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Contrasting the Middle Paraná and Mississippi Rivers to develop a template for restoring large floodplain river ecosystems

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ABSTRACT

Effective rehabilitation of large rivers requires a concept of normal floodplain river behavior – the reference condition – to understand system-level disturbance history and to develop plans to improve river health. However, reference conditions are difficult to obtain for large rivers. Using Correspondence Analysis of a select subset of the world's great rivers, we show that the Paraná and Mississippi Rivers are relatively similar at the watershed scale based on general geographical and physico-chemical variables, although these rivers differ substantially in disturbance history. We believe that the less disturbed Paraná River provides reference conditions for the more disturbed Mississippi River for some processes and functions whereas the Mississippi River provides a compelling vision of the future state of the Paraná River unless sustainable development plans are developed and implemented. By integrating information between them, this pair of rivers provides a unique opportunity for scientists to develop more robust conceptual models and improved deterministic models to better guide river management and rehabilitation actions. We suggest that development of large river reference conditions may be better obtained through expanded inter-hemispheric scientific collaboration on multiple systems than through increased focus on a single impacted system.

Keywords: Mississippi River; Paraná River; river restoration; river ecosystems; floodplain rivers.

1 Introduction

Large flood plain rivers occupy major portions of continents and may cross numerous geological, ecological, and political boundaries. They are dynamic systems integrating terrestrial and fluvial processes nested in spatial scales from continental to local, all set against a backdrop of climatic pattern, geological history and antecedent disturbances. Their processes may be driven by a range of temporal scales of hydrology, weather, and climate that span hours to millennia. The fish and wildlife communities they support are often ancient and diverse and are linked to river processes in ways that resist easy discovery and description. The sheer range in inherent temporal and spatial scales that characterize the world's great rivers make them a challenge to monitor and manage and an even greater challenge to restore once altered by human activity.

Large flood plain rivers have been severely altered by river regulation (Petts *et al.*, 1991). The timing and magnitude of their flows have been altered by abstraction, impoundment, and land use changes. Their geomorphology has been altered directly by impoundment, dredging, construction of channel training structures and levees, filling of backwaters, and fragmentation by dams. Their geomorphology has been indirectly impacted by basin land use alterations that affect sediment dynamics and groundwater recharge. Biogeochemical cycles, tied to geomorphology and inputs of nutrients, organic matter of different forms, sediments, and contaminants from the watershed, have been similarly disrupted.

The normal functioning of many of the world's great floodplain rivers is disrupted because the blend and scaling of processes that characterize them in their natural states have been shifted to new states (Petts *et al.*, 1995). The new states are often unsustainable, characterized by major environmental quality problems, and seldom provide the template of physical and chemical conditions necessary to support native biodiversity. River restoration planning is hindered by limited understanding of mechanisms regulating large floodplain river ecosystems and, therefore, resource managers lack knowledge of the proper blend and scaling of processes constituting river health. Without this knowledge and understanding, restoration activities may easily degrade into unending series of expensive, ecologically ineffective, disjointed, potentially conflicting "techno-fixes" focused on a limited number of species in isolated river segments. Concern about ecological health and integrity of large floodplain rivers has

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stimulated considerable debate on how best to restore them (for brevity, we use restoration and rehabilitation interchangeably, but restoration implies return to a previously existing state whereas rehabilitation implies improvement, or naturalization, towards a new target state).

System-level disturbance history cannot be understood and recovery cannot be effectively planned without a concept of normal behavior of flood plain rivers (Sparks *et al.*, 1990). Normal behavior is best understood by studying real systems – the reference – to develop a template to guide restoration planning because the present state-of-the-art in ecosystem forecasting is insufficient to "design" an ecosystem in the same way that farmland is managed. A reference represents the desired future state of the river to be achieved through restoration and thereby embodies integrated, system-level goals for river restoration. Goals for river restoration, when not considered at a system level using a reference river, are typically lists of localized objectives that, as a group, may be unsustainable, mask inherent trade-offs, or worse, contain mutual exclusivities. A reference provides knowledge about interactions of critical physical and chemical processes, subsequent biological responses and feedbacks, the role of multi-scale temporal and spatial variability, and other information necessary to characterize a desired future state.

