Ecology and Management of Large South American Rivers and their Floodplains

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Abstract:

South American large river-floodplain systems played already a mayor role for the human population in pre-Columbian times for water supply, navigation, agriculture, hunting and fishery. Today, these ecosystem services are still very important. In addition the rivers are also used for other purposes, such as disposal of domestic and industrial waste and the generation of hydroelectric energy. Brazil, Paraguay, Peru, Venezuela, Ecuador, Colombia and Chile generate >93, ~100, 74, 73, 68, 68 and 57% of their electrical energy from hydropower, respectively (World Commission on Dams 2000).

Most South American large rivers are subject to predictable monomodal flood pulses that inundate large areas and drive the ecology of the river–floodplain systems, including important economic activities such as fishery, small-scale agriculture and cattle ranching. The potential of inland fishery of the Amazon River basin is estimated to be about 9×10^5 t y^{-1} (Bayley & Petrere 1989). The flood pulse is also of fundamental importance for the maintenance of biodiversity.

Improved natural-resource management methods of the floodplains are required to hinder floodplain degradation and increase fish, timber, crop and cattle production, but efficient management planning in all South American countries takes place at the sidelines. For example, the canalisation of the upper Paraguay River (*hidrovia)* through the Pantanal, a large wetland of 1.6×10^5 km^2 at the borders of Brazil, Paraguay and Bolivia and downriver of Argentina and Uruguay, would seriously affect not only the integrity of the Pantanal, but also the hydrology of the lower Paraguay River. The Brazilian Government officially desisted from the project, however private enterprises continue with its realization at low speed.

Environmentally harmful projects are strongly opposed by national and international non-governmental organizations that are becoming increasingly efficient in environmental protection. A rising number of protected areas and improvement of environmental legislation indicate advances in environmental protection, but there are serious deficiencies in implementation. To overcome governance deficiencies, different types of decentralized, community-based management systems are being tested that hand over part of the administration of natural resources to local communities, e.g. sustainable-management reserves and the selection of floodplain lakes for community based management of fish stocks.

1) Introduction:

The South American sub-continent is dominated by large rivers. The Amazon River, Orinoco River, and Paraná/Paraguay/La Plata River occupy positions 1, 3 and 10 in the worldwide ranking of river discharge. Together, they transport about 8×10^{12} m^3 of water per year to the Atlantic Ocean (Milliman & Meade 1983, Meade 1996). Their drainage areas cover about 1×10^7 km^2 (Tab. 1). Large parts of the catchment areas have human population densities of <5 people km^{-2}. Highest densities are found in the upper and middle Paraná River basin and its mouth area and in the upper Magdalena River basin.

Since pre-Columbian times humans preferred for colonization the shores of the large rivers, because they provide water, transport facilities. South American large rivers, except the Sao Francisco River, are accompanied by extended fringing floodplains rivers that provide abundant animal protein and, in the case of white water rivers, fertile alluvial soils for agriculture. Human population in pre-Columbian times was as high as today and the management of natural river-floodplain resources was obviously sustainable as shown by the large populations of river turtles, manatees, caimans, and fishes observed by the early European conquerors. In a few centuries, the stocks of many species became depleted by excessive exploitation, but the ecosystems as such were little affected, because hydrology as driving force and mayor structures and functions were not seriously modified.

Since the middle of the last century this situation is changing with accelerating speed. Traditional management methods are substituted by modern ones, and demands, formerly not known, provide new possibilities but are also rising new environmental and social problems. For instance, approximately 60 reservoirs, including the giant Itaipu Reservoir (14,000 MW), have been constructed along the upper and middle Paraná River and its tributaries, and the number of reservoirs in other river catchments is rising. Insufficient environmental impact analyses and politically oriented decisions have already led to the construction of reservoirs with a very low energy output and serious negative ecological and social side effects, e.g. the Balbina Reservoir in Amazonia.

The following presentation describes the status of environmental health of the Amazon River, Orinoco River, Magdalena River, São Francisco River, Upper Paraná River, and La Plata-Paraná-Paraguay River. It also discusses their development potential, describes the threats for the environment and presents options for a sustainable development and protection.

