ECOHYDROLOGY & HYDROBIOLOGY

DOI:10.2478/v10104-009-0016-x

Vol. 8
No 2-4, 205-223
2008

Ecohydrological Processes and Sustainable Floodplain Management

Application of the ecohydrological concept for sustainable development of tropical floodplains: the case of the upper Paraná River basin

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Abstract

The degradation of natural resources in the upper Paraná River's floodplain remnant has been caused by local use of land, and by alterations in the flood regime promoted by more than 100 large reservoirs located upstream from the plain. This destruction appeared irreversible 15 years ago, although the area has been partly rehabilitated through the construction of three large conservation units that encompass the entire remnant. These units, which imposed different levels of restrictions on soil use, have resulted in clear benefits to terrestrial components. However, aquatic ecosystem function is still harmed by artificial regulation of discharge. This regulation reduces biological diversity and the resources traditionally exploited by indigenous people. In this paper, we examined the conditions of the upper Paraná River basin in detail, and we discussed the application of the ecohydrology concept to promote sustainable development in this region.

Key words: Flood control, biodiversity, reservoir, hydroecology, flood and fisheries

1. Introduction

Brazil has one of the biggest river networks on the planet, which drains an area of over 8 500 000 km^2. This large surface area, coupled with variations in the features of the landscape (hydrology, physiography, and geomorphology), results in a great heterogeneity of freshwater ecosystems with a profusion of distinct habitats. Brazil's aquatic biodiversity is among world's most diverse (Agostinho *et al.* 2005), and is directly correlated with the abundance of habitat rivers in the biomes of South America.

The aquatic ecosystems of Brazil and South America are becoming more difficult to maintain, especially in floodplain regions (Gopal *et al.* 2000; Junk 2002). Population growth in the last century has led to an expansion in agriculture, an increase in urban population, and a proliferation of industry. These events have occurred in all large basins, but with a higher intensity in basins located in the south and southeast of Brazil. Population growth has directly impacted these regions through eutrophication, contamination with pesticides and industrial residues, drainage of water bodies, accumulation of sand, removal of vegetation in the basin and near rivers (riparian), introduction of alien species, and overexploitation of natural resources. Additionally, the natural hydrosedimentological dynamics of floodplains have been profoundly altered by the construction of dams (Agostinho *et al*. 2007a). Natural dynamics in pristine rivers include seasonal but predictable variations in river discharge, modifications in the degree of hydrological connectivity, and the periodic exchange of matter, energy, and nutrients among environments (Junk *et al*. 1989; Neiff 1990; Thomaz *et al*. 2007). These dynamics are responsible for the proper function of floodplains: to maintain productive dynamics, nutrient cycling, and biological structure.

Damming alters several physical, chemical, and biological properties of rivers and their associated floodplains (Petts 1984; Tundisi, Matsumura-Tundisi 2003; Agostinho *et al.* 2004a), but one of the most conspicuous negative impacts is the decline in populations of migratory fish species (Agostinho *et al*. 2007b). These species require certain types of habitats and particular hydrological conditions to complete their life cycle (for example, tributaries, "várzeas", and lotic stretches). The construction of dams may obstruct access to some essential habitats, or even alter environmental conditions that determine reproductive success (Agostinho *et al*. 2003). As a result, recruitment of juveniles to dammed stretches may be seriously affected, and may sometimes cause a population to run the risk of extinction.

The relationship between dam construction and migratory fish species conservation has been debated by researchers for decades. In addition to a vital ecological role in the function of freshwater systems (Freeman *et al.* 2003; Taylor *et al.* 2006), migratory species are quite large in size. They are therefore economically important, and supply wages for several families in all river basins of Brazil (Bayley, Petrere Jr. 1989; Petrere Jr. 1996; Godinho, Godinho 2003; Okada *et al.* 2005; Agostinho *et al.* 2007b). The economic loss caused by the effect of dams on migratory species has motivated a series of management actions including stocking, fishery control, and fish passage construction to restore and/or conserve migratory fish populations in the environments influenced by reservoirs. Intense efforts have been applied to the management of these resources, especially during the last 50 years. However, there are no indications that these actions have yielded satisfactory results, as demonstrated by the depletion of the most important fish stocks in the higher stretches of the upper Paraná River (Agostinho *et al.* 2004b; Pelicice, Agostinho 2008). Consequently, negative impacts of damming still persist, as do those related to other components and processes that occur in floodplains. There is a pressing need for alternative approaches to rehabilitate the natural dynamics of these ecosystems, preferably one that is less reductionist and fragmented.

The ecohydrological approach assumes a strict interdependence between hydrological and ecological processes. This approach represents an interesting alternative in the management of aquatic resources due to its holistic perspective in treating ecosystems. In ecohydrology, successful maintenance of aquatic resources depends on actions that restore natural ecological and evolutionary processes that are dependent on regional hydrological dynamics (Zalewski 2000). Thus, the restoration of spatiotemporal hydrosedimentological dynamics at the basin level is fundamental in this approach: river, floodplain, adjacent landscape, and biota are viewed as a completely integrated system (Ward 1998; Ward *et al.* 2002). Based on a deep knowledge of the dynamics that underlie natural rhythms, ecohydrology aims to increase the capacity of systems in reabsorbing environmental impacts, by using properties of the ecosystem itself as management tools (e.g., rehabilitation of natural hydrological pulses, heterogeneity of habitats, and riparian vegetation; Zalewski *et al.* 1997; Zalewski 2002). It is expected that this approach promotes sustainable human development by preserving functions and services provided by aquatic ecosystems.

In this paper, we considered the use of ecohydrology as a framework for solving environmental problems of floodplains influenced by large dams, given the intrinsic value of wetland rehabilitation and river natural dynamics (Poff *et al.* 1997; Buijse *et al.* 2002). To achieve our goals, we used the upper Paraná River basin as a template. This basin has an enormous number of large dams, but still represents a single floodplain remnant. While this stretch is intensely influenced by the operation of several dams located upstream, it still plays a relevant role in maintaining biodiversity and fishing stocks in the region (Agostinho *et al.* 2007a). Specifically, we discussed how ecohydrology may contribute to the maintenance and restoration of the floodplain remnant of the upper Paraná River, in the context of multiple usages, serious conflicts in the use of resources, and a long history of environmental actions based on reductionist management.

2. Flood regime and floodplain processes

The upper Paraná floodplain was originally a 500 km stretch on the western margin of the Paraná River, between the municipalities of Três

Lagoas (Mato Grosso do Sul State) and the Salto de Sete Quedas in Guaíra (Paraná State). After construction of the Itaipu Dam downstream of the area in 1982 and the Porto Primavera Dam upstream of the area in 1998, the stretch of floodplain was reduced to 230 km (Fig. 1). This remnant is influenced by the discharge control promoted by Porto Primavera and by several other dams located upstream. However, this floodplain still presents a great heterogeneity of habitats because there are several tributaries (rivers, streams, and creeks), secondary channels, islands, and lakes with distinct degrees of connectivity and pools (Agostinho *et al.* 2004c).

The higher third part of the floodplain has been studied for more than 20 years, and several aspects of its structure and dynamics are therefore well known. As in other river-floodplain systems around the world, the natural flood regime is the main force working on these ecosystems (Junk *et al.* 1989; Thomaz *et al.* 2007), molding community structure and function. Variations in the natural hydrological cycle average near 2.5 m (Thomaz *et al.* 2004) with maximum amplitude of about 7.5 m. Although there are some interannual variations, the floodplain presents a clear seasonal regime of floods, resulting from the pluviometric dynamics of the basin. High water levels (flood phase) coincide with the rainy seasons of spring and summer, and usually occur between November and March. During this period, there is a clear elevation of Paraná River water levels, which overpass natural levees and inundate plain habitats, increasing hydrological connectivity. Consequently, the hydrosedimentological pulse contributes to the fertilization of environments in the plain (Thomaz *et al.* 1992), and interrupts succession processes of communities. It is also fundamental for biota dispersion, allowing access to previously isolated habitats, as is the case in several floodplain lakes. The pulse therefore promotes homogenization of the ecosystem in relation to chemical, physical, and biological aspects (Thomaz *et al.* 2004; 2007).