Two broad categories of references are possible: physical and virtual. A physical reference system can be a historical condition or an existing system. Historical conditions may appear to be the best source of reference information, but typically are inadequately supported by data or represent an unrealistic goal because of irreversible land use changes in the basin or commitments to water resources development strategies that preclude return to historic conditions. Some opportunities exist for exploring historical conditions using pre-settlement geomorphic information (such as is available for the Upper Mississippi River) supplemented with process information from the present system. A self reference is possible under two conditions. First, an impacted system may contain one or more smaller subsystems that can be shown to exhibit either historical conditions or non-historical conditions that appear desirable to society and sufficiently sustainable to guide restoration of the larger system. For example, although smaller in scale, the Chippewa River in Wisconsin, a tributary of the Mississippi River, is still connected to its floodplain and could be studied as a physical reference for the upper Mississippi River. Second, extreme events in an impacted system can also be used to partially understand natural processes and functioning. For example, the flood of 1993 in the highly regulated Missouri River can be considered a reference point to gain insight into biotic response and habitat recovery during a flood pulse within the limitations of such a setting (Ward *et al.*, 1999). Self-references, while useful, do not provide the comprehensive, system-level guidance because of their small relative size or short duration. References near the impacted system are preferred but, unfortunately, most continents contain only one or a few large, floodplain rivers. The use of reference conditions from other continents has not been considered, but could provide useful information.

Virtual references are of two types: conceptual and mathematical. A conceptual reference may be based on guiding principles extracted from studies of many rivers that vary in size and setting. Alternatively, a conceptual reference may be created by a description and analysis of historical impacts and disturbances relative to regional restoration priorities (e.g., The *Habitat Needs Assessment* for the Upper Mississippi River, Galat *et al.*, 1998). Unfortunately, conceptual references lack the operational detail necessary to identify specific management actions or are insufficiently quantitative so that feedback and mutual exclusivities in processes cannot be evaluated. For example, many of the general concepts presently used to describe large rivers were developed on studies of the Amazon River.

A mathematical reference can be constructed to explore possible system states and ultimately develop a set of ecosystem attributes that are sustainable, system-level, and socially desired in lieu of a physical reference condition. However, a mathematical reference requires data from a relatively undisturbed system for model formulation, calibration, and validation. Use of a mathematical reference constructed by hind casting to data from a highly impacted system is tenuous because the accuracy of the forecasted, restored condition is unknown. Use of a mathematical reference is the most challenging of the reference alternatives and, unfortunately, the most needed because societal pressures and associated practical considerations generally prevent restoration to a historical condition and because other types of references have the liabilities described above.

Our goal is to explore the possibility that reference conditions developed for a less disturbed large floodplain river in one continent (South America) may have applicability to guide restoration of a large river located in another continent (North America). If successful, this approach may overcome the usual limitation on finding reference conditions on highly disturbed systems and provide a unique opportunity for scientists to develop more robust conceptual models and improved deterministic models to better guide river management and rehabilitation.

2 Method

We use correspondence analysis (Greenacre, 1993) of data summarized in Esser and Kohlmaier (1991) on general physical, chemical, and watershed characteristics to uncover and explore similarity patterns of the world's large rivers. Correspondence analysis is based on chi-squared tests (X^2) to measure discrepancy between observed frequencies in a contingency table and the expected frequencies calculated under the hypothesis of homogeneity of row or column profiles. Such discrepancy is expressed in term of inertia and can be interpreted as the weighted average of squared X^2 distances between the row profiles and their average profile or equivalently between the column profiles and their average. Results are displayed in two-dimensional scaled maps to explain the inertia (variation) along the first and second axis. Correspondence analysis results were supplemented and confirmed with data ranging from qualitative, worldwide categorizing frameworks (e.g. Depetris and Paolini, 1991; Welcomme,

1985) to comparisons of specific variables such as carbon and mineral transport (Degens, 1982; Degens and Ittekot, 1985; Degens *et al.*, 1983; Degens *et al.*, 1985; Degens *et al.*, 1987). We did not include the Amazon River in the analysis because the sheer size and diversity of its immense basin places it in a category by itself – e.g., it has more than 10 times the discharge of the Mississippi or Paraná Rivers and its basin spans the eastern slope of the Andes Mountains to the tropics.