2) Geographical setting:

The South American subcontinent covers an area of 17.85 million km^2. It reaches from about 13° North to 55° South and from 36° West to 82° West . Most Rivers drain to the Atlantic in the East, because the Sub-Continent is delimited to the Pacific by the Andean mountains that extent along its entire western rim. This mountain range developed during the separation of the sub-continent from Africa that occurred about 110 million years ago. Inside the continent are two major mountain systems, the Guiana shield in the North and the Central Brazilian shield and connected mountain ranges in the South-East. They are separated by the Amazon basin. The core areas of the shields belong to the oldest formations on Earth. The Central Brazilian shield is in part covered by ancient sediment layers of different age and origin that form rather flat and deeply eroded plateaus. It is assumed that the Magdalena, Orinoco and Amazon Rivers developed with the uplift of the Andes and that the older São Francisco, Tocantins and Paraná Rivers were probably associated with the separation of South America and Africa in the Jurassic and Cretaceous (Potter 1994).

Most of the subcontinent is well supplied with water. Annual precipitation ranges from >7,000 mm at the eastern slopes of the Andes near the Equator to 200 mm in the lower São Francisco catchment. There is a pronounced seasonality in rainfall over most parts of South America.

The lowlands near the Equator are covered with tropical rain forest that in the West at the foothills of the Andes changes from 500 to 700m upwards to different types of mountainous and cloud forests and later to high Andean Puna grasslands. North and south of the forest belt different types of Cerrado and savanna vegetation occur. The southern Cerrado belt in Brazil is actually under strong human pressure. About 50% of the area has already been converted into pasture and cropland, mostly soybean. Agriculture is slowly advancing into the Amazon rain forest as shown by the frequent fires observed during the dry season along a 2000 km long “fire arch”. Along the Atlantic coast down to Argentina there is a forest belt that has been mostly converted to crop land and pasture (Fig. 1).

The subcontinent is characterized by the following large river systems (from North to South): Magdalena River, Orinoco River, Amazon River including Tocantins and Araguaia Rivers, Sao Francisco River and Paraná/Paraguay River. Size of the catchment area, discharge and water level fluctuations are given in Tab. 1. Lakes in the lowlands are shallow, often embedded in floodplains and of young age. Most of them are subjected to strong oscillations in size and depth and may dry out temporarily. Lake Titicaca in an endorheic basin of the Andes at about 4000m altitude is the only large and deep old lake at the sub-continent.

Total human population in South America is about 365 million people (20.5 persons km^{-2}). About 50-70% live in urban areas. In the country site, population concentrates along the shores of the rivers that provide water, fish, transport facilities, and often fertile alluvial soils for agriculture and animal farming. Even so, population density in large parts of the river catchments is low (in the Amazon River basin <2 persons km^{-2}) except the Magdalena River basin that has a size of about 260,000 km^2 and harbours 32 million people, the upper Parana River basin (880,000 km^2 and 55 million people), parts of the Atlantic coastline and the mouth areas of the Amazon and Paraná Rivers.

3) Limnological conditions and habitats

Because of predictable pronounced dry and wet seasons in their catchments, all large South American rivers are characterized by a predictable monomodal flood pulse. Only the Magdalena River shows a bimodal flood curve. During high water level, extended areas along the middle and lower courses of the large rivers are inundated forming large floodplains of different shape with many floodplain lakes. In addition to these riverine floodplains, there are large interfluvial wetlands that are flooded during the rainy season mostly by rainwater and that are periodically or permanently connected to the large rivers. The different types of wetlands are indicated in Fig. 2.

All large South American rivers have a low to moderate electrolyte content that varies between 6-20 uS cm-1 in nutrient poor and acidic blackwater water tributaries of the Amazon River and reaches up to 300 uS in others. (Tab. 2). Floodplain lakes show at high water pronounced hypoxia or anoxia near the bottom. Therefore benthos is often impoverished and fish kills can occur despite many adaptations of the fish fauna to low oxygen conditions, when holomixis occurs during heavy rainstorms and temperature declines.