Fig. 1. The upper Paraná River basin showing the location of large dams. The shadowed area represents the last free flowing stretch of the river within the Brazilian Territory (modified from Agostinho et al. 2007a).

Conversely, low water levels (dry phase) coincide with small amounts of rain, and usually occur between March and November. During this phase, the Paraná River flows constantly in its bed, and several environments remain isolated (floodplain lakes, channels, and pools). Additionally, local factors are the most important for determining the dynamics and the successional trajectory of communities during the dry phase (Thomaz *et al.* 2007). Hundreds to thousands of small bodies of water are created, all without superficial connection to the river. This situation persists for months, intensifying patterns of β-diversity (Ward, Tockner 2001; Petry *et al.* 2003; Thomaz *et al.* 2007), and increasing regional diversity in wetlands (Scheffer, Geest 2006). However, if isolation persists for too long, it may facilitate the development of unfavorable conditions, both biotic and abiotic (Okada *et al.* 2003; Petry *et al.* 2003; Thomaz *et al.* 2004), including the complete desiccation of environments.

3. Current Paraná River impoundments

In 1911, the first hydropower dam was constructed in the upper Paraná River basin (Edgard de Souza, Tietê River; height: 34 m, surface area: 3.5 km^2). Since then, more than 145 large dams, according to the criteria established by the Word Commission on Dams, have been built in this basin. More than 70% of these dams are used to generate electricity. Although the number of reservoirs increased from 1911 to 1960, they tended to be small and were constructed in tributaries of the Paraná River. In subsequent decades, technical capacity for land removal and the concrete technology evolved, enabling the construction of large dams with an exponential increase in the accumulated impounded area (Fig. 2).

The total surface area of all reservoirs is near 16 700 km^2, almost half of the total area inundated by reservoirs within Brazil (Agostinho *et al.* 2007b). The 20 most important reservoirs inundated a combined area of 13 800 km^2, and only two of them completed before 1960 (Chavantes Reservoir in 1959; Mascarenha de Morais Reservoir in 1956) – Table I.

Current management actions

Historically, management actions to mitigate negative impacts of dams on migratory fishes in upper Paraná River encompassed stocking, fish passages, and fishery control. Unfortunately, these actions were not based on technical or scientific information, nor were results properly evaluated or monitored (Agostinho *et al.* 2004b).

Until the 1950s, the main purpose of Brazilian management programs was to ensure the movements of migratory fish through dams by constructing fish ladders. These passages failed due to design flaws, and in the following decades, management focus shifted to promote increased fishery yield by stocking alien or native species. In the 1990s, fish passage construction was reconsidered. Fishery management shortcomings of the past half century can be attributed to reductionist approaches, inadequate protocols, unclear subjects, absent or inadequate monitoring, and failure to make decisions based on common sense.

As a management strategy, fish passage construction has not taken into account the possibility of one way displacement or the demand for regional conservation. Pelicice and Agostinho (2008) studied two fish ladders located in the upper Paraná River basin originally designed for the conservation of fish populations; they concluded that these ladders may function as ecological traps for migratory fish species. These authors suggest that the same may be happening for several other ladders in South America. The detriment of ecological traps would be transference of fish populations from high quality (riverine) to low-quality (reservoir) environments, ultimately leading to decreased individual fitness.

In another failed management strategy, stocking attempted to recover migratory fish populations and fisheries in impounded rivers. However, in some instances, this effort has been met with total failure: wrong species have been released, fishes have been released at inappropri-

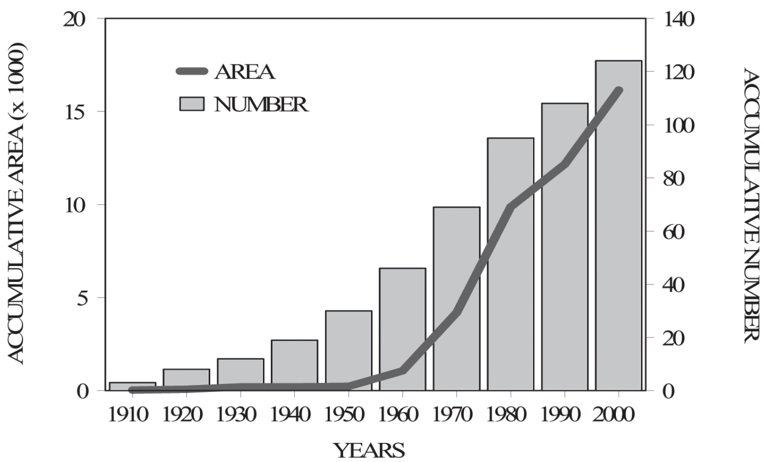

Fig. 2. Accumulated number and area of large reservoirs in the upper Paraná River basin during the last century (after Agostinho *et al.* 2007b).

Table I. Some characteristics of the main reservoirs located in the upper Paraná River basin. These reservoirs all serve to generate electricity (after Agostinho et al. 2007b).

Reservoir	Power Company	Dam Completion	River	Area (km^2)
Porto Primavera	CESP	1998	Paraná	2250
Furnas	Furnas	1963	Grande	1440
Itaipu	Itaipu Binacional	1982	Paraná	1350
Ilha Solteira	CESP	1978	Paraná	1195
Três Irmãos	CESP	1993	Tietê	785
Itumbiara	Furnas	1980	Paranaíba	778
São Simão	CEMIG	1978	Paranaíba	722
Água Vermelha	AES Tietê	1979	Grande	647
Capivara	Duke	1970	Paranapanema	576
Promissão	AES Tietê	1977	Tietê	530
Emborcação	CEMIG	1982	Paranaíba	485
Nova Ponte	CEMIG	1994	Paranaíba	447
Marimbondo	FURNAS	1975	Grande	438
Jurumirim	Duke	1962	Paranapanema	425
Chavantes	Duke	1959	Paranapanema	400
Jupiá	CESP	1974	Paraná	330
Barra Bonita	AES Tietê	1963	Tietê	308
Mascarenha de Moraes	FURNAS	1956	Grande	250
Volta Grande	CEMIG	1974	Grande	222
Rosana	Duke	1987	Paranapanema	220

ate sites, fishes of improper size, number, or genetic quality and fishes have been released in the wrong season. In fact, stocking has been carried out with clear political objectives and with pseudo-conservationist institutional marketing (Agostinho *et al.* 2005). It was sometimes difficult to obtain fry of native species in hatcheries, so alien species were used in stocking programs until the 1990s; this contributed to the spread of several introduced species in the basin. Today, stocking is based essentially on the available species, and not on conservation or fishery demands

Fishery control has had a long history of controversy. Brazilian legislation is severe and restricts fisheries by imposing limits on quantities, gear employed, habitats, and seasons; however, the lack of information on fishery landings, fish stocks, and insufficient financial resources and workforce makes enforcement difficult. Overfishing is a constant issue, and sometimes operates synergistically with other disturbances (e.g., impoundments), resulting in severe stock depletions. For example, large migratory species of fishes, the most appreciated in the market that historically constituted main landings, are rare in commercial catches in many areas in the upper Paraná River.

The focus of the management actions has also been historically directed toward the impounded areas of the reservoir. River stretches below dams, where the impacts can be similar or even more intense than upstream (Agostinho *et al.* 2007b), are systematically neglected by managers in Brazil. This fact is more worrisome when downstream stretches include floodplain areas, because of their high biological diversity and importance in at least part of the life cycle of large migratory fishes.