3 Results

3.1 Quantitative similarity patterns

Correspondence analysis explains 90% of the total inertia in the data set with axis 1 explaining 60% (comprised primarily of elevation, litter content, and watershed area) and axis 2 explaining 18% of the variability (comprised primarily of mean annual temperature, DOC, mean discharge, precipitation, and evapotranspiration). The analysis further shows that some rivers group into clusters. Some of these groupings are expected, such as the group that includes the Rhine and Columbia Rivers because both occur at about the same latitude and elevation. However, more surprising was the strong similarity between the middle reaches of the Paraná River and the Mississippi River (Figure 1). The similarity between the Mississippi and Paraguay Rivers (a major tributary of the Paraná River) in scale, flow, and geomorphology has been previously recognized (Gottgens *et al.*, 2001; Grubaugh and Anderson, 1989). In addition, both the Upper Mississippi and Paraná Rivers have been extensively studied so that considerable data are available for analysis and model development. The Paraná River also groups close to other rivers such as the Nile, suggesting that some additional data could be available from these less-intensively sampled rivers to supplement information from the Mississippi and Paraná Rivers.

Correspondence analysis results also reveal that rivers on different continents may be more similar than rivers on the same continent. In South America, for example, the Orinoco and Middle Paraná Rivers are not as similar as the Mississippi and Paraná Rivers. Even though the Orinoco River has a large natural floodplain, hydraulic connection to its floodplain is not as well developed as the connection of the Middle Paraná River to its floodplain. Reduced connectivity reduces organic carbon export from the floodplain to the main channel of the Orinoco River (Lewis *et al.*, 2000) making the Orinoco River a poor choice for physical reference for either the Mississippi or Paraná Rivers.

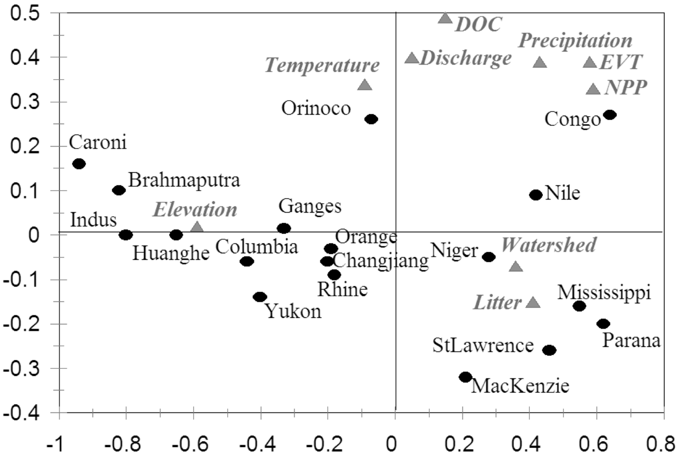

Figure 1 Resemblance among large rivers as shown by Correspondence Analysis (data from Esser and Koklmaier, 1991).

3.2 Qualitatively contrasting the Mississippi and Paraná Rivers

Both rivers generally flow north and south, although the Mississippi River flows from a temperate to subtropical area whereas the Paraná River flows from subtropical to warm temperate area. Watershed area is an important variable because it is a correlate of river length and discharge and, therefore, affects potential input of nutrients, organic matter, floodplain development, nutrients spiraling, flood pulses, biotic adaptations, and other factors that are scale dependent (Spink *et al.*, 1998). Below, we provide parallel summaries of the general hydrology, geomorphology, and nutrient dynamics of these two floodplain rivers as a prelude to describing how complementary information of management value can be obtained from the two systems. We concentrate on the Paraná River because it is less known than the Mississippi River and because its less disturbed condition enhances its value as a reference for flood plain river restoration.

