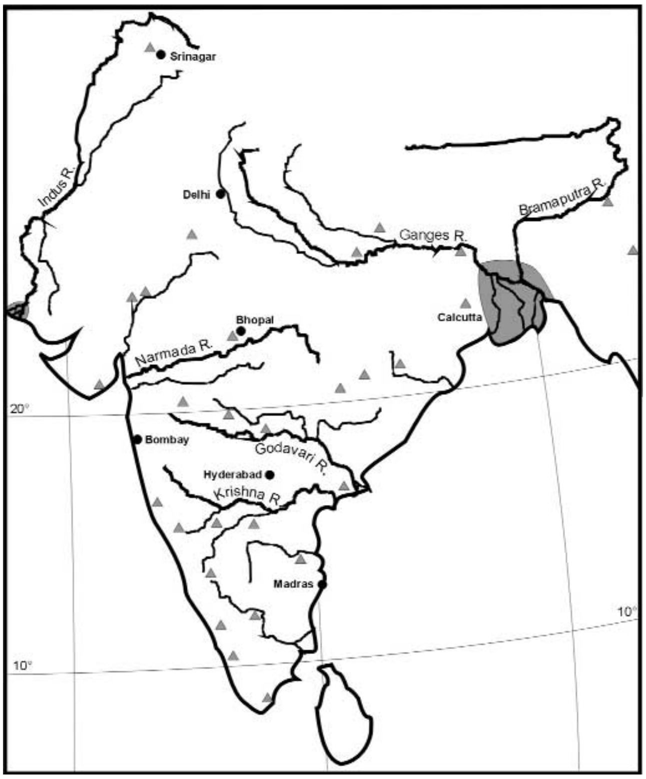

Figure 4 Some important wetlands of the Indian subcontinent (according to Gopal 1982, with permission).

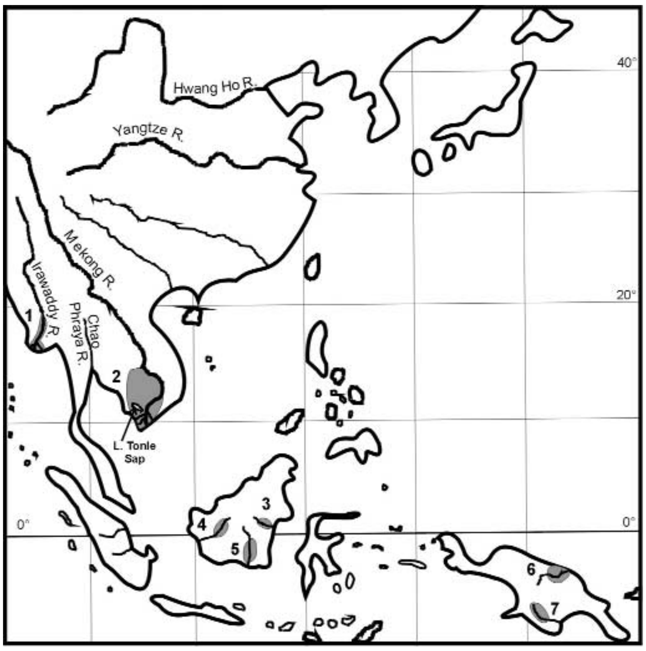

Figure 5 Some important wetlands of South-East Asia:
1. Irawaddy, 2. Tonle Sap and associated wetlands, 3. Mahakam River, 4. Kapuas River, 5. Barito River, 6. Sepik River, 7. Fly River (modified from Welcomme1985, with permission).

world's most polluted large rivers. This also affects the connected wetlands and their plant and animal life (Dudgeon 2003).

In many rivers, fish overharvesting has already occurred, most notably in China and India. Fish and waterfowl diversity in Asian river flood plains is disproportionally large in comparison to their catchment area and the synergistic effects of different threats have endangered a considerable part (Groombridge & Jenkins 1998; Dudgeon 2003). A ranking of countries by total number of threatened bird species is headed by Indonesia, Brazil, the Philippines, China and India (Collar *et al*. 1994).

A serious threat for many animals is market globalization. At least 90 species of freshwater turtles occur in the area, almost three-quarters of them threatened (IUCN 2000*b*). China, Japan, Korea and Chinese ethnic communities around the world represent a huge market for turtle meat and shell for medical purposes (Van Dijk *et al.* 2000). Asian rivers are probably the most endangered ecosystems in the world (Dudgeon 2003).