Water regulation by dams

The construction of dams on the tributaries and main channel of the upper Paraná River has had a direct negative impact on the water discharge

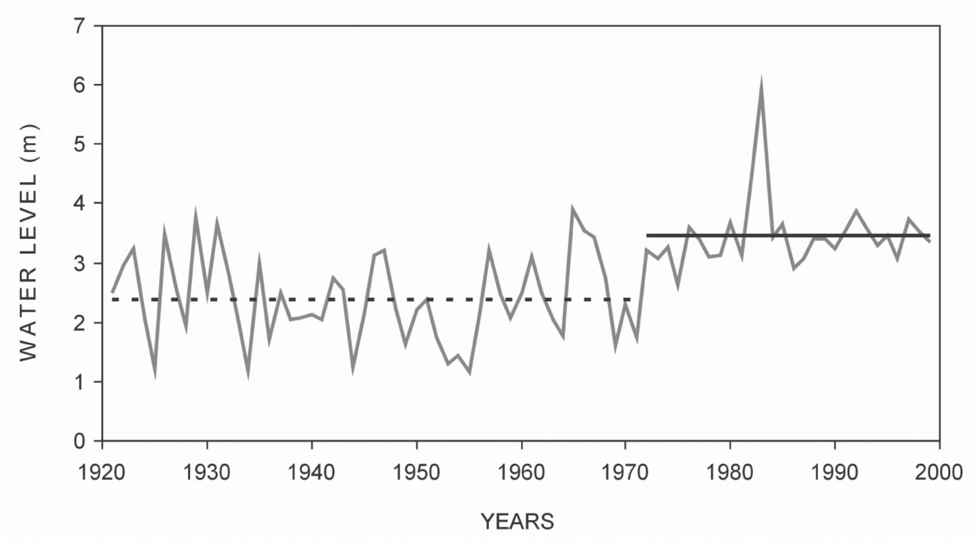

Fig. 3. Historical temporal variations (annual averages) of the water level (m) in the station of Porto São José (modified from Rocha *et al.* 2003).

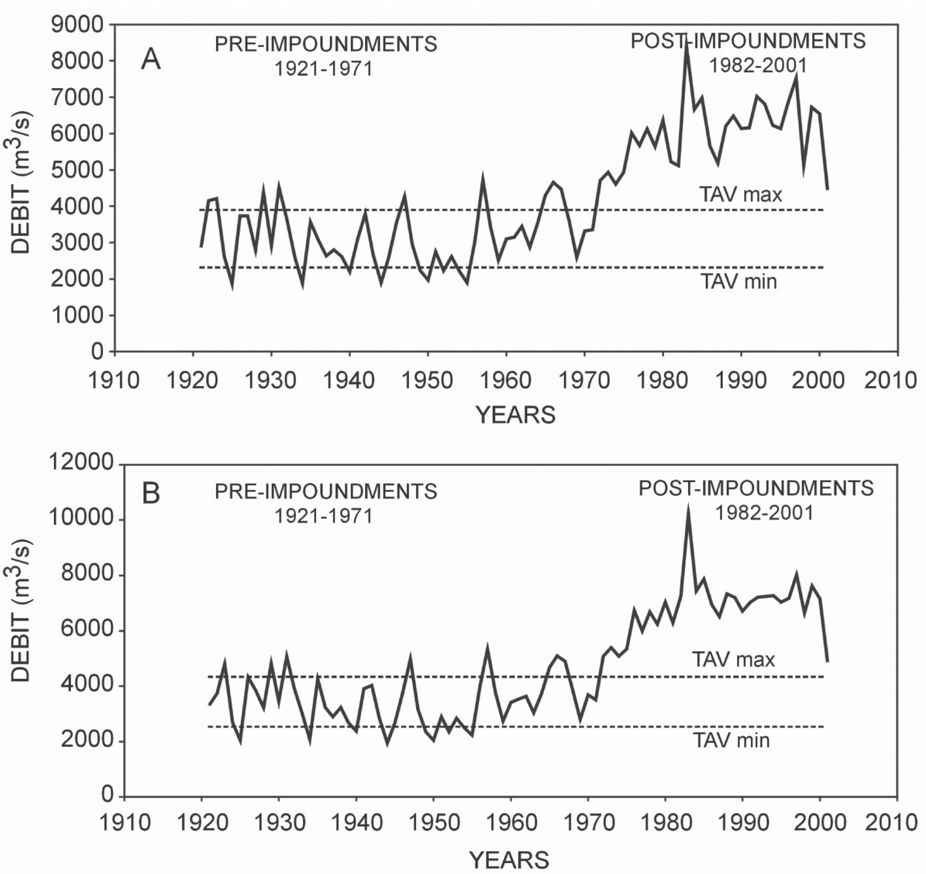

Fig. 4. Historical variation in minimum annual discharge in one day (A), and average minimum values in thirty days (B). TAV = approximated rate of natural variability (modified from Rocha *et al.* 2002).

regime. In the remnant stretch of the floodplain, the water regime registered before 1971 was natural. After 1971, dams already affected extreme values (Rocha *et al.* 2003) (Fig. 3). It should be noted that only six (total surface area of 3 399 km^2) out of 20 (total surface area of 13 798 km^2) large dams were completed before 1970.

Rocha *et al.* (2003) used historical data from the stations of São José and Guaíra until 2001, and verified that the period prior to 1970 consisted of natural flow. However, the period between 1972 and 1981 was considered as transitory, since the evaluated parameters varied according to the completion of the dams. Finally, these authors considered the period after 1982 to be one of controlled discharge, as all studied parameters of fluvial discharge were significantly altered from this point on.

The main alterations identified until 2001 related to lower discharges, such as minimal annual discharges. Discharge control eliminated daily and monthly extreme maximum values (Fig. 4).

Additionally, flood regimes were mainly altered in relation to frequency, duration, and periodicity until 2001. That is, flood events became more frequent, but with shorter durations (Fig. 5), and peaks started to occur a month in advance. In a natural period, floods should occur in February and March; however, in the period between 1972 and 2001, they occurred in January and February.

The completion of Porto Primavera Dam in late 1998, located immediately above the upper Paraná River floodplain remnant, further increased the discharge control of the Paraná River. The magnitude of flood events was also affected. The fluvial discharge ranged within a narrow interval of variation, as described by Silva (2007), and flood periods began to occur once a year in March, with a mean duration of 12 days (Fig. 6).

Another effect imposed by the Porto Primavera Dam were rapid modifications in discharge during the course of one day, leading to intense variations in water level between morning and afternoon, and vice-versa. A comparison between the water levels obtained from the station of Porto São José at 6:00 and 18:00 hours showed more than 10 cm variation in water level for 55% of the days, and more than 30 cm for 9% of the days. The greatest variation was 122 cm in 12 hours.

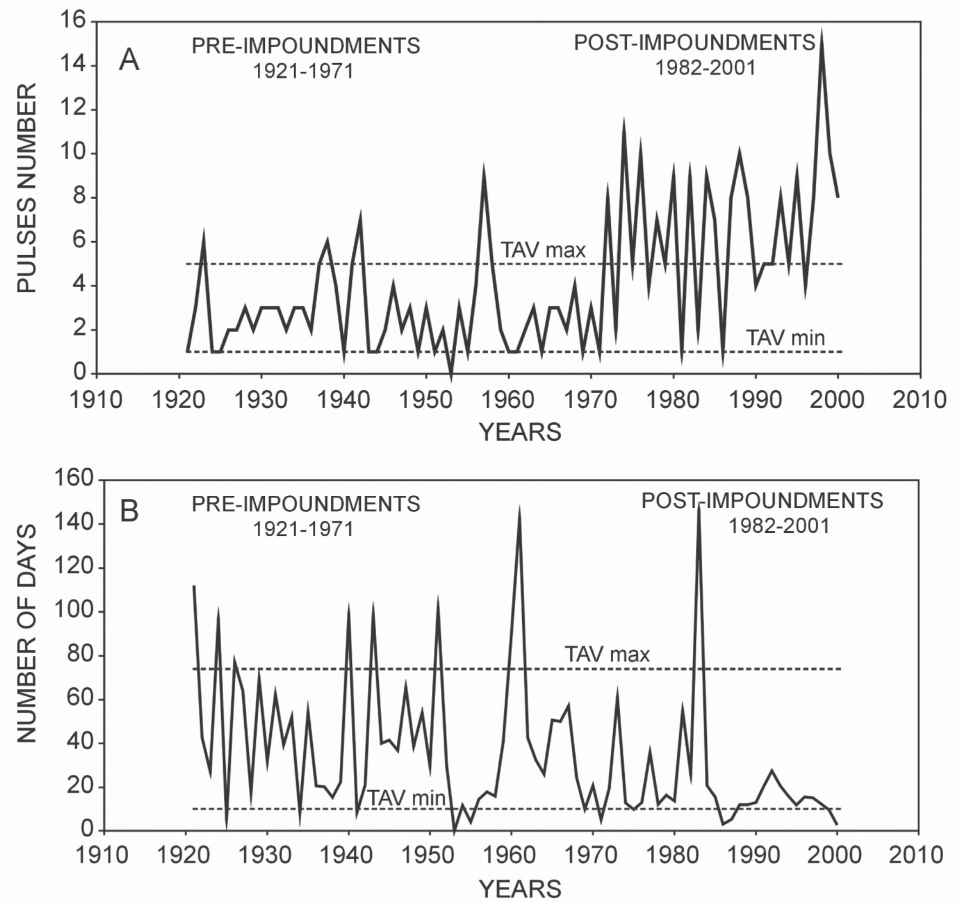

Fig. 5. Temporal variations in the number of flood pulses per year (pulses number; A), and flood duration (number of days; B). TAV = approximated rate of natural variability (modified from Rocha *et al.* 2002).