3.2.1 The Mississippi River case study

The Mississippi River is the largest river in North America with a drainage area of 4,759,049 km^2 and flows 3,730 km from its northern headwaters at Lake Itaska in Minnesota southward to Louisiana where it splits into several distributaries that empty into the Gulf of Mexico (Figure 2). Different segments have been identified based on natural geomorphology (Fremling *et al.*, 1989). The headwater reach starts in Lake Itaska and ends at St. Anthony falls and comprises eleven lock and dams that substantially affect stage but not flow and six headwater reservoirs that marginally affect flow. The Upper Mississippi River (UMR) flows from St. Anthony Falls to the Missouri River junction and is modified from its natural condition by 29 navigation dams, wing dikes, revetted banks, and other channel modifications for improved navigation. Channelization and construction of levees and dikes force flows into the main channels so that side channels are abandoned or have limited hydraulic connection to the main channel. Discharge in this reach generally varies with rainfall because reservoir storage is limited. Navigation dams have insufficient storage to affect discharge, but they have substantial impact on water level so that the main channel, side channels, and floodplain maintain high water levels during most of the year. Dams have increased the area of inundation during seasonally low discharge from 971 km^2 before dams to 1495 km^2 after dam construction, permanently submerging 23 percent of historic wetlands and seasonally inundated floodplain (Schramm, 2004). Maintenance of artificially high water levels affects temporal patterns of habitat availability, habitat connectivity, transport of nutrients, sediment dynamics, and primary and secondary production. For example,

Figure 2 Location map of the Mississippi River system.

maintaining a minimum water level to allow commercial navigation prevents summer dewatering of shallow floodplain areas and germination of emergent aquatic vegetation.

The upstream boundary of the Middle Mississippi River is at the mouth of the Missouri River and the downstream boundary is at the mouth of the Ohio River. In this reach, levees reduce flooding, but also limit hydraulic connection to, and surface area of, the flood plain. Wing dikes and revetments constrain the main channel. Secondary channels are commonly perched above the main channel and often dewatered during low flow periods. Throughout the 1,000 km of this reach, levees have severed connection of the river from 90 percent of its historic 103,000 km^2 floodplain (Schramm, 2004).

The Lower Mississippi River extends from the Ohio River confluence downstream to Head of Passes in Louisiana where the majority of flow from the Mississippi River enters the Gulf of Mexico. A substantial amount of flow is diverted from the Mississippi River to the Atchaflaya River at the Old River Control Structure. The lower Mississippi River includes remnant natural floodplains that cover about 90,600 km^2. However, the river has been extensively modified by 3500 km of levees, 330 km of dikes and 1370 km of revetments. These modifications impede expansion of flood pulses into wetlands and floodplains, cause wetland losses, reduce main channel–floodplain connectivity, and isolate 90% of total floodplain areas. Most of the floodplain area has been cleared of forest and converted to agricultural use. Further, dikes and levees diminish channel width and increase water depth. A number of meander loops have been eliminated which have decreased river length by 230 km.

Land use changes in the basin also affect the Mississippi River. In the upper reaches, about 50% of the total alluvial valley of 6.5 million hectares supports agriculture and only about 23% of the original floodplain is still seasonally inundated. Agricultural development, urbanization, ditching, and use of field tiles for drainage have further altered the relationship between river and watershed. Only two main tributaries, the Illinois and the Missouri Rivers, still exhibit partial natural floodplain connection to the main channel through annual pulses (Sparks, 1995). Degradation of the health and ecological integrity in the Mississippi River affects its receiving water, the Gulf of Mexico. Flow alteration and sediment reduction of about 75% of normal riverine sediment inputs were found to be a major cause of marsh salinization (Martin *et al.*, 2002). Sediment inputs from the Missouri River, historically the largest source of sediment to the Mississippi River, have been retained by main stem Missouri River dams. Much of this increased nitrogen loading in the Gulf of Mexico has produced hypoxia in portions of the Gulf of Mexico (Martin *et al.*, 2002). Loss of both wetlands and riparian buffers in the Upper Mississippi River may exacerbate hypoxia in the Gulf of Mexico (Mitsch *et al.*, 2001). In the Mississippi River, natural habitat spatial complexity provided by oxbow lakes, marshes, meanders, and side channels was replaced by a new habitat complexity comprised of wing dikes, rip-rapped and revetment banks, spillways, locks, dams, and tail waters.