Vegetation cover of the large floodplains corresponds to certain degree to the vegetation in the surrounding uplands. High lying areas of floodplains in the rain forest belt are covered by highly flood tolerant forests, lower lying areas by flood or drought tolerant perennial herbaceous plants. Lowest lying areas are colonized at low water period by annual grasses, sedges and herbs. In nutrient-rich white water rivers, abundant emergent and free floating macophyte communities develop during high water level. Submersed species are rare or absent because of unsuitable light conditions. In nutrient-poor blackwater aquatic macrophytes are rare because of the low nutrient status of the water and/or the low pH value. Floodplains in the savanna belts have flood tolerant forests along the river courses and drought tolerant forests or shrublands in little flooded areas, where drought stress and fire stress are heavier than flood stress. Large parts are covered during the terrestrial phase by grasses, sedges and herbaceous plants and at high water by submersed, emergent and free floating aquatic macrophytes. Floodplain lakes are colonized by emergent and free-floating aquatic macrophyte communities. Submerged vegetation occurs only in lakes of floodplains with little fluctuating water level.

Specific habitats are currents and waterfalls that occur in large numbers at the foothills of the Andes and the Guiana and Central Brazilian shields and separate the lowland parts of the rivers from the headwaters in the mountainous regions. They harbour a specific rheophilic flora and fauna but are also important biogeographic barriers for part of the aquatic fauna that is not able to cross the obstacles upriver.

4) Biodiversity

The total contribution of South American Rivers to aquatic biodiversity can not be estimated, because of insufficient knowledge of many groups. Available numbers are not representative and often misleading. Best known are fishes that will be treated here as an example.

Today, the "Check List of the Freshwater Fishes of South and Central America" recognizes 4,475 fish species but many areas in South America are insufficiently sampled. Another 1,550 undescribed species may be estimated from author's expertise, bringing the estimated existing fish species in Neotropical freshwaters to 6.025 (Reis et al.2003). This is much less than Schäfer's (1998) extrapolation of more than 8000 species. In any case, the Neotropics contribute with 20 to 25% to the total fish fauna on Earth.

Center of species richness is the Amazon basin. Species numbers decrease considerably with increasing altitude and towards the cold southern end of the sub-continent. At the foothills of the Andes fish fauna changes at an altitude of 500 to 700m that represents also the border of the tropical lowland rainforest. Described species numbers for the large river catchments are indicated in Fig. 3.

Much diversification of modern neotropical fish fauna occurred during at least the roughly 70-million-year period from the Late Cretaceous through Miocene. Late Miocene through Holocene Earth history events had very little impact on taxonomic diversity. Great antiquity and static history of almost all modern lower taxa can be shown by fossil traces. For instance, over the course of the last 13.5 million years or longer, fish such as the *tambaqui* (*Colossoma macropomum*) persisted, apparently without changing its diet of fruits and seeds (Lundberg 1998, Lundberg et al. 1998). There are only few examples of allopatric speciation, for instance, in Pleistocene Lago Valencia, which contains four endemic species (Mago-Leccia 1970). Reproductive isolation by assortative mating that is used to explain rapid intralacustric speciation in large African lakes obviously does not play a mayor role in the hydrologically variable South American river systems. However, there are many cases of late and post-Miocene local extirpation of modern groups, as for instance, in Argentina, Chile, the Magdalena Basin, the north coast of Venezuela, and the high Cuenca Basin of Ecuador (Lundberg et al. 1998).

5) Use of rivers and management of water and aquatic resources

All large rivers are important navigation routes and have increasingly been used since the colonization by the Europeans. Today, Ocean going vessels travel along the Amazon River about 3000 km up to Iquitos in Peru and 1000 km along the Paraná river up to Asuncion in Paraguay. There is a strong pressure to canalise several rivers to improve ship traffic as shown later.

Inland fisheries is of large importance for protein supply of the local population. Stocks of Magdalena River in Colombia are heavily overfished and stocks of São Francisco River and Paraná River in Brazil are depleted. The fishery potential of the Amazon River, Orinoco River and Paraná/Paraguay River is not fully exploited. For instance, Bayley & Petrere (1989) estimate an inland fishery potential of about 900,000 t yr^{-1} for the Amazon River basin, but actually only about 40% are used. Fishery concentrates on a few species only. Some of them show already signs of overfishing, such as Pirarucu (*Arapaima gigas*), Tambaqui (*Colossoma macropomum*) and the large migrating catfishes (*Pseudoplatystoma, Brachyplatystoma*). The former abundant stocks of other aquatic species, such as manatee (*Trichechus inunguis*) and the large river turtles (*Podocnemis* spp.) were already strongly depleted at the beginning of the 20th Century and are now in danger of extinction. Fishery legislation in all large river basins is not adequate and its implementation insufficient to protect the stocks.