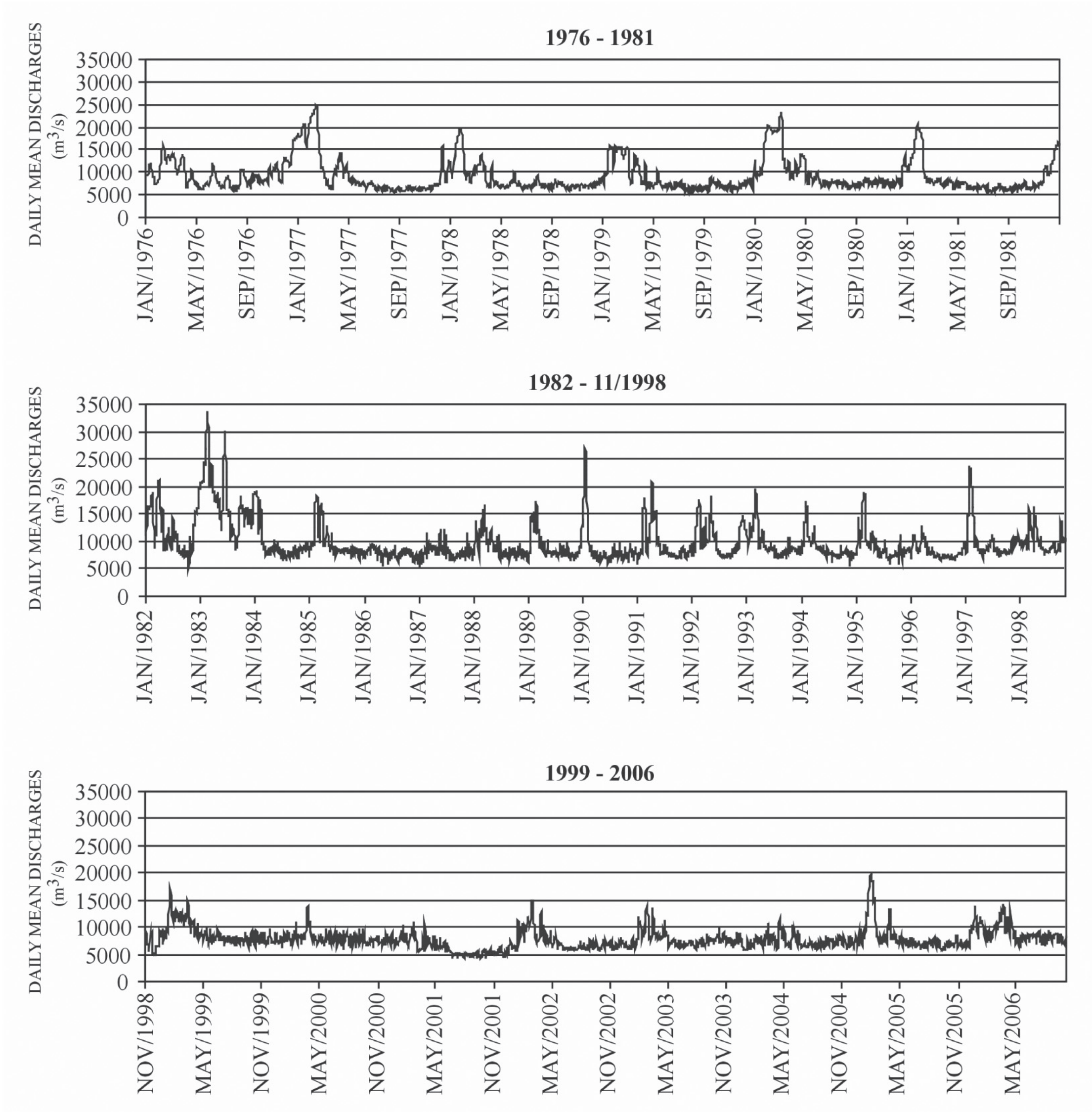

Fig. 6. Hydrograms representing daily discharges in the Station of Porto São José (modified from Silva 2007).

The reduction in the variability of discharge magnitudes affected floodplain function in two ways: (i) the absence of lower discharges resulted in an increase in humid areas in the floodplain along the year, prohibiting isolation of water bodies during dry periods; and (ii) the absence of high flood values led to less inundated areas, decreasing the connectivity of water bodies throughout the floodplain. These effects were compounded by the decreases in flood pulse frequency and duration, and by the displacement of the flood period to March.

The variations in water levels along the day length caused two effects: (i) the sharp decreases in water levels led to piping erosion in the river margins (Rocha *et al.*, 2002); and (ii) the daily variations in humidity and water body size resulted in areas of ecological stress.

4. The control of the flood regime by dams and the fish fauna

Physical, chemical, and biological components of fluvial ecosystems are shaped by the hydrological characteristics of a river (Petts 1986). Properties of water velocity, discharge variability in different temporal scales, and frequency of extreme discharges have fundamental control over the nature of the habitats and on the organisms inhabiting rivers and associated environs. In natural systems, communities are the result of long evolutionary processes, and species exist with their life cycles entwined with the dynamics of the hydrological regime.

In contrast to natural development, dams are built to alter the distribution of discharge in time and space. This jeopardizes some aspects of river dynamics that are fundamental to the maintenance of aquatic ecosystems (WCD 2000), including fishes and their habitats.

In the floodplain remnant of the upper Paraná River, discharge control prompted by dams is the main source of ecological impacts, and includes timing, frequency, and intensity of the pulses. Several other relevant impacts that deserve attention include retention of sediments and nutrients, blockage of fish migration routes, and alteration in the quality of released water.

As mentioned previously, the formation of Porto Primavera Reservoir inundated almost half of the original plain. This reservoir has attenuated the flood intensity, elevating minimum and reducing maximum discharges, and has led to significant habitat losses in the floodplain remnant. Natural seasonal dynamics have been lost: extensive areas are inundated during dry periods, whereas others are not flooded, and connectivity between the river and the plain is reduced.

Seasonality and connectivity are critical for the biological integrity of floodplains (Petry *et al.* 2003; Agostinho *et al.* 2004a; Thomaz *et al.* 2007). Reduction of floods in these environments affects fish fauna, either directly (migration, spawning, and initial development) or indirectly (productivity of riparian areas, floodplains, and deltas).

Communities of riparian plants supply food and provide shelters and nutrients. These communities are controlled by the interaction of floods and sediments, and several species depend on shallow aquifers to germinate and grow. These waters must be reloaded seasonally by the floods. The seasonal variations of water levels attach wide areas of terrestrial habitats to the fluvial system (aquatic-terrestrial transition zone – ATTZ). These zones promote intense environmental fluctuations that act on biological processes, and on the structure and function of fish assemblages. Therefore, seasonal fluctuations determine the availability of shelter and food, spawning, growth, mortality, competition, predation, and parasitism. The importance of the upper Paraná River's flood regime on the life cycle of fishes is highlighted by the high degree of synchrony between floods and the main events of the reproductive cycle (oocyte maturation, migration, spawning, and development of juveniles). In addition, the success of these biological processes is highly correlated with the recruitment, timing, duration, and amplitude of floods (Gomes, Agostinho 1997; Agostinho *et al.* 2001; Okada *et al.* 2003; Agostinho *et al.* 2004a).