3.3 The Middle Paraná River case study

3.3.1 General description

The Paraná River flows for 2,570 km (3,740 km if the Paranaiba River is included) and drains a watershed of 2,800,000 km^{2}from its headwaters in Brazil to its mouth at the Rio de la Plata estuary (Table 1). The alluvial valley of its middle section has a surface area of 19,200 km^2 consisting of a main channel and fringing floodplain composed of anastomosing and meandering secondary channels and internal deltas (Drago, 1973). The Paraná River, the primary tributary of the Rio de la Plata basin, is the second largest river in South America (after the Amazon River) and the world's fourth largest by drainage area. The Paraná River drains 32% of the land area of Argentina and is divided into three main segments (Bonetto, 1994): the upper, middle, and lower Paraná River with the middle and lower portions being the focus of this study. The upper reach of the Paraná River has been severely impacted by damming and urban pollution (Petrere, 1989), but the middle and lower Paraná basin (Argentina) still exhibit many attributes of a natural riverscape (Bonetto *et al.*, 1989). The Middle Paraná River, with a drainage area of 370,000 km^2 (Figure 3), starts at the confluence of the Paraguay River and ends south of Diamante City, Argentina. South of this city, the Paraná River forms a delta of 15,000 km^2 (lower Paraná River) that ends in the headwaters of the 1,000 km-long by 300 km-wide Río de la Plata estuary. Yacyreta Dam is upstream of the Middle Paraná River but its influence on the Middle Paraná River flow statistics is limited because its impoundment has only a 12 day residence time. About 50% of

Table 1 General geomorphic, biological and chemical characteristics for the Paraná River (Argentina) and the Mississippi River (USA)

Characteristics	Middle Paraná River[1]	Mississippi River at Bel Chase
Mean elevation above sea level (m)	980	1200
Drainage area (km^2)[a]	2.8×10^{6} km^2	3.2×10^{6} km^2
Length (km)[a]	2570/3740 (3740 if the Paranaiba River is included)	3700 km
Runoff (mm)	171	154
Mean annual discharge (m^3)	15,000	17,000
Mean annual sediment load (t/year)	79×10^{6}	15×10^{7}
Mean annual total dissolved solids (t/year)	38×10^{6}	142
Mean annual total suspended sediments (t/year)	80×10^{6}(40×10^{6}– 100×10^{6})	296
Dissolved organic carbon (DOC) (mg/l)	6 to 10	3.5
Dissolved organic carbon (t/year)	7.5×10^{6}	6.6×10^{4}
Particulate organic carbon (POC) (mg/l)	2.1	0.8
Particulate organic carbon (t/year)	16.3×10^{5}	57.6×10^{5}
Secchi disk (m)	0.09 – 0.39	0.04, 2.91, 0.525, 0.361[a]
pH	6.26 – 7.92	5.70, 9.90, 7.98, 0.510[a]
Conductivity (μS/cm)	57.6 (32 – 115)	0.400, 1930, 453, 151[a]
Alkalinity (meq/l)	0.69 (0.21 – 1.5)	
Chloride (mg/l)	6.47 (4.2 – 12.5)	0.001, 173, 12.8, 13.6[a]
Hardness (meq/l)	0.45 (0.24 – 0.72)	150 – 220 mg/L [b]
Calcium (mg/l)	6.92 (2.18 – 11.7)	0.001, 110, 46.3, 21.3[a]
Magnesium(mg/l)	2.09 (1.13 – 2.7)	0.039, 56.2, 20.0, 9.62[a]
Sodium (mg/l)	5.32 (1.27 – 10.1)	0.100, 173, 12.8, 13.6[a]
Potassium (mg/l)	3.65 (1.64 – 6.3)	0.030, 70.0, 2.61, 1.89[a]
Total phosphate (mg/l)	1.1 (0.06 – 2.5)	0.001, 7.84, 0.18, 0.22[a]
Oxygen (mg/l)	8.14 (4.43 – 10.8)	0.022, 48.4, 10.0, 3.44 [a]

[1] Bonetto *et al.*, 1969.

[a] Data collected from the Upper Mississippi River in Pools 4, 8, 9, 13, and 26 and in the open river reach during the period from April 1995 through February 2003 (United States Geological Survey Upper Midwest Environmental Science Center Water Quality Database Browser, http://www.umesc.usgs.gov/data_library/water_quality/water1_query.shtml, 10/27/2004). Data for each characteristic are listed in the following order: minimum, maximum, mean, standard deviation.