Human population pressure is very high in Bangladesh, India and some parts of Indonesia. A considerable part of the wetlands in Java, Bali and Sulawesi has already been converted to rice fields or fish culture ponds (Lehmusluoto *et al.* 1999). In 1990, only 40% of the wetland area of south Sulawesi was in its natural state and only 24% of non-lake wetlands were natural; a mere 1–2% of the freshwater swamp forest and 20% of the mangrove estuaries were relatively undisturbed (Giesen *et al.* 1991).

Large areas suffer from water deficiency that is aggravated by the very low level of sewage treatment. High population growth rates severely threaten even traditionally managed wetlands, because the number of people surpasses the carrying capacity. Water allocation for irrigation and domestic and industrial uses will severely affect aquatic resources and wetlands in the future.

Australia

On the largely dry Australian continent, wetland modification started with non-Aboriginal population growth about 160 years ago (Finlayson & von Oertzen 1996; Jacobs & Brock 1993). The large annual and interannual variability of rainfall has required water-storage dams for domestic use, irrigation, urban and industrial development, and recreation; there are 486 large dams in Australia (World Commission on Dams 2000). The introduction of sheep and cattle led to wetland modification on a landscape scale due to grazing, tree-clearing, tillage, sedimentation from erosion, and drainage of periodically flooded land for pasture and to reduce diseases and bogging risk. On the temperate Northern Tablelands of New South Wales, nearly 70% of wetlands have been lost and the majority of those remaining have had their water regime altered (Brock *et al.* 1999). More than half of Australian wetlands have been transformed by urban development and agriculture.

Many Australian surface ecosystems, including most inland pastoral holdings, depend on groundwater (Hatton & Evans 1998). About 9% of the Australian groundwater resources have been developed (Smith 1998), but there is little knowledge about their renewability and sustainability. Overextraction of groundwater has been found in seven of 13 groundwater systems considered under stress (Alexandra *et al.* 1993) and this has led in some areas to groundwater table lowering and seawater intrusion into the aquifer.

Regulation of the flow regime of most rivers has led to a decrease of the flood amplitude, flood frequency and a change of flood period, disconnecting flood plains and permanent water bodies from rivers. About 80% of the Murray-Darling River (Fig. 6) flow is used for off-stream purposes (Cullen *et al.* 1996) and this has led to a decline in wetland areas; for example the Macquarie marshes have decreased by at least 40–50% in area (Kingsford & Thomas 1995). Regulation of the River Murray has eliminated most of the floods and changed the timing, resulting in loss of biodiversity (Walker & Thoms 1993).

Irrigation schemes are still being planned for many Australian rivers and will severely affect connected inland and coastal wetlands by water extraction and changed flow regime. Furthermore, in arid zones, wetlands are threatened by salinization because of a rising groundwater table due to irrigation. However, it is predicted that economic growth can be maintained up to the year 2020 by improving water-use efficiency (Australian Academy of Technological Sciences and Engineering 1999).

Australia has made considerable efforts to classify and list its wetlands. The third edition of the directory of important wetlands cited 851 sites (including marine and coastal wetlands) with a total area of 57 829 522 ha, of which 74% are

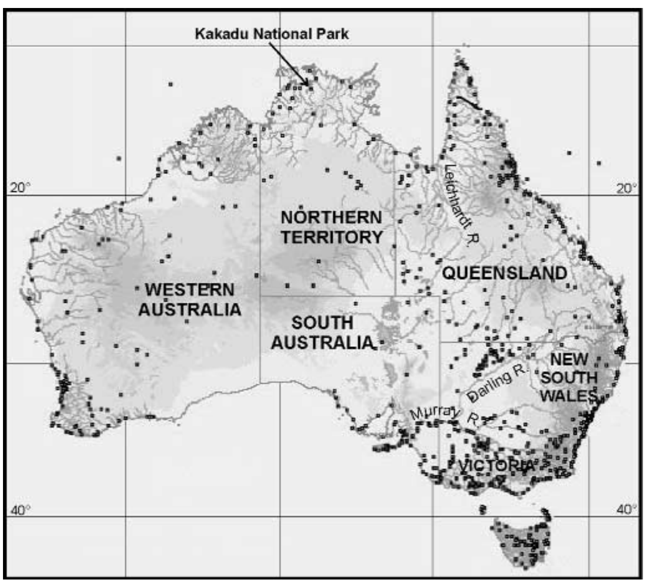

Figure 6 Important wetlands of Australia (according to Environment Australia 2001).

in Queensland (Environment Australia 2001). These sites are carefully managed, but they represent only part of the total wetland area that, for the whole country, is unknown. In the State of Victoria, about 75% of the important wetlands are on public land, but public-land wetlands make up only 20% of the total wetland area. About 37% of the total wetland area has already been lost, mainly due to drainage; more than 90% of this loss is on private land. Major wetland areas are indicated in Figure 6. The detailed map indicates that the scientific community, the public, and the central and state governments are aware of the problems related to wetland loss and have established high-level programmes to survey, study and mitigate negative impacts (Bunn *et al.* 1997; Williams 1998; Boulton *et al.* 1999).