Fish species with different life history strategies appear to have responded to the flood regime changes in different ways. Thus, fishes that have a sedentary strategy of parental care are less dependant on water level elevation than are fishes that must migrate long distances to spawn in the upper stretches of the basin and whose offspring inhabit flooded areas during juvenile development. Studies conducted in the floodplain remnant of the upper Paraná River showed that the abundance of individuals from sedentary species with ripe or spent gonads was greater during dry years, whereas the abundance of migratory individuals with gonads in the same stages was greater during flood years. Short distance migratory species presented an intermediary tendency. However, for all species, fewer juveniles were present during years of droughts (Agostinho *et al.* 2001).

Flood duration correlated with higher success of migratory species recruitment, especially if the floods occurred between September and March. Long floods beyond this period did not influence recruitment (Gomes, Agostinho 1997). Biomass samplings of juveniles from species belonging to distinct reproductive strategies were conducted sixth months after the spawning peak of the main species in three marginal lagoons of the upper Paraná River floodplain, for seven consecutive years. These studies showed that migratory species are favored when the annual period of flood lasted longer than 75 days (Agostinho *et al.* 2004a). However, sharp decreases in water level due to the operation of dams located upstream of the floodplain adversely impacted recruitment, even if spawning occurred (Sanches *et al.* 2006).

Short-term pulses are determined by the demand for electricity and can vary daily, weekly, or even seasonally in a year. Since the Porto Primavera Dam started operation, increased demand of electricity in the evening can cause daily river elevations of more than one meter. In the floodplain, these variations can isolate lakes where large amounts of fries are concentrated. Some of these floodplain lakes dry out completely during water level fluctuations, causing high mortality of fish larvae and fries.

Retention of suspended solids and nutrients is common in any reservoir (Agostinho *et al.* 1995). Annual averages of suspended material concentrations in the Paraná River 25 km downstream of the Porto Primavera Dam were reduced from 24.9 to 10.8 mg dm^{-3} in the two first years of the dam's completion (Crispim, Stevaux 2001). The retention of bottom sediments is higher, as verified by Souza Filho *et al*. (2004). This retention does not allow transported particles to be repositioned, leading to the removal of large amounts of riverbed deposits spanning tens of kilometers (Souza Filho *et al.* 2004; Souza Filho 2009 in press).

Lesser loads of suspended solids give greater erosive capacity to water downstream of dams. This can promote morphological and granulometric alterations in habitats and can affect benthic communities and other species. In addition, increased transparency (Secchi depth) may augment mortality of fish eggs and larvae through pre-

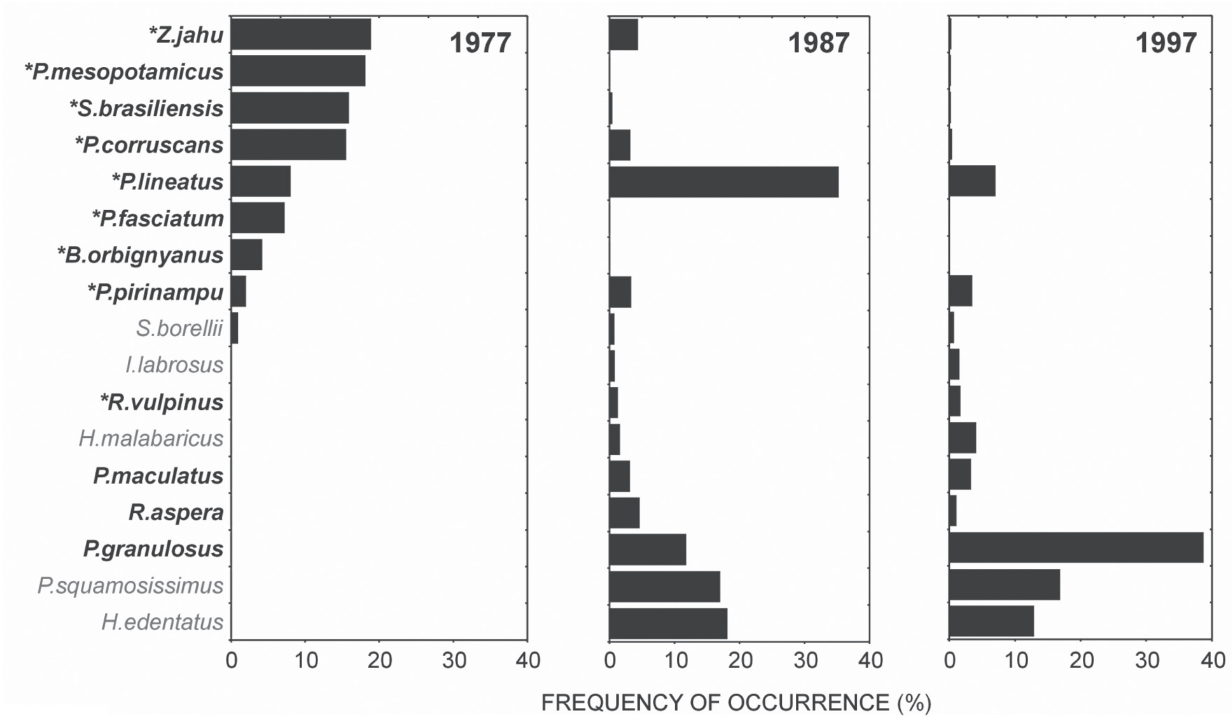

Fig. 7. Fish species composition in the landings of an artisanal fishery in the Itaipu Reservoir before (1977) and after the impoundment (1987 and 1997). Names in bold denote long distance migratory species; asterisks identify species that reach total lengths over 60 cm (modified from Agostinho *et al.* 2003).

dation. Notably, migratory fish species spawn during rain periods, taking advantage of decreased water transparency to protect their offspring from visual predators (Agostinho *et al.* 2003).

In relation to the retention of nutrients, reservoirs tend to impoverish downstream areas (Barbosa *et al.* 1999). Reductions in the fertility of floodplains and river deltas resulted from nutrient retention have been studied in some African countries, and effects on agriculture and fishery and fauna diversity have been reported (WCD 2000). In the Paraná River, annual phosphorus concentrations dropped from 29.8 to 11.2 µg dm^{-3} after the formation of Porto Primavera Reservoir (Agostinho *et al.* 2004a).

Studies conducted in the Paraná River before the construction of the Porto Primavera Dam raised the possibility that pre-existing reservoirs already exerted strong control on the fertilization of the floodplain by nutrient removal. Total phosphorus and chlorophyll concentrations in the Paraná River channel were low in the stretch immediately downstream of the Jupiá Dam, but clearly increased after passing through the floodplain (Agostinho *et al.* 1995). Although some of this increase may be due to tributary input, the fact that phosphorus concentration dropped by more than half in floodplain lakes but increased during flood peaks indicates that upstream reservoirs are capable of impoverishing floodplain areas.

5. Economic and psychosocial impacts

The Paraná River and its tributaries provide professional occupation for a relatively small number of people. However, much of the economic activity of the region is directly or indirectly related to the river. For example, fishery maintenance, tourism, leisure activities, and sand extraction are directly related to the river. Cattle ranching, farming, and the service sector are indirectly related to the river, but are still affected by river variations (Tomanik 1997). Thus, alterations in the seasonality or in the intensity of the flood cycle or in the physical-chemical characteristics of the water may significantly impact regional economic activities.

Of the Paraná River's regional economic activities, professional (artisanal) fishery requires the most direct, intense, and permanent contact with the floodplain. Because of this, the artisanal fishery has been studied in great detail. The discharge control of the downstream Porto Primavera is known to directly affect fisheries in the upper Paraná River channel, floodplain remnant, and in the Itaipu Reservoir located downstream from the plain.

Data on landed fish from the floodplain are scarce compared to data gathered in the Itaipu Reservoir since 1986. However, the fishery maintained in the floodplain was studied for economic and psychosocial reasons. In general, the fisheries of the entire region are only somewhat profitable, and are centered on species with low commercial value (Okada *et al.* 2005; Costa 2007). Fisheries were more profitable in the past, and were based on large migratory species with high commercial values (Fig. 7). This shift may have been caused by impacts from dams, as well as other anthropogenic activities, in addition to droughts.