[b] Data representing the Mississippi River from Royalton, Minnesota to New Orleans, Louisiana over the period from 1987 to 1992 (Contaminants in the Mississippi River 1987–92, United States Geological Survey Circular 1133, Robert H. Mead, editor, Reston, Virginia, 1995, http://water.usgs.gov/pubs/circ/circ1133/.

the Middle Paraná flow comes from the Paraguay River, which is still unregulated.

The main channel of the Middle Paraná River (a segment of the Paraguay – Paraná River axis) traces a tectonic boundary for about 700 km and divides the basin into two major geological regions. Channel sediments are composed primarily of medium sands (Drago and Amsler, 1998) with dunes up to 12 m high (Drago, 1977). The channel is classified as a braided meandiform (Shumm, 1985) and often forms two or more secondary channels that isolate islands and extensive sand bars. The Middle Paraná River has no dams, relatively few levees, and channel improvements to support navigation are restricted to the vicinity of river ports. Main channel width of the Middle Paraná ranges from 5 km at its upper end to about 2 km in the lower end with mean depth ranging from 5- to 10-m. This river has not been shortened by excavating through channel bend meanders. Channel sinuosity is 1.2 and mean channel slope is 0.0045 m km^{-1}(Paoli and Cacik, 2000).

3.3.2 Hydrology, sediment, and floodplain structure

Large river geomorphology is driven by timing, duration, magnitude, and predictability of flooding. At short temporal scales and small spatial scales, sandbars, undercut banks, and levees may be modified by high flow events. At longer time scales and greater spatial scales, channel migration, oxbow lake formation, and meander avulsion may occur. River discharge in the Middle Paraná drainage is determined primarily by outflows from the Upper Paraná. The hydrological regime of the Middle Paraná River is presented in detail by Paoli *et al.* (2000) and briefly described below. The Paraná River exhibits a complex pattern of seasonal flows comprised of a single low flow period (July to October) and primary (October to February) and secondary (May to June) high flow peaks. The primary peak flow is in response to precipitation occurring in the upper Paraná River. Secondary peak flows are in response to the influence of Paraguay River discharge, but occasional flash floods in the Iguazu River may also influence discharges in the Middle Paraná (Figure 4). However, discharge

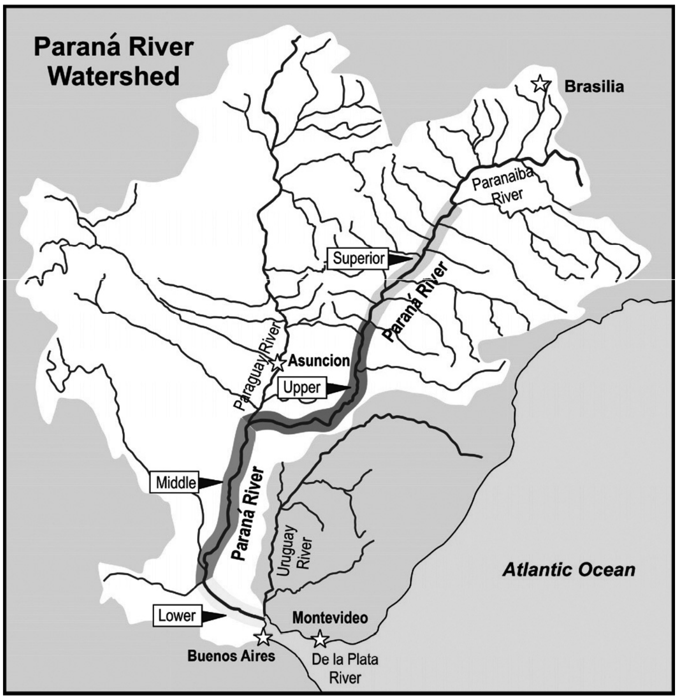

Figure 3 Location map of the Paraná River system.