The experience in the temperate and dry south favours wetland protection in the tropical north of the continent. Comprehensive knowledge of the extent of wetlands loss and degradation in northern Australia is unavailable, but in general terms, wetlands are still comparatively undisturbed. Possible threats are water pollution by mineral processing and extraction, the increase of irrigated land that will require additional dam construction, increased cattle and buffalo ranching and salt water intrusion due to sea-level rise (Douglas *et al.* 1998). Important wetland sites are under strict protection in Kakadu National Park (Finlayson *et al.* 1998).

The invasion of wetlands by alien species is especially well documented in Australia and a major threat also to the wetlands in tropical northern Australia. For a few years the South American cane toad *Bufo marinus* has been dispersing over the continent and has recently reached Kakadu National Park. The voracious toad feeds on a large variety of animals and has no natural enemies because it is poisonous to predators. The rice industry spends A$ 14 million annually on herbicides, mostly to control the South American *Echinochloa* sp. Other widely distributed neotropical aquatic weeds are *Salvinia molesta, Eichhornia crassipes, Pistia stratiotes, Parkinsonia aculeata* and *Mimosa pigra*. For some years the para grass *Brachiaria mutica* has been spreading in Kakadu National Park and causing increasing concern (Douglas *et al.* 1998). Feral water buffaloes introduced to the Northern Territory during the middle of the 19th century, have spread and seriously damaged the wetlands. They were drastically reduced in numbers during the 1980s by a control programme to eradicate bovine tuberculosis (Finlayson & von Oertzen 1996). After the removal of feral buffaloes, feral pigs (*Sus scofra*) proliferated in the wetlands of the Northern Territory (Corbett 1995).

CONCLUSIONS

Wetlands are scattered over the continents like islands in the oceans. This gives them specific characteristics and makes generalizations difficult. This review paper can only indicate general outlines and perspectives. Detailed problem analyses and recommendations for solutions have to be elaborated on a case-by-case basis in close cooperation between scientists, local decision makers, wetland managers and the people living in the respective wetlands.

In temperate regions, the economic importance of wetlands has changed over the last decades. After a period of heavy wetland destruction mainly in Europe, North America and south Australia, many societies have dramatically changed their attitude to the multiple values of wetlands, increased wetland protection and initiated costly restoration projects. A global value for ecosystem goods, services, biodiversity and cultural considerations of US$ $6579 \times 10^9\,yr^{-1}$ has been estimated for all inland waters and wetlands in comparison to US$ $5740 \times 10^9\,yr^{-1}$ for all other non-marine ecosystems combined. The average values per unit area of rivers (US$ 8498 $ha^{-1}\,yr^{-1}$) and wetlands (US$ 14 785 $ha^{-1}\,yr^{-1}$) are higher than those of the most valuable terrestrial ecosystems, such as forests (US$ 969 $ha^{-1}\,yr^{-1}$) and grasslands (US$ 232 $ha^{-1}\,yr^{-1}$) (Costanza *et al.* 1997).

In tropical countries, the discussion about the value of wetlands is still restricted mostly to the use of land resources for food production and of water resources for irrigation, and domestic and industrial use, although in different degrees according to the specific situations of each country.

On a continental scale, the large South American wetlands have the best chances of surviving until the year 2025 at least in part in fairly pristine conditions, because of relatively low population density and growth rates, low development pressure, sufficient water supply, large number of protected areas and rising pressure of environmental groups. Of major concern are plans for the construction of large hydroelectric power plants and hidrovias, which often do not consider ecological arguments. Floodplain forests are under heavy pressure from logging and transformation to pasture and agricultural land. Small wetlands are threatened by large-scale agro-industrial projects and deforestation. In Central America and Mexico, the situation is far less favourable because of higher population density, greater demand for water and land, and smaller wetland areas. Strict protection of existing wetlands and wetland restoration are required.