Hydroelectric power generation is already of large importance in South America and will further increase. Brazil generates >93%, Paraguay nearly 100%, Peru 74%, Venezuela 73%, Ecuador 68%, Colombia 68% and Chile 57% of their electrical energy from hydropower, (World Commission on Dams 2000). Strongly impacted are the upper course of the Magdalena River, the São Francisco River and the Brazilian part of the Paraná River. Approximately 60 reservoirs, including the giant Itaipu Reservoir (14,000 MW), lie along the upper and middle Paraná River and its tributaries. In the São Francisco River catchment area there are 33 reservoirs, 9 of them on the main stem. Most of them are used for hydroelectric power generation but also for water supply for agriculture and urban areas. Rising energy demand will dramatically increase the number of reservoirs in the next decades. The hydroelectric potential of the Brazilian Amazon basin is estimated in about 100,000 MW. For the production of this amount of energy 90 reservoirs would be necessary, covering a total area of about 100,000 km^2, and affecting all mayor tributaries of the Amazon River. The Tocantins River would become transformed into a series of 27 reservoirs (Junk & Nunes de Mello 1987). Some reservoirs have a very low energy output per unit area and are considered as very harmful for the environment, such as Balbina at Uatuma River in the Brazilian Amazon region, that produces <0.1MW km^{-2}. The reservoir covers an area of about 2430 km^2 of former undisturbed rain forest and will be a long term source of methane because of large amounts of inundated organic material and its large aquatic-terrestrial transition zone (Fearnside 1989, 1995).

Water is a limiting factor for agriculture mostly along the dry Pacific coast and in the Northeast of Brazil. There are plans of the Brazilian government to transfer water of the São

Francisco River to adjacent river basins to improve water availability for irrigation agriculture and urban centres. Environmentalists and many scientists strongly oppose these plans with the argument that the São Francisco River is already heavily modified by reservoir construction, pollution and water abstraction, and improvement of storage capacities and infrastructure for a better use of the available water in the other catchments would bring about more benefit for the local population and protect the environment. Large engineering efforts for water transfer would benefit mostly the construction companies and large farmers, and heavily affect the environment.

6) Habitat health, threats and protection

The abundance of water in most parts of South America results in negligence of management strategies for water and aquatic resources. Inventories and classifications of wetlands are incomplete. Most countries don't have an adequate legislation that deals specifically with wetlands that have key functions in water storage, maintenance of water quality and biodiversity. When there is such a legislation, as for instance for the protection of the riparian vegetation, the implementation is insufficient. Environmental impact analyses concentrate on the rain forest and let aside aquatic resources.

Human impact on large South American rivers is largest in basins with high human population, mainly in the Magdalena River and the upper Parana River basin. Sewage treatment plants are rare and do not correspond to modern standards. Efforts to improve sewage treatment are counteracted in urban centres by the quickly increasing human population. Destruction of riparian vegetation and smaller wetlands is common. Longitudinal connectivity is interrupted by dams and reservoirs. The construction of fish ladders in the upper Paraná River basin has shown to be very costly and little efficient for the highly diverse fish fauna and was abandoned by the Brazilian Company for Hydroelectric Energy Generation (ELECTROBRAS). Furthermore, rivers with reservoirs in cascades may not provide relevant nursery areas for migrating species (Agostinho et al. 2002).