A survey conducted during the 1990s in the urban area of Porto Rico, located in the east margin of the Paraná River, identified 52 men and four women for whom fisheries were the main professional activity. This group corresponded to 5% of the local population and to 6.6% of the total local workforce. Another 17 were identified who fished to increase family incomes (Tomanik *et al.* 1997). Qualitative evaluation conducted during the surveys showed that the professional fishers of Porto Rico considered the activity to be laborious and not very profitable. According to these individuals, the main difficulties with the profession are: (i) shortage of fish in the Paraná River and tributaries of the region, such as the Baia and Ivinheima rivers; (ii) low prices obtained for landed fish, and difficulties in getting the fish to market, relying on middleman to sell fish in bigger urban centers; (iii) high cost of materials (ice and fuel) and equipment (boats, engines, and nets) used in the fishery; (iv) short life span of equipment due to natural harsh conditions, and to continuous and intense use (Tomanik 1997).

The hardships cited with more frequency and with more emotion were laws related to fishery control, especially law enforcement. Fishers recognized losses resulted from fishing conducted in periods and when using inappropriate fishing techniques. Fishers also discussed other difficulties, but with lower frequency. These included: (i) the nature of the profession, which is difficult and dangerous due to water characteristics, climatic conditions, and the constant threat of poisonous and aggressive animals; (ii) professional insecurity; (iii) fish traits, which are viewed as "suspicious" or "frightened"; (iv) intense and inordinate occupation of the land in the region, due to deforestation and pesticides (Tomanik 1997).

During the first survey, the existence or operation of dams were not extensively mentioned. Only a few fishers pointed out the completion of the Itaipu Dam (in 1982) as the reason why fish stocks decreased in the region, why some target and valuable species disappeared (long distance migratory species), and why less profitable species appeared (such as stingrays). Therefore, dams were not considered a major source of concern for fishers. In this survey, some individuals demonstrated their desire to continue fishing, but were considering alternate professional activities due to low income.

Fishery ability and knowledge are usually passed from father to son, or within a more general family group. For this reason, a second study was conducted to evaluate the willingness of fishers to continue their profession. We interviewed sons and young fishers from the city of Porto Rico in January of 1999 (immediately after the completion of Porto Primavera Dam), and in January of 2000 (one year after the completion; Paiola 2000; Paiola, Tomanik 2002). In January of 1999, 15 people were interviewed; 12 were engaged in the fishery, but three had abandoned the activity. One of the three ex-fishers wanted to return to the fishery, but he felt it was too difficult to maintain his needs by fishing. For those individuals engaged in the fishery, ten (83%) felt that the fishery situation was worse than in previous periods. According to these individuals, fish numbers had decreased sharply due to diminished floods, and to the completion of Porto Primavera Dam. Therefore, immediately after the dam completion, impacts were noticed by fishers in Porto Rico.

In January of 1999, fishers cited other factors that complicated their profession, such as the soil usage, deforestation, cost of fishing materials, and the low market values of the fish (Paiola 2000). Despite these hardships, eight out of 12 fishers declared that they would not leave fishery because they liked working without someone controlling them ("no one gives us orders"), and they liked to be in contact with nature. To them, this was enough to make their profession pleasant.

In January of 2000, we attempted to re-interview the same eight fishers. Two could not be found because fishing season was closed and they were working in another town. Of the six who could be located, one had abandoned the profession, despite his previous desire to continue fishing. The five remaining fishers declared that their profession had become more difficult than the year before. One of them did not speculate why, but the other four pointed to the control of discharge promoted by dams as the main reason for the changes. Only one fisher cited the removal of riparian vegetation as another factor responsible for the decrease in fish stocks of the region.

Comparison of a new census conducted by Tomanik and Godoy (2004) with a previous census (Tomanik *et al.* 1997) revealed that activities directly linked to the river decreased from 7.4% of the total number of inhabitants of Porto Rico (5% in the fishery) to 4.6% (2.5% in the fishery). In addition to the alterations in the natural conditions of the region, macroeconomic processes that occurred in Brazil also seriously affected professional activities in the city of Porto Rico, but the interviewed fishers did not mention them. In social knowledge construction processes, Berger and Luckmann (1985) and Moscovici (2004) stated that immediate elements are usually clearly noticed; these elements gain more importance in the development of representations shared by groups. Therefore, it is not strange that fishers did not cite less immediate factors related to national politics or international economic processes as a cause of their hardships. Scientifically, it is not possible to clearly evaluate the relative weight of each element that drives social transformations experienced by interviewed fishers in the mentioned studies. Regional events such as land occupation, land use, and dam construction interact with and are part of macrosocial processes. Thus, it is not possible to consider that the construction of Porto Primavera Dam is the sole factor that promoted the changes observed in the city of Porto Rico. However, there can be no doubt that the dam has had negative and profound impacts on the individuals who live in the region, especially those who maintain close and continuous contact with the Paraná River and its tributaries. For this reason, the impacts caused by the Porto Primavera Dam were clearly noticed because they directly affected the fishing profession and the living conditions of fishers.

In addition to these economic and occupational aspects, the existence of traditional populations in the vicinity of Porto Rico is another cause for concern. According to Diegues (1996), traditional populations present the following features: (i) a "way of life" that depends on nature and natural cycles; (ii) a profound knowledge of nature and its cycles, which reflects in strategies to explore and manage natural resources - this knowledge is usually passed from generation to generation in an oral fashion; (iii) an importance of subsistence activities and low accumulation of capital; (iv) the use of simple technology that promotes few environmental impacts; (v) very poor political power; (vi) self-identification of belonging to a distinct culture.

The future of the fishing profession in Porto Rico is uncertain. Certain factors (construction and operation of large dams) have forced fishers to change the way they conduct business. These factors have resulted in profit loss, a decreased number of professional fishers, and a change in perception of how fishers view the river. This reduction in the region's fishery does not imply a single economic change, but rather an extinction of traditional ways of life. This more traditional lifestyle varies greatly from urban lifestyles, and contributes to the maintenance of unique knowledge, beliefs, feelings, and social relationships. This complex culture tends to disappear quickly if the professional activity that supports it comes to an end. From an ecological perspective, the elimination of a cultural construction is similar to the extinction of a species. As noted by Moscovici (2007): every destruction of nature is followed by a destruction of a culture.

In the Itaipu Reservoir (located downstream from the floodplain), some fishers that fished in the river prior to the impoundment still live in the area. The formation of this reservoir changed their environment, main species, and strategies. Nevertheless, it should be mentioned that the fishery in the reservoir is strictly related to the hydrological events that occur in the floodplain (recruitment). Thus, the fishery is considered to be of low yield (Agostinho *et al.* 1999; Gomes, Miranda 2001; Okada *et al.* 2005). In the Itaipu Reservoir, the fishery plays an important social and economic role for a great number of fishers who, in general, would not have any alternative legal employment. Fishing in this region occurs in a border area (Brazil–Paraguay) where illicit activities such as smuggling, drug trafficking, and transportation of stolen vehicles across the border are common. Therefore, the fishery in this reservoir and in other parts of the basin needs increased government attention to address successive yield decreases that threaten to push these fishers to the brink of absolute marginality. Therefore, the maintenance of fish stocks in the upper Paraná River depends on the integrity of the floodplain remnant. This would allow for the continuation of the fishery in the region, and would support the traditional population represented by artisanal fishers.

6. Ecohydrological solution

Dams meant to generate electricity are usually constructed in plateau areas, to take advantage of natural slopes and to reduce costs. In the upper Paraná River basin, dams are located above a wide floodplain area. Dams and associated reservoirs promote redistribution of discharge throughout a year, affecting the natural flood regime that is the main force regulating floodplain processes (Junk *et al.* 1989; Agostinho *et al.* 2007a; Thomaz *et al.* 2007). Discharge regulations profoundly affect these ecosystems, which present high biological diversity and maintain fisheries in several river basins throughout the world.

