Human impacts on hydrology in the Pantanal wetland of South America

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Abstract Inundation patterns in the Pantanal remain in a relatively natural state, yet a number of significant human influences have occurred in the past, and there is potential for more severe human impacts as development of the region continues in the future. The objectives of this paper are 1) to briefly review the linkages between hydrology and ecological structure and function in the Pantanal; 2) to review some documented cases of historical influences of human activities on hydrology in the region; and 3) to consider potential future impacts, particularly in regard to the recently proposed navigation project known as the Paraguay-Paraná Waterway (or Hidrovía).
Keywords Brazil; floodplain; hydrology; impoundment; navigation; Paraguay River; river

Introduction

The Pantanal is one of the world's largest tropical wetlands, occupying an area of approximately 450 by 250 km (140,000 km^2) in the Paraná River watershed of South America (Figure 1). Most of the region is in Brazil, with smaller areas in Bolivia and Paraguay. Floodplain ecosystems such as the Pantanal are defined by their seasonal cycles of inundation and desiccation, shifting between phases with standing water and phases in which the soil surface is dry and the subsurface water table may fall to well below the rooting zone. The spatial and temporal patterns of floodplain inundation vary within and among the large floodplain systems of South America (Hamilton *et al.*, in press), and this variation has numerous ramifications for ecological structure and function, as articulated in the Flood Pulse Concept (Junk *et al.*, 1989).

Inundation patterns in the Pantanal remain in a relatively natural state, yet a number of significant human influences have occurred in the past, and there is potential for more severe human impacts as economic and industrial development of the region continues in the future. The objectives of this paper are 1) to provide a brief overview of the linkages between hydrology and ecological structure and function in the Pantanal; 2) to review some documented cases of historical influences of human activities on hydrology in the region; and 3) to consider some potential future impacts, particularly in regard to the proposed navigation project known as the Paraguay-Paraná Waterway (or Hidrovía). A more complete overview of the linkages between hydrology and ecological structure and function in the Pantanal, including extensive literature citiations, can be found in Hamilton (in press).

Scientific studies have been carried out mostly in the Brazilian Pantanal; the Bolivian and Paraguayan portions are generally more remote and remain much less studied. A rich body of research on the Pantanal exists in the Brazilian scientific literature, written largely in Portuguese. The English-language literature contains a number of reviews of scientific information on the Pantanal that vary in their emphasis, including plant and animal life (Heckman, 1998; Junk and da Silva, 1995), environmental problems and management (Mittermeier *et al.*, 1990, da Silva, 2000), and the potential impacts of navigation projects in the Paraguay River system (Ponce, 1995; Hidrovia Panel of Experts, 1997). The

increasing international attention paid to the Pantanal has accelerated scientific progress through multinational research programs, and has also led to important conservation initiatives by governmental and non-governmental organizations. The recent designation of the Pantanal by UNESCO as both a Biosphere Reserve and World Heritage Site should help to further focus international attention on the region.