The Orinoco River, Amazon River and lower Parana River and Paraguay River basins show a very low human population and are over large parts still in rather pristine conditions. However, human impact is steadily rising and increasingly impacting aquatic habitat health and biodiversity. In the Amazon basin, agro-industries destroy in large scale the natural Cerrado vegetation along the southern headwaters that harbour endemic aquatic species, many of them still undescribed. The agro-industries and logging companies increasingly enter the rain forest area, often without permission of the environmental agency IBAMA. The destruction of riparian vegetation facilitates sediment input because of increased soil erosion and reduces habitat diversity and diversity of aquatic organisms (Wantzen 1998). The fish fauna of the Paraná River shows increased levels of persistent organic pollutants. Most floodplain forests along the lower Amazon River and its large tributaries are destroyed by clear cutting for cattle ranching or degraded by heavy logging. There are plans for improving navigation of several large southern tributaries of the Amazon, such as the Madeira, Tapajos, Xingu, and Araguaia Rivers. Large preoccupation rise plans to rectify and deepen the upper Paraguay River inside the Pantanal, that would threaten one of the most beautiful wetlands of the world and heavily affect downriver areas.

The accelerating environmental destruction in all South American countries rises the question about the possibilities for the sustainable use and protection of the large river-floodplain systems and their resources. Protection measures can be classified in a hierarchic order.

Certainly a prerequisite at the top level is the elaboration and implementation of integrated catchment area management plans, because rivers represent to a certain extent the physical, chemical and biological conditions of the entire catchment area by the run off of precipitation and groundwater. Human activities in the catchment will sooner or later affect the connected aquatic systems. Therefore, any management plan has to consider the impact on the environmental health of the river system, and try to avoid or minimize negative side-effects. At the next level the elaboration and implementation of integrated management plans for the different rivers and associated wetlands is required. This includes the inventory and classification of water bodies and wetlands according to climatic, geographic, hydrological, chemical and biological parameters. At the third level, environmental impact analyses of the different management practices have to be done to optimise their economic and social output and minimize negative side-effects on the environment. In all South American countries there are serious deficits at all levels.

Sustainable management includes also the establishment of protected areas. During the last decades priority has been given in South America to the protection of terrestrial ecosystems, assuming that they would cover aquatic ecosystems occurring therein. In South America, their exist many protected areas that include large wetland areas and parts of river courses. Their number and often their size, however, is not sufficient to maintain habitat diversity and guarantee protection of the aquatic biota. For instance, the Mamiraua Reserve for Sustainable Development at the central Amazon River Floodplain (11,240 km^2) and the nearby Jaú National Park (22,720 km^2) that covers the entire catchment of the Jaú River, a tributary of the Negro River in Brazil are large enough to maintain habitat diversity related to river dynamics and certainly protect the local river and wetland flora and fauna. But large rivers cross different landscapes by distances of several thousand kilometres and have catchment areas of hundreds of thousands square kilometres with different plant and animal communities. Some fish species perform spawning migrations that extend over hundreds and even thousands of kilometres. Therefore, new concepts are required for the establishment of protected areas that represent entire river systems and their aquatic biota.

Environmental legislation and its implementation is precarious in all South American countries. Low political priority, inefficient administration and a high level of corruption facilitate the destruction of rivers, wetlands and their resources. Since three decades, national and international environmental organizations are playing an increasing role in environmental protection, mainly by establishing protected areas, involvement in environmental education of the local population, controlling governmental development policies, and realizing research projects for environmental protection.

The increasing globalization of commerce requires also the globalization of efforts for research and the formation of human resources in environmental sciences. Since some years, Australia followed by South Africa have taken the lead in the development and implementation of modern concepts for the sustainable management of rivers, wetlands and aquatic resources such as the Environmental Flow Assessment (Tharme 2003). An intensified South-South collaboration will certainly accelerate the development of modern policies for the sustainable management of South American rivers, wetlands and their resources.

7) Conclusions

South America is with few exceptions a wet continent, dominated by large rivers that are accompanied by large fringing floodplains. Some rivers are also connected to large interfluvial wetlands. Probably about 10 - 15% of the entire continent is periodically or permanently flooded. Most of the wetlands occur in the moist tropics and subtropics.

Habitat diversity in river-floodplain systems is large and results in high species diversity as shown for fishes. About 4500 fish species are already described for the Neotropics and a total of 6000 to 8000 species is supposed to occur, corresponding to about 20 - 25% of the worlds fish fauna.