In the upper Paraná River, and throughout Brazil, floodplains receive little attention in the programs developed to mitigate impacts from impoundments. Most of the actions are restricted to the inundated area, and predominantly relate to population manipulations (Agostinho *et al.* 2007b). Actions to reestablish migration routes in stretches with dams appear inadequate because displacements are essentially unidirectional, promoting additional impacts by removing individual downstream dams (Agostinho, Gomes 2002; Agostinho *et al.* 2007b; Pelicice, Agostinho 2008).

Except for the blockage of migration routes, impacts to floodplain stretches downstream of dams are related to loss of habitats and/or their

Table II. Mean (Q_m), maximum (Q_{max}), and minimum (Q_{min}) discharges (m^3) in the periods of 1972-1981, 1982–1998, and 1999-2006 (after Silva 2007).

Period	Qm	Qmax	Qmin
1972 - 1981	9144	20522	5623
1982 - 1998	9772	18414	5997
1999 - 2006	7816	14580	5593

deterioration, and are caused by factors linked to the quality and quantity of water released in the distinct seasons of the year. In this context, any action taken to mitigate impacts should necessarily consider the manipulation of discharge from the dams, in order to meet habitat and biota demands. Due to the importance of floodplains in biological diversity (spatial and temporal heterogeneity of habitats) and fisheries, conservation and sustainable development should be applied in management schemes. The interactions between local processes and other uses of the basin, such as removal and pollution of water, require the consideration of regional processes. In addition, the basin approach is essential for reservoir cascades, in which operation of one dam is dependent on the operation of the others.

Collectively, needs require ecohydrology (Zalewski *et al.* 1997; Zalewski 2000) to solve the problems associated with the water, the people, and the environment of the upper Paraná River floodplain. Ecohydrology is based upon the suggestion that sustainable development of water resources is dependent on the ability to maintain evolutionarily established processes of water and nutrient cycling and energy flow at the basin scale (Zalewski 2002). This concept considers the functional interrelations between hydrology, aquatic ecosystems, and their biota at the watershed scale. The timing and availability of water is intimately linked to ecosystem processes, and to the goods and services provided by inland waters to societies.

The ecohydrology approach depends on a deep understanding of all processes in wide and detailed temporal and spatial scales (Zalewski 2002). Knowledge accumulated over 20 years of floodplain studies of the upper Paraná River provides a good understanding of the structure and processes involving the biota, including impacts that result from discharge control and retention of nutrients. However, some important aspects related to the application of ecohydrology are still not known.

Retention of nutrients and suspended solids negatively impact floodplain productivity and these problems are difficult to solve because retention mainly occurs in the superior parts of reservoirs. Release of superficial or deep water through turbines or spillways could partially mitigate these problems. To this end, local studies should be conducted to evaluate the viability and efficacy of this strategy. On the other hand, the discharge control promoted by upstream reservoirs, especially Porto Primavera, should also be considered. Mean discharges obtained in distinct periods between 1972 and 2006 (Table II) show that it is possible to release more water to the

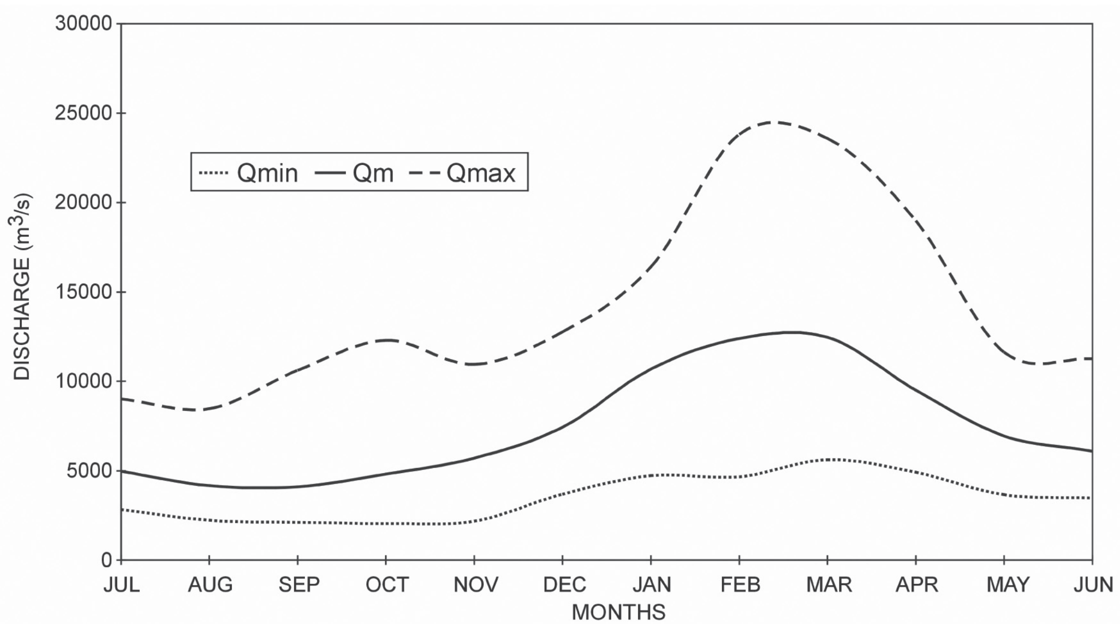

Fig. 8. Minimum (Q_{min}), mean (Q_m), and maximum (Q_{max}) monthly discharges in the period between 1920 and 1971. Data are from the station of Porto São José.

Paraná River channel, which would result in a better seasonal distribution of discharges.

Data collected in the floodplain area indicate that pristine habitats with high biological diversity and fisheries centered on large migratory fish species were abundant until the 1970s. Since then, there has been a constant increase in the control of discharge from upstream dams and in the occupation of islands and "várzeas", leading to environmental degradation and fishery depletion. However, in the 1990s, three large conservation units were created (Environmental Protected Area of the Paraná River Island and Várzea; Ilha Grande National Park and Ivinheima State Park) in the floodplain remnant, which permitted recuperation of vegetation and terrestrial fauna. Unfortunately, long-term monitoring of the same regions' aquatic fauna has not identified an equal benefit for aquatic communities. It is clear that intense flooding with low recurrence (not controlled by the reservoir) positively affects fish stocks, but that these effects are reduced by successive periods of low discharges (Agostinho *et al.* 2004a).

Therefore, efforts to restore the floodplain to pre-1971 conditions should presuppose minimum dam operations (Fig. 8). Similarly, variations in water level between morning and afternoon should not exceed 10 cm, which would minimize the negative effects of dam operation. For this goal to be reached, the problem of the Paraná River bed's transformation must be resolved. The removal of riverbed deposits has augmented the efficiency of water movements, increasing mean flow velocity (Crispim, Stevaux 2001; Martins 2004). Therefore, the new flow conditions need urgently be identified that would allow for the establishment of discharges to maintain certain water levels.

An important point remains that almost all Brazilian power plants are linked to the "Sistema Integrado Nacional" (SIN – National Integrated System; 96.5% of the electricity produced in the country), and are controlled by the "Operador Nacional do Sistema Elétrico" (Electric System National Operator – ONS). The integrated system for the upper Paraná River above the floodplain area is shown in Figure 9. Here, the dam operation is controlled by ONS, a private, not-for-profit company. The ONS is composed of members of the generation, transmission and distribution of electricity, "Ministério de Minas e Energia" (Ministry of Mining and Energy) and of consumer representatives. Although discharge control is one of the main impacts from dams, there is no representation of environmental agencies or non-government organizations (see http://www.ons.org.br). The only environmental preoccupation of the ONS is the control of catastrophic floods. The mission of the ONS is to operate SIN dams in an integrated way, with transparency, equity, and neutrality, in order to guarantee security, continuity, and fair prices for Brazilian electricity. Therefore, any dam operation protocol must be established with the ONS, which has the capacity to make all decisions regarding the upper Paraná River floodplain.

Considering the inundated area of Porto Primavera Reservoir (2250 km^2), it is possible to operate this reservoir with small variations in water level. A reduction of 10 cm in the level of Porto Primavera is enough to release an additional 6250 $m^3\ s^{-1}$ of water in ten hours. The variation of the level of Porto Primavera is not necessary if there is political interest in operating all dams above the floodplain area in a cascading fashion.