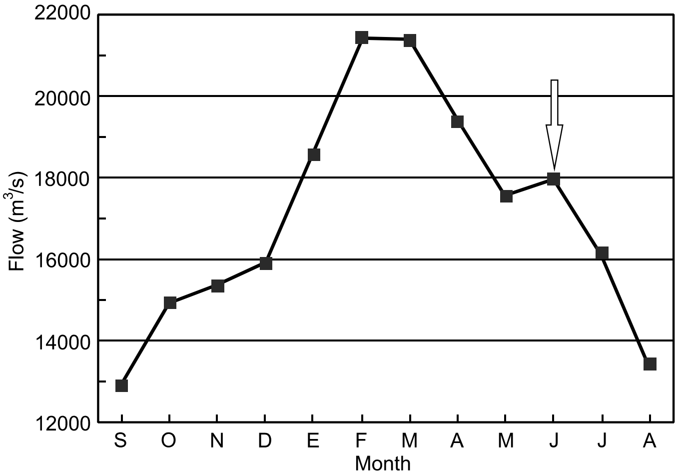

Figure 4 Hydrological regime of the Paraná River at Paraná City. Arrow identifies the secondary peak caused by the Paraguay River discharge in the fall.

can vary among years and sites within the Middle Paraná due to climatic variability within the catchment (Neiff, 1990a). Mean annual discharge is 15,000 m^3/s, but in the last 25 years 68% of the peaks surpassed 30,000 m^3/s and 4 times exceeded 40,000 m^3/s. Current speed in the main channel ranges from 0.5-m/s during low flow up to 3-m/s during high flow.

The Middle Paraná River exhibits the extensive sediment dynamics typical of a large alluvial river. Most of the silts and clays transported by the Paraná River derive from the Bermejo River, a major tributary of the lower Paraguay River (Depetris and Lenardón, 1982). The Paraná River transports a mean load of total suspended solids of 80×10^6 tons/year (Depetris and Paolini, 1991; Depetris *et al.*, 2003). Suspended sediment concentrations as high as 4,500 mg/l are common (Drago and Amsler, 1981) and can reach 8,000 mg/l during the rainy season (Amsler and Prendes 2000). The Bermejo River supplies 50–80% (Drago; 1973, Bertolino and Depetris, 1992) of the Paraná River sediment load, estimated at 40×10^6 t/year to 100×10^6 t/year (Depetris and Paolini, 1991). Mean sediment concentration is estimated at 6.5 mg/l (Drago and Amsler, 1981). Such sediment dynamics can help provide information on natural erosion and deposition patterns typical of large floodplain rivers such as the upper and middle Mississippi River where upstream locks and dams have altered natural geomorphology patterns.

Unlike most of the Mississippi River, the Middle Paraná is still connected to an extensive fringe floodplain that ranges from 13 to 60 km in width, still exhibits the complex spatial geometry typical of undisturbed floodplain rivers, and still exhibits a flood pulse that provides hydraulic connection and material exchange between the main channel and floodplain. Its floodplain has a surface of 19,240 km^2 (Paoli and Cacik, 2000) and is composed of anastomosing and meandering secondary channels and internal deltas (Drago, 1973). Semicircular, shallow ponds connected by temporal and permanent anabranches occupy almost 50% of the alluvial valley (Drago, 1990). Small streams that cross the floodplain alternate between shallow reaches and scour holes 5 to 15 m deep during the wet season (Marchese *et al.*, 2002) and often become dry during the low flow season. Shallow lakes (up to 5 m deep) of varying surface area with clay and silt bottoms and shorelines of fine sand also occur (Marchese *et al.*, 2002).

3.3.3 Variability in the middle Paraná River

The Middle Paraná River is primarily the product of dynamic, multi-scale hydrogeological processes that create an heterogeneous mosaic of geomorphologic patterns. The different parts of the mosaic represent a palette of reference conditions with minimum effects of levees, dikes, dredging, and impoundments. This makes the Middle Paraná river a natural laboratory for the study of river processes and functions of value to river restoration (Figure 5). Some discrete sub-regions of the Middle Paraná are as follows. The main channel is constricted at several locations to a width of 0.5- to 1.5-km with a corresponding depth increase to ~ 40-m (Paoli and Cacik, 2000) (Figure 5a). In the north, the channel is characterized by a high left bank and an extensive floodplain on the right bank. In the middle, several paleochannels are evident such as the Saladillos Dulce and Amargo systems (Figure 5b) with relict shallow ponds of different sizes and shapes connected by secondary channels during high flow periods. At the end of the Pelistocene or beginning of the