Most large river floodplain systems and interfluvial wetlands are still in a rather pristine stage excepting Magdalena River, Upper Parana River and Sao Francisco River.

Major threats are water pollution in basins with high human density (Magdalena River, Upper Parana River and Sao Francisco River, and reaches of other rivers below large cities), reservoir construction, interrupting longitudinal connectivity and leading to river floodplain degradation, and large scale agro-industrial projects in the catchments that lead to accelerated aquatic habitat degradation because of increased soil erosion and pesticide input.

Knowledge about the ecology of natural water bodies and wetlands, their structure, functions and multiple services including biodiversity is insufficient. Abundant water results in lack of political will to sustainably manage water resources. Inadequate environmental legislation and inefficient administration and control lead to accelerating degradation of rivers, associated wetlands and their aquatic resources.

For the maintenance of the ecological integrity of large rivers and their floodplains integrated development plans are required at the catchment level and the river-floodplain level. Environmental impact analyses of development projects have to consider possible negative side effects on the integrity of rivers, wetlands and their biota. New concepts are required for the establishment of protected areas to protect aquatic diversity of large river systems.

Large national and international research projects are important for South American Rivers not only to increase knowledge and train human resources but also to call attention for ongoing environmental destruction. National and international NGO's play already a major role in rising awareness of the local population and the political leadership. In a time of accelerated globalization of commerce the international community should also make use of their strength in stimulating efforts for protection and sustainable use of aquatic resources in South America.

Table 1: Hydrological parameters of South American large rivers.
*= after reservoir construction. ** = diminishing downriver. *** at Mompox depression

	Length	Catchment area km² 10⁶	Discharge M³ sec.⁻¹	Water level fluctuations m
Amazon River	6,436	7.40	170,000	6-12**
Paraná/Paraguay River	4,695	3.20	20,000	4-10**
Orinoco River	2,500	1.10	38,000	12
São Francisco River	3,199	0.62	5,000	3-4*
Magdalena River	1,540	0.27	7,400	7***
Murray-Darling River	2,530	1.05	320	?

Table 2: Some limnological parameters (means or ranges) of South American large rivers (main stem)
* = decreasing from the Andean foothills to the mouth, ** = near the bottom, *** = after reservoir construction

	El. Conductivity $\mu S\ cm^{-1}$	PH	Susp. Matter $mg\ l^{-1}$
Amazon River	40-80	6-7	50-100 (up to 1000**)
Orinoco River	10-50	6-7	30-200
Upper Paraná River	42-72	6.5-7.9	4-40 (3-4***)
Lower Paraná River	80-130	7.2-7.7	170 (10-700)
Paraguay River	40-300	6.9-8.2	160 (12-900)
São Francisco River	30 - 50	6.5-8	<5***
Magdalena River	180	7.1	570
Blackwater tributaries	6-20	4-5	< 5