Research needed

Research, monitoring, clear goals, and clear objectives are needed to understand the complexity of hydrological processes and their interactions with the biotic and social components. Although an understanding of discharge and interactions of biotic and social components in the floodplain is fundamental, it represents only a first step in ecosystem restoration. Broadly, the reestablishment of natural discharges is incompatible with the operation of dams. This is true because the production of electricity is the cause of the spatial and temporal alterations in water distribution. The challenge to researchers is to determine a dam operation protocol that meets the needs of electricity generation and the social and environmental demands linked to the downstream floodplain. To effectively promote floods in the upper Paraná River floodplain, we need a better understanding of some hydrological, social, and environmental aspects. We must:

- Evaluate past hydrological tendencies in the Paraná River, and predict how these tendencies relate to the future.
- Estimate ecosystem responses to variations in the annual duration, amplitude, intensity, and timing of the floods.
- Estimate when annual floods will occur. There is strong evidence that the alternation of drought years and flood years plays an important role determining the reproductive success of several species (Abujanra *et al.* 2009).
- Conduct surveys of human water requirements, and their spatial and temporal variations.
- Identify potential incompatibilities regarding the use of water resources in different scenarios.
- Evaluate flexibility in the operation of upstream dams, and the impact of different operational scenarios.
- Evaluate deep-water discharge, suspended load, and water quality in Porto Primavera Reservoir near the dam, and the implications of releasing water in distinct river levels on water quantity downstream.

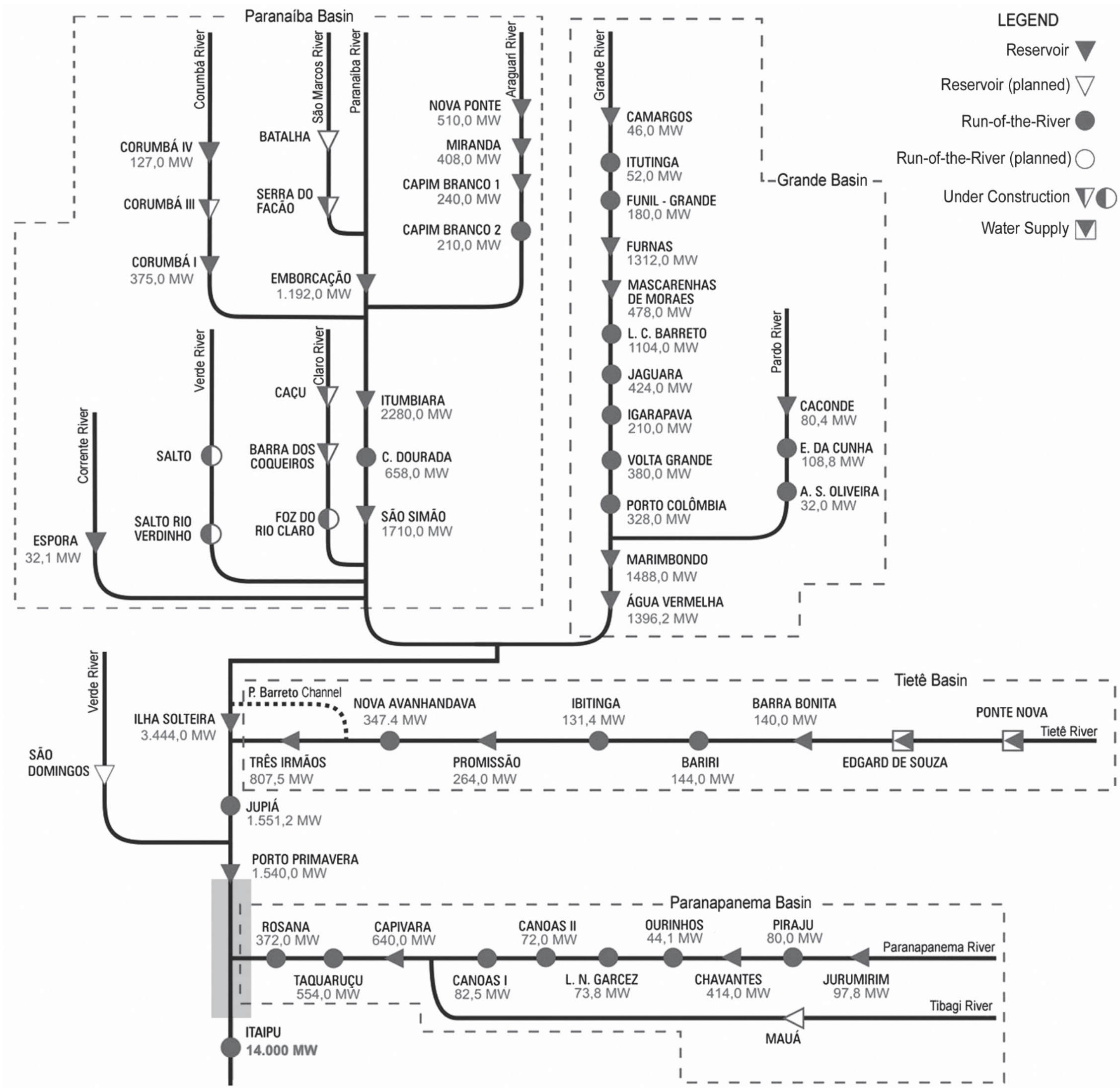

Fig. 9. Hydropower integrated system in the upper Paraná River. The shadowed area represents the remnant floodplain (from http://www.ons.org.br).

- Design an adaptive management plan. According to Richter *et al.* (2003), this should include supplementary research, monitoring, funding, governance, and adaptability.

7. Final remarks

The creation of conservation units encompassing all floodplain remnants in the upper Paraná River was successful because the units contributed to the conservation of islands and "várzeas". Use restrictions in these units have ameliorated terrestrial degradation processes that were noted ten years ago. Although enforcement difficulties persist, one decade was sufficient to reestablish vegetation and some threatened species in the units.

However, the units did not affect aquatic flora and fauna. For instance, populations of migratory fish showed clear decreases over 10 years, and large species remain rare in experimental catches. If low recurrence floods did not occur, such as those related to "El Niño" (El Nino Southern Oscillation – ENSO), these species would now be locally extinct. ENSO related floods cannot be controlled by the reservoirs above the floodplain. Therefore, floods are key phenomena for the functioning of river-floodplain systems, including the ones related to recruitment of large sized fish that sustain the fisheries. Any management or conservation schemes that do not consider floods and their importance have little chance to promote positive results.

Changes in dam operation in the upper Paraná River to simulate floods to solve problems of stock depletion and biodiversity loss in the floodplain were considered decades ago (Gomes, Agostinho 1997; Agostinho *et al.* 2000; Agostinho *et al.* 2001; Agostinho *et al.* 2004a, b; Agostinho *et al.* 2007b). We know that there is flexibility in the operation of dams to promote floods without relevant loss of electricity generation. This is clear if we compare the artificially flooded area of the basin (ca. 14 000 km^2) and the stretch that demands the flood (230 km long; <500 km^2 of floodplain). For the floodplain located below Três Marias Reservoir (São Francisco River basin), studies showed that supplemental water releases, simulating a natural flood, benefited the fishery. Economically, the benefits of water release to the fishery were greater than the gain of generating electricity (Godinho *et al.* 2007).

Therefore, it is fundamental that aquatic ecologists with knowledge of the ecohydrological approach have seats on or are heard by the regulatory institution of the Brazilian electric sector, the "Agência Nacional de Energia Elétrica (National Agency of Electric Energy – ANEEL), or in the agency that operates the sector, the ONS. Decisions of these agencies excessively affect aquatic resources in floodplain, putting the integrity of these ecosystems, their biological diversity, and the livelihoods of the families that depend on these resources at risk

Acknowledgements

We thank Jaime L. L. Pereira for re-drawing the figures, Núcleo de Pesquisas em Limnologia, Ictiologia e Aquicultura (Nupélia) from the Universidade Estadual de Maringá for supplying the infra-structure. CNPq provided grants for researchers and CNPq/PELD and UNESCO financial support.

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