Hydrology of the Pantanal and its watershed

The climate of the Pantanal is tropical with a marked wet season. Annual rainfall is 1,000–1,500 mm across much of the watershed, with most rain falling between November and March. The upland drainage basin surrounding the Pantanal occupies 356,000 km^2 and consists of elevated plateaus and low mountains to the north and east (250–1,200 m
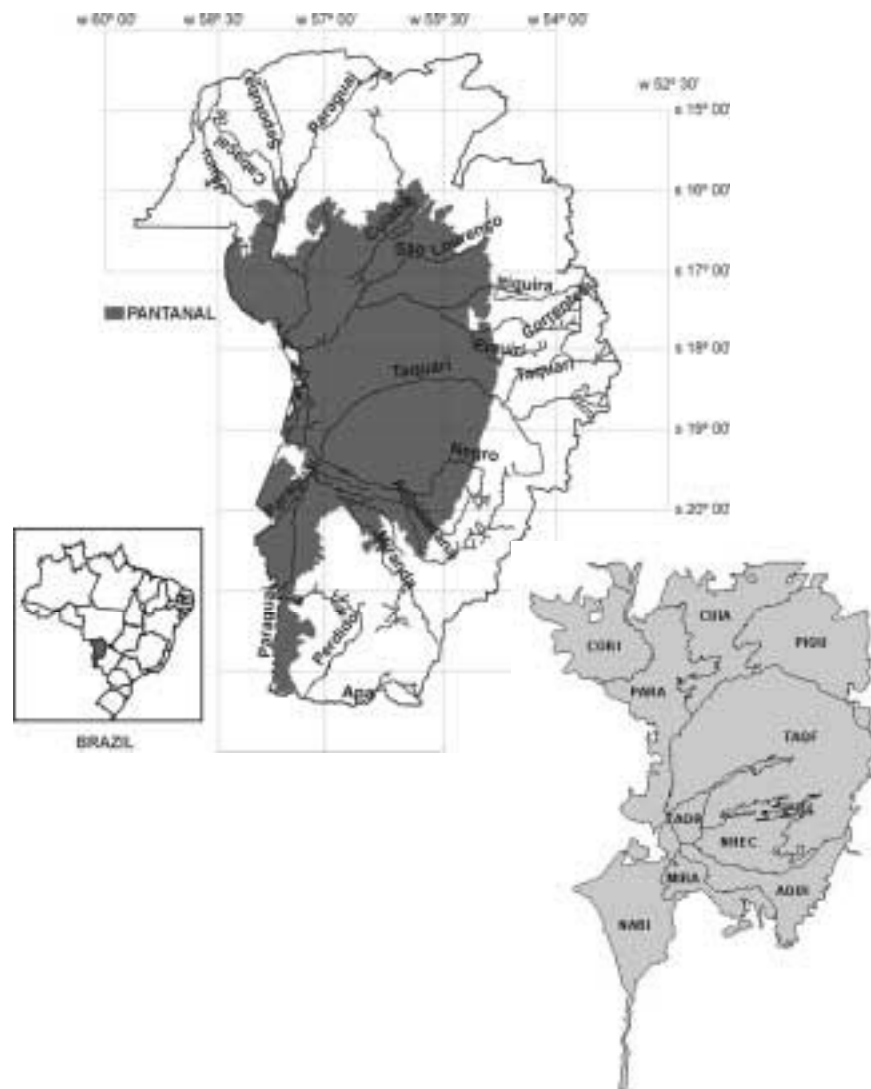

Figure 1 Major rivers of the Pantanal and its upland watershed in Brazil (upper map; modified from PCBAP 1997), and hydro-geomorphic subregions within the Pantanal floodplains as delineated by Hamilton *et al*. (1996). Subregion codes are as follows: CORI = Corixo Grande; CUIA = Cuiabá; PARA = Paraguay River; TAQF = Taquari Fan; TAQR = Taquari River; NHEC = Nhecolândia; MIRA = Miranda; AQUI = Aquidauana; NABI = Nabileque

elevation) and flat plains to the west. Rivers in the Brazilian uplands have much steeper gradients with relatively little floodplain, and they deliver most of the water and sediment to the Pantanal. Their discharge regimes reflect the seasonality of rainfall. In contrast, the much flatter uplands to the west in Bolivia and Paraguay normally contribute little water to the Pantanal; they receive less rainfall, and a larger proportion of this water is lost by evaporation and infiltration. The hydrology of the upland and floodplain river network remains largely unregulated, although a large dam on the Manso River (an upland tributary of the Cuiabá River) has recently been completed.

Major upland tributaries of the Paraguay River flowing into the Pantanal include the Jaurú, Cuiabá-São Lourenço, Taquari, and Miranda rivers, all draining Brazilian territory (Figure 1). The Abobral River drains a floodplain area located between the Taquari and Miranda rivers, and its discharge is highly seasonal. Several other floodplain watercourses can carry substantial discharges during inundation and are locally denominated as rivers. For example, the Paraguai-mirim and Nabileque rivers collect water primarily from overbank flow of the Paraguay River, although they also receive water from adjacent floodplain areas.

The Paraguay River runs from north to south along the western side of the Pantanal, collecting water from the various tributaries and non-channelized floodplain flow paths (Figure 1). Water levels in the Paraguay River fluctuate seasonally by 2–5 metres; water level fluctuations in most other parts of the Pantanal are less than this. The major tributary rivers can lose much of their discharge to the floodplains at high stages, resulting in a strong attenuation and delay of the flood pulse, and depending on the location the water lost to the floodplain may or may not be regained by the tributary channel before reaching the Paraguay River. The Paraguay River itself loses substantial discharge to the floodplain in certain reaches, particularly in the north above its confluence with the São Lourenço River. On a regional and annual scale, about half of the flood waters is lost to evapotranspiration but a roughly similar amount is gained via precipitation directly onto flooded surfaces (Hamilton *et al*., 1997).

The Pantanal contains a variety of floodplain subregions with distinct geomorphological, hydrological and ecological characteristics. Hamilton *et al*. (1996) delineated 10 subregions on the basis of hydrological and geomorphological differences (Figure 1). Flooding in all subregions is distinctly seasonal, but the flood seasons vary because the flooding period may be delayed for as long as 6 months after the rains due to slow passage of floodwaters through the Pantanal. Many areas are flooded by riverine overflow and are thus true floodplains, while other areas normally flood with local rainfall, although their geomorphological origin may be alluvial. Hamilton *et al*. (1996) analyzed passive microwave remote sensing observations made by satellite from 1979–87 to reveal inundation patterns throughout the Pantanal. The flood pulse is typically unimodal in most of the Pantanal, although more erratic patterns are often observed in the floodplains of the southern Pantanal, particularly those affected by the Miranda and Aquidauana rivers. Areas where flooding is controlled by the Paraguay River show the most regular, predictable flood pattern. The total area inundated at a given time fluctuated between 10,000 and 110,000 km^2 during 1979–87.

Rainfall shows considerable interannual variability, which in turn causes variability in the flooding patterns. Multiyear series of higher or lower rainfall dramatically affect the flooding in the region (Hamilton *et al*., 1996). A comparative study of inundation patterns showed that interannual variation in flooding is greater in the Pantanal than in five of the other major floodplains of South America (Hamilton *et al*., in press). The Paraguay River level at Ladário provides a good indication of overall flooding in the region because of its central location along the Paraguay River axis. Hamilton *et al*. (1996) used the relationship

between stage of the Paraguay River and area inundated throughout the Pantanal during the 9 years of satellite observations (1979–87) to extend the inundation record over the period of stage records (1900–95); that record is further extended to 2000 in Hamilton *et al*. (in press). Occasional prolonged dry periods are apparent from this inundation record, with the longest in the record occurring between 1960–73, but the annual flooding has been relatively predictable during the last quarter of the century.

The progress of floodwaters through the Paraguay River system is likely to be regulated by occasional geomorphological control points (Ponce, 1995). These control points may be composed of resistant bedrock, gravel, clay lenses, or conglomerates that confine the river channel, preventing further excavation and/or widening of the channel to accommodate excess discharge. Although the locations of all of these control points remain uncertain, their existence can be inferred from the water surface profiles of the major rivers. Because of the low elevational gradients within the Pantanal, backwater effects control river water levels and thus floodplain inundation (Hamilton, 1999). The occasional control points affect water levels not only in the river channels but also in adjacent floodplains and tributary courses. Water levels of the tributaries are controlled by the Paraguay River near their confluences. The peak discharge of these tributaries tends to occur earlier than that of the Paraguay River, and the later rise of the Paraguay impounds the lower courses of the tributaries, decreasing their current and sometimes even reversing their flow temporarily. Thus the highest water levels in the lower courses of these tributaries do not necessarily correspond with their peak discharges. This backwater effect extends for considerable distances upriver.