In the arid and semi-arid regions of Africa, pressure on wetlands is already high and high population growth rates in the next decades are likely to dramatically increase the demand on water and wetland resources for food production. Political instability and inefficient management methods will also aggravate the situation up to the 2025 time horizon in the moist tropics. Watershed management is required to maintain the principal structures and functions of the wetlands, and is also the key to wetland restoration in the semi-arid and arid zones

In large areas of tropical Asia, the population density is already very high and wetland degradation is far advanced. High population growth rates will require strict measures for the protection of the remaining intact wetlands and restoration projects for degraded wetlands if the prospects for the year 2025 are to be positive.

After a period of heavy wetland destruction, mostly in the semi-arid and arid temperate zone of Australia, public concern about sustainable use of water and wetland resources is rising. Australia has started very ambitious research, management and restoration programmes, and this expertise could contribute considerably to wetland management in other semi-arid tropical regions. Many wetlands in the tropical moist Northern Territory are well protected and managed. Of major concern are invasive exotic species.

There are some attitudes that are common to most tropical countries and that have to be changed for the protection and sustainable development of wetlands.

Many politicians in tropical countries still believe that environmental protection counteracts development. In fact, it has been shown that poverty follows environmental degradation (Barbier 2000). Degradation and losses of wetlands are mainly due to decisions which ignore their multiple functions and values, the main reasons for this being policy deficiencies, deficient planning concepts, limited information and awareness, and institutional weakness, as for the wetlands in the Lake Victoria basin (Kassenga 1997). In the future, protection measures for wetlands have to better integrate ecological needs with management requirements for the benefit of the local population (Pimbert & Gujia 1997; Gopal 1991). Traditional management practices need to be studied, adapted and integrated into development plans, to satisfy the requirements of a rapidly growing population and changing economic conditions. Most of the cost-intensive high-impact methods developed for wetland management in temperate regions are not suitable for tropical countries, because they do not consider the specific environmental, social, cultural and economic conditions. Intensive south-south cooperation is required with respect to the use and improvement of low-cost and low-impact management methods.

Some governments are beginning to pass responsibility for the management of natural resources to local communities. In the Brazilian Amazon River flood plain, experiments have started on a decentralized administration of fishery resources (McGrath *et al.* 1999). Other examples of community management are the Danau Sentarum Wildlife Reserve in west Kalimantan, Borneo (British Overseas Development 1995) and some Kenyan wetlands (Gichuki 2000).

The use of goods and services which wetlands provide for the human population should maintain the ecological integrity of the wetlands, defined as the capacity to support or maintain a natural and balanced biological system (Karr 1996). The ecological integrity of wetlands, however, depends on integrated forms of watershed management that in semi-arid regions may encompass large areas and many stakeholders who are not directly related to the wetlands. Integrated management requires the cooperation of all stakeholders in the catchment area who have to renounce some of their benefits in favour of sustainable use of the resources by all members of the community and environmental protection, as shown for Australian dryland rivers (Kingsford *et al.* 1998). This integration requires a high level of understanding of ecological and socioeconomic interactions that scarcely exists in most countries. There is therefore an urgent need to improve environmental education at all levels of the population (Thompson 1996).

Many tropical countries still require national wetland policies and structures for their application. Institutions are required to monitor wetland uses and provide extension services that encourage the sustainable use of wetlands and their resources. Limiting for the development of national wetland policies is an insufficient infrastructure and lack of manpower for science, technology, planning and management. Most countries will require intensive assistance from the international community. However, it would be a tragic error to simply transfer temperate-region wetland models and management methods to the tropics. Most of them are not suitable for tropical wetlands, because they are cost-intensive and do not fit with the ecological and socio-economic requirements of the respective countries. For the sustainable management of large still fairly pristine wetlands, south-south exchange of expertise is required.

The protection of wetlands and related biodiversity is considered of global importance. Therefore the international community, mainly the rich countries, should assume greater responsibility by supporting governments in poor tropical countries to establish and maintain protected areas. International environmental organizations will play an increasing role in the protection of key wetlands. There are today about 1072 sites of international importance with a total extent of 81 748 609 ha throughout the world (RAMSAR 2001). About 5.7% of the sites (6.5% of the area) are in Australia, 8.6% (24.5%) in Africa, 5.1% (20.0%) in South and Central America, and 2.7% (2.5%) in tropical Asia (without China). Considering that some South American countries are not tropical, we can assume that about 20% of the sites corresponding to 50% of the area protected are in the tropics. In the short term, the Convention's goal is to have at least 2000 sites in the Ramsar list by 2005.

Despite the fact that international mechanisms like the Ramsar Convention have no power to impose adequate management methods or control protection measures, they provide 'moral authority' and guidelines for local governments (Bartley 2000). International and national NGOs will play an increasing role in the future as pressure groups for the protection of both the wetlands and ethnic minorities and their traditional management methods.

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