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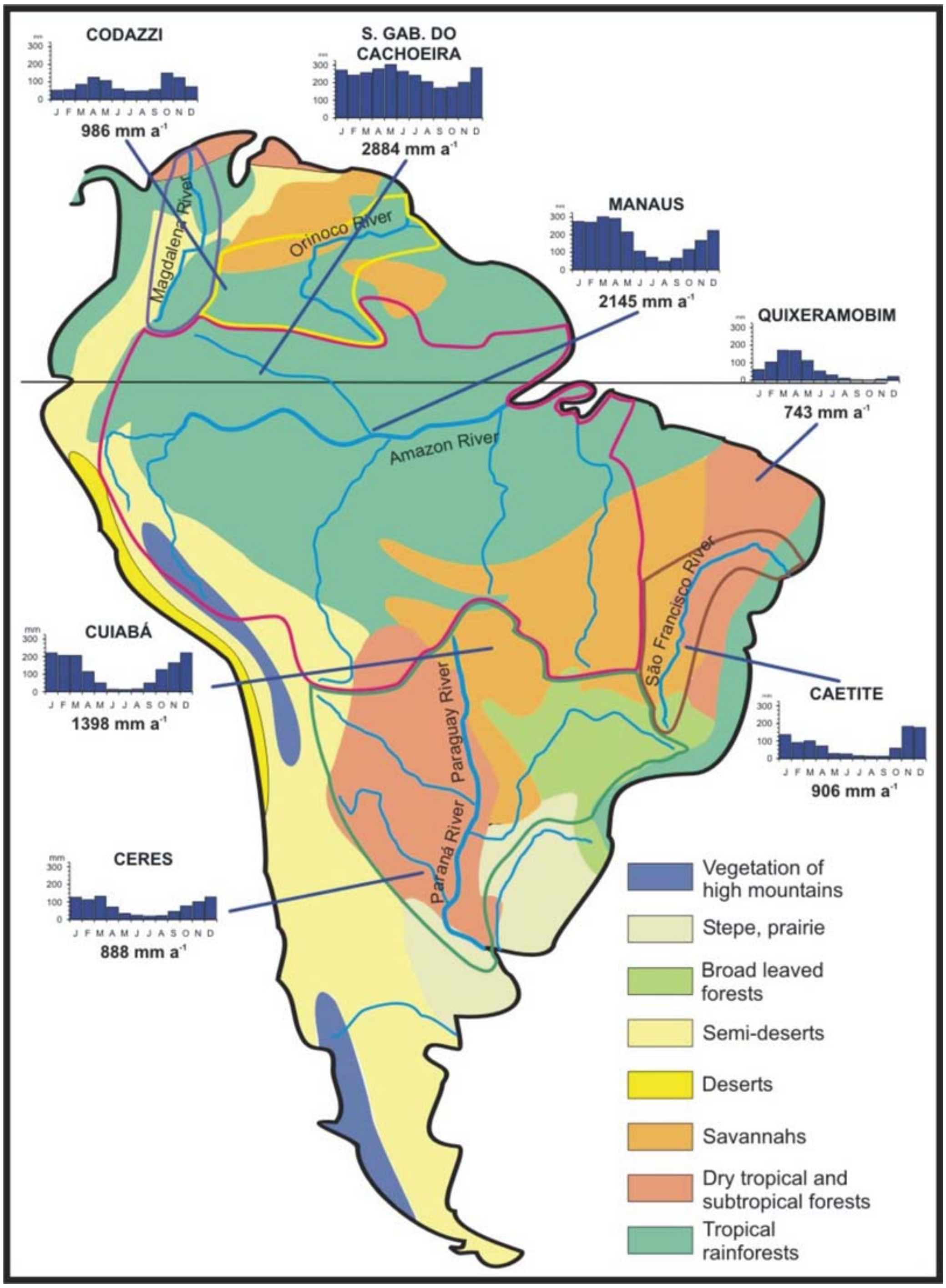