Hydrological controls on ecological structure and function

Much attention has recently focused on the importance of natural flow regimes, including particularly their range of variability, in maintaining or restoring river and stream ecosystems (Poff *et al*., 1997). River regulation projects such as dams and navigation works have tended to reduce the range of variability in natural flow regimes, resulting in long-term changes in channel geomorphology, river-floodplain connectivity, and riparian and floodplain vegetation. Research on relatively unaltered tropical floodplains such as those of the mainstem Amazon River and the Pantanal in Brazil has underscored the importance of the natural regime of seasonal inundation, referred to as the flood pulse, as the primary force controlling the structure and function of floodplain ecosystems (Junk *et al*., 1989; Junk, 1997; Hamilton, in press).

The principal hydrological processes that are likely to control ecological structure and function in the floodplains of the Pantanal can be deduced from work on other fluvial systems as well as the existing body of knowledge for the Pantanal. The salient hydrological characteristics of the seasonal flood pulse include frequency (generally once per year in most subregions of the Pantanal: Hamilton *et al*., 1996), depth of inundation (ranges from <10 cm to 2 m or more; overall the mean depth of maximum inundation is probably around 0.5 m), and the duration of inundation (variable but usually continuous over 1–2 months or longer). The sources of flood waters are also ecologically important, as river overflow tends to be richer in dissolved and suspended materials compared with floodwaters originating as rain that falls directly on the floodplain (Junk and da Silva, 1995). Flow paths across the floodplain are important because river waters can lose their nutrients and suspended material as they flow across the floodplain. Finally, the severity of the dry season is important to consider as well; this is dictated not only by the duration of inundation but also by the timing of inundation relative to local rainfall, and by the nature of the soils. For example, in the northern Pantanal inundation coincides approximately with the wet season, while in the southernmost floodplains, inundation occurs during the local dry season (Hamilton *et al*., 1996).

The high species diversity and biological productivity of the tropical floodplain ecosystem is explained by the seasonal inundation, which maintains a spatially and temporally variable environment with both aquatic and terrestrial characteristics (Junk *et al.*, 1989). Periodic inundation also brings nutrients to the floodplain ecosystem, stimulates nutrient fluxes, and maintains plant communities in early stages of community succession. Measurements of the primary productivity of aquatic vascular plants in the Amazon floodplain reveal that these plant communities rival the productivity of the most intensively managed agricultural crops in spite of the seasonally changing conditions (Junk, 1997).

Floodplains such as the Pantanal seem to be in a constant state of disturbance, and many of the plant and animal species must be resilient to flourish in such an environment. However, the predictability and extended duration of the seasonal flood pulse has allowed organisms to adapt to it (Junk *et al.*, 1989). The regular occurrence of seasonal inundation invokes a pulse stability to the floodplain ecosystem (sensu Odum, 1969: Mitsch and Gosselink, 2000). The greatest diversity and abundance of wildlife occur in areas subject to partial inundation, probably because these areas offer habitat for both terrestrial and aquatic animals throughout the year, and tend to support a mosaic of forest, savanna and marsh environments.

Past and current impacts of human activities on hydrology

The following discussion summarizes the most important environmental changes that result from anthropogenic hydrological alterations, which include erosion and sedimentation, interference with natural openings in river levees, construction of raised roads and dikes, impoundment of upland tributaries, and river channel alterations to facilitate navigation.

As a result of changing land use in the uplands, accelerated erosion and sedimentation of rivers that enter the Pantanal has evidently already occurred (Godoy *et al.*, 1998). A large proportion of the upland basin has been converted from natural *cerrado* savanna to managed pasture or intensive agriculture during the past 25 years, which greatly increases erosion rates and may alter runoff patterns as well. Many areas in the *Planalto* have been completely deforested. There is considerable anecdotal evidence that sedimentation of the rivers has reduced fish populations and made the rivers less navigable (e.g. Emory, 1985). The problems seem to be particularly acute in the Taquari, Piquiri, and São Lourenço river systems. In the case of the Taquari basin, the soil erosion is evidently most severe in areas used for pasture, as opposed to those converted to row-crop agriculture. In the lower part of the Taquari River fan, occasional changes in the river course in recent decades have considerably altered the distribution of flooding, and these changes may be related to the increased sediment load of the river. However, the levee openings where water exits the main channel towards the floodplain have historically been manipulated by local residents, including excavation during the dry periods to bring water to outlying areas and infilling with dredge spoils during wet periods to reduce inundation. Accelerated sedimentation of the river bed could have enhanced the geomorphological instability of the river channels, but the geomorphology of the Taquari system has apparently always been dynamic, as evidenced by historical maps of the river channels.

Construction of raised roads within the Pantanal can have serious ecological consequences. As recently as 1981–83 regional development plans included an extensive network of ca. 800 km of roads to be built within the Pantanal (Emory, 1985). Most of these roads were not constructed but the *Transpantaneira* did reach the São Lourenço River from Poconé. In addition to increasing access to the region, raised roads often alter the natural hydrological flow patterns during inundation, particularly if they do not run parallel to the direction of water flow. Even when occasional culverts or bridges are present, a difference

in water level between the upstream and downstream sides of roads is often visible, and eventually the vegetation may develop differences. Decreased flow of floodplain waters reduces the nutrient supply and often leads to greater probability of oxygen depletion, particularly where dissolved oxygen concentrations are low under normal conditions (Hamilton *et al*., 1995). On the other hand, the numerous borrow pits created for construction of raised roads can be important permanent water bodies during the dry season for aquatic and terrestrial wildlife. The attraction of wildlife to the vicinity of roads has positive and negative consequences; animals are more readily viewed by tourists but are also more susceptible to disturbance and mortality by vehicles and poaching.

Raised dikes have been constructed in a few places in the Pantanal to exclude flood waters, including a 60,000-ha area at Ilha Camargo in the Cuiabá subregion that was diked in the early 1970s (Emory, 1985). The Ilha Camargo project is generally regarded to have caused negative environmental effects, resulting in problems with undesirable plant species invading the diked area, diminished carrying capacity of the land for cattle, and possibly increasing flood levels outside of the dikes. Another diked area was constructed along the Paraguay River downriver of Ladário; the dike was to be part of the Transpantaneira Highway and the floodplain inside the diked area was to be used for agriculture. This project is also regarded as a failure; the land was not found to be useable, and the dike is now open to allow exchange of water with the river. However, the dike still interferes with natural flow patterns, and waters within the diked area are typically stagnant compared with natural floodplain areas.

Potential future impacts of human activities on hydrology

A number of dams have been proposed for the tributary rivers entering the Pantanal, including the Sepotuba, Cuiabá, Itiquira, and Taquari river systems. So far the only significant dam was completed in 1998 on the Manso River, a major tributary of the Cuiabá River. This and the other dams were originally proposed in the 1970s for the primary purpose of flood control, although the Manso Dam is also a hydroelectric facility with 210 MW of installed generating capacity. At the time of this writing (2001), the Manso reservoir was still filling; the dam was closed in late 1999. Downstream impacts of the Manso Dam have yet to be studied but will certainly include altered flow and flood regimes in the Cuiabá subregion of the Pantanal, where flood waters across much of the area are supplied by overbank flow from the Cuiabá River. There is no indication of active plans to build any other significant dams in the region.

A recently proposed navigation project known as the Paraguay-Paraná Waterway (or Hidrovía) would modify the Paraguay River channel to facilitate year-round navigation of barge trains through the Pantanal. The river channel alterations required for this project have aroused concerns about the potential environmental impact on adjacent floodplains (summarized by Hidrovía Panel of Experts, 1997; Gottgens *et al*., 2001). The potential direct hydrological impacts of navigation projects within the Pantanal may be grouped as follows: 1) destabilization of the river channels; 2) degradation of riparian areas; and 3) alteration of river-floodplain exchanges of water, materials, and aquatic animals.

Perhaps the greatest risk inherent in any modification of the channel of a large river involves changes in the geomorphological controls that regulate the river's velocity, discharge, water surface elevation, and sediment load. For example, enlargement of the channel at its control points may lead to faster flow, resulting in more rapid drainage of water and a less equitable distribution of discharge over the course of the year (Ponce, 1995). Once the control points are altered, the river channel is likely to become unstable as it attempts to reach a new equilibrium. Lateral channel migration rates are likely to increase (Drago, 1990), impacting gallery forests and other riparian areas.

The role of the river channels as habitat for aquatic animals is particularly critical during the dry season and during fish migrations. During the dry season, inundated floodplain may persist only in certain areas close to the main river channel, such as the vicinity of the larger lakes and around the confluences of the Cuiabá-São Lourenço and Paraguay rivers (Hamilton, 1999). These areas serve as refuges for fishes, water birds, caiman and other animals that depend on aquatic environments, including endangered species such as the Giant River Otter. Given that the inundation area in the Pantanal can be reduced by a factor of 10 between high and low water (Hamilton *et al*., 1996), aquatic animals can become highly concentrated in these refuges. The survival of these animals is critical to provide populations to disperse into the newly flooded environments in the following high-water season (Welcomme, 1985). Some terrestrial animals habitually stay near permanent water bodies as well, such as the Jaguar and the Marsh Deer (Quigley and Crawshaw, 1992). During extended dry periods, these refuges must become even more important.

The riparian areas, which are often the highest ground on the floodplain and generally support gallery forest, are critical components of the floodplain landscape. They are also the terrestrial environment that would be most severely impacted by dredging activities, spoils deposits, construction of navigation infrastructure, and enhanced erosion of river margins. The gallery forests contain many plant species that are not found in the more low-lying areas, and their species composition is just beginning to be documented. Floodplain forests contain a unique combination of tree species that tolerate the seasonal alternation between soil saturation and desiccation, and any long-term changes in either the inundation or dry phase could alter their species composition.

Destruction of the gallery forests would represent a serious loss of habitat for wildlife. They are often important as a dry refuge for terrestrial animals during high water. Fragmentation of the gallery forests would interrupt an important wildlife corridor used by animals such as capybaras and large cats, which need to migrate to avoid seasonal flooding (Mittermeier *et al*., 1990). The gallery forests are also used as roosting and nesting sites by many species of water birds that forage in the river or backswamp environments. The gallery forests are important sources of food for certain riverine fishes which are adapted to feed on fruits and seeds from trees and shrubs, particularly during high water (Goulding, 1980).

The gallery forests are important in stabilizing the river banks, greatly increasing the resistance of the banks to erosion by anchoring the levee soils with their root systems and by reducing current velocities over the levees. A strip of floating aquatic plants such as water hyacinths (*Eichhornea* spp.) typically grows between the gallery forest and the river channel, providing protection to fishes and other aquatic animals and buffering the erosive action of waves and currents; in many reaches, the forest may be necessary to anchor this vegetation along the bank. Removal or degradation of the forest vegetation is likely to result in more rapid rates of lateral channel migration, such as those observed in the largely unforested Middle Parana River floodplain in the vicinity of Santa Fe, Argentina (Drago, 1990).

River channel alterations for navigation could potentially alter river-floodplain exchanges of water, materials, and aquatic animals. The Paraguay River in the Pantanal is distinct from other large rivers of the world because of the very high proportion of its discharge that contacts the floodplain, either before or after entering the main channel (Hamilton *et al*., 1997). Exchanges of water between the river and the floodplain occur through channels that pass through occasional breaks in the levees (tie channels) or as non-channelized flow across lower spots along the levees. These exchanges are complex and often display seasonal changes in flow direction at a particular point, depending on the relative levels of the river and floodplain.

Significant alterations in river levels and discharge patterns will affect these river-floodplain exchanges (Hamilton, 1999). The net ecological impact of such changes is likely to be negative for floodplain environments if riverine through-flow on the floodplain is reduced, if drainage of floodplain waters back to the river is accelerated, or if the annual flood pulse becomes less predictable (Junk *et al*., 1989). Reduced riverine through-flow would result in reduced nutrient supply to and oxygenation of floodplain waters; stagnant floodplain waters are frequently noticeably less productive, containing sparser and more stunted aquatic plants and fewer large fishes. Accelerated drainage of the floodplain would reduce the hydroperiod, thereby invoking changes in floodplain vegetation and increasing the severity of the dry season for biota dependent on aquatic environments (Junk *et al*., 1989). Invasion of the floodplain by woody plants may occur more commonly, decreasing the value of these areas as natural pasture and encouraging more disruptive land management practices by ranchers.

By deepening and straightening the main channel of the Paraguay River, navigation projects such as the Hidrovia could result in lower water levels with respect to the adjacent floodplain (Hamilton, 1999). Even a seemingly small mean decrease of ca. 20 cm could dramatically affect the amount of river water exiting the main channel, and might reduce the total area of floodplain that is inundated at a given river discharge. The backwater effects that are presently propagated far up the tributary courses might be reduced. Large-scale changes in floodplain vegetation, wildlife populations, and fish production could ensue.

Once a navigation project such as the Hidrovia is established, economic interests will be dependent on year-round navigability of the Paraguay River. In times of drought, there will be strong pressure to restrict outflows from the main channel to maintain better conditions for navigation. This has already been attempted in the Pantanal, as for example when the tie channels feeding the floodplain leading to the Paraguai-mirim River system were blocked during the 1960s to reduce water losses from the main channel. Such actions are easily implemented but could result in untold ecological damage to downstream floodplain ecosystems.

The extent of floodplain that might be influenced by channel alterations of the Paraguay River is difficult to determine precisely, but it is likely that the entire western half of the Pantanal along the Paraguay River axis would be affected (Hamilton, 1999). Significant portions of the Corixo Grande, Taquari River, lower Cuiabá, and lower Negro-Aquidauana subregions would also be affected if backwater effects are reduced or eliminated. Together these areas comprise much of the total floodplain area in the region that is subject to deeper, longer lasting inundation (Hamilton *et al*., 1996). Areas that are least likely to be affected include the Taquari Fan, Piquiri-São Lourenço, and Miranda subregions, and upper portions of the Corixo Grande, Cuiabá, and Negro-Aquidauana subregions.

In conclusion, the ecological structure and function of Pantanal ecosystems are intimately tied to the hydrological regime of seasonal inundation and desiccation. The considerable spatial variability in hydrological regimes explains many of the ecological differences among subregions. Conservation and management of these floodplain ecosystems requires consideration of the natural hydrological regime and its range of variability. Projects resulting in hydrological alterations, such as dams, raised roads and dikes, and river channel alterations for navigation, require careful analysis of their potential environmental impacts. Alternatives that cause the least perturbation of the natural flood regime should be adopted whenever possible.

In the United States and Europe, large floodplain rivers have been extensively altered for navigation, hydropower, and floodplain "reclamation", and the consequent losses in natural resources and ecosystem services are only now being fully appreciated. For

example, using the Illinois River (a major tributary of the Mississippi River) as a case study, Sparks *et al*. (2000) have demonstrated how the historical reengineering of the river channel for navigation and flood control led to the degradation of important river fisheries and ultimately created a host of environmental problems. Throughout the Mississippi River system, alternatives to structural flood control are now being seriously considered as evidence accumulates to suggest that the overall effect of engineering modifications of the river system has been to exacerbate the magnitude of large floods and their resultant costs to society. Some degree of restoration of the original hydrological connectivity between the river channels and their floodplains is now considered a viable and attractive option. In the case of the Pantanal and other large floodplain river systems that still retain their natural hydrology, economic development must be planned with ample consideration of the mistakes of the past in other great rivers of the world, lest that unfortunate history be repeated.

Acknowledgements

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