Fig. 1: Vegetation cover and rainfall periodicity

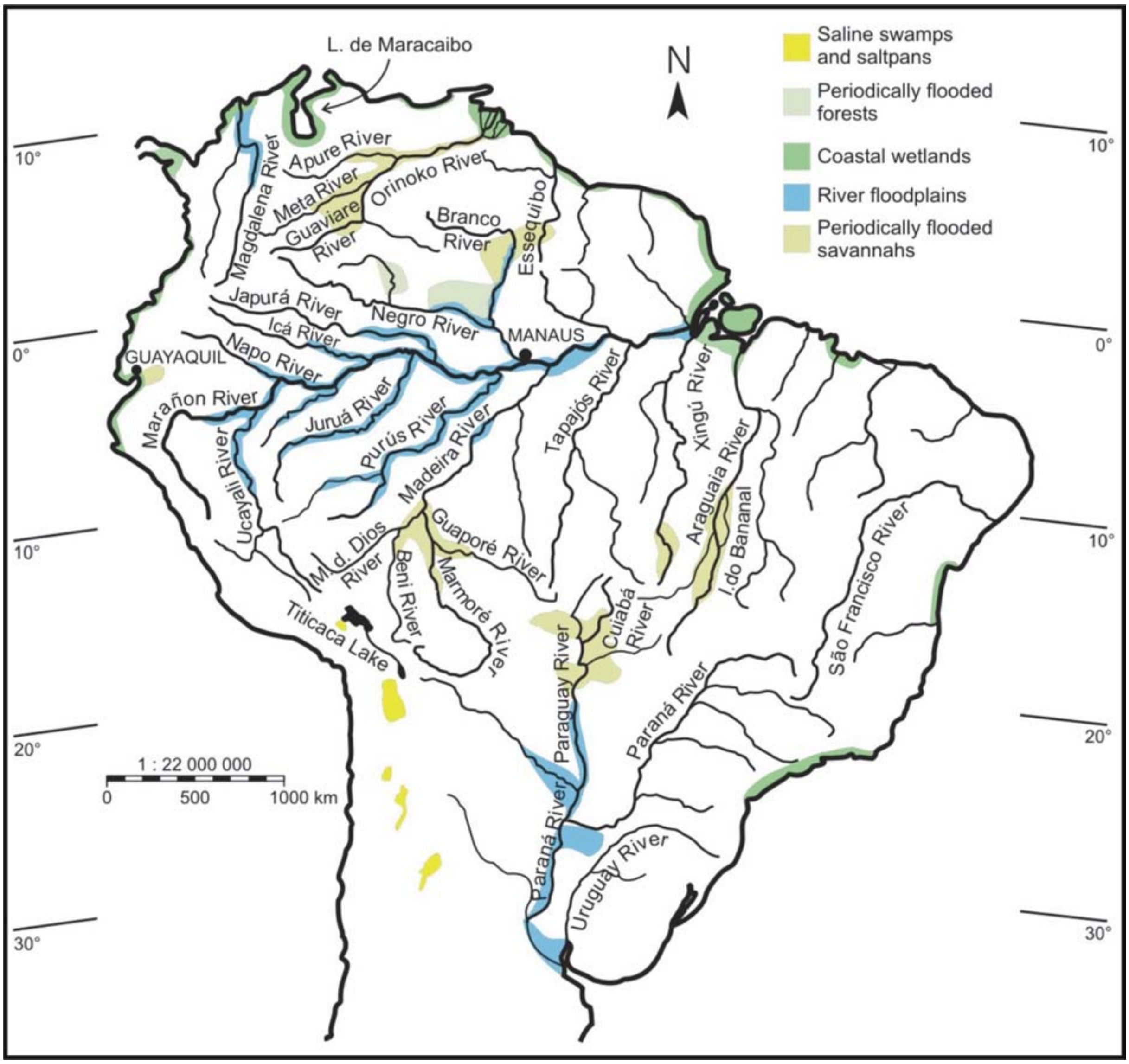

Fig. 2: Occurrence of mayor floodplain types in South America

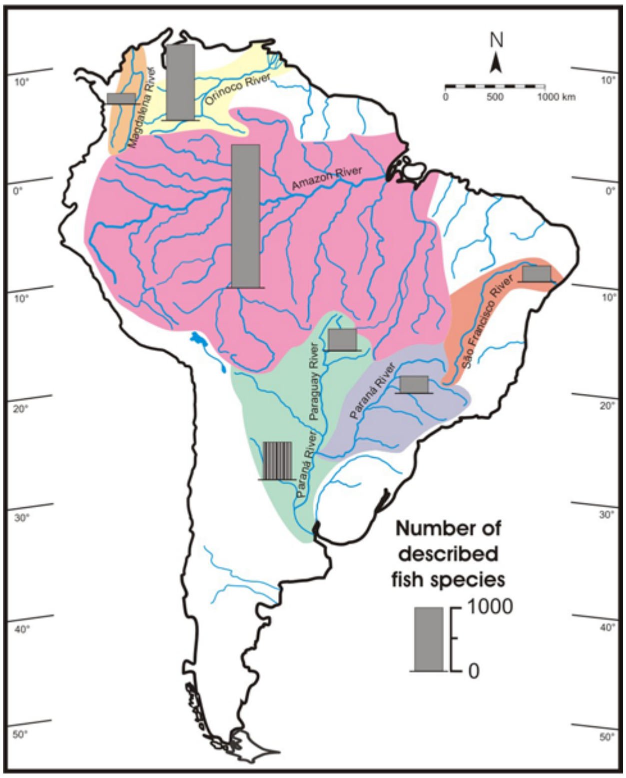

Fig. 3: Fish species diversity in major South-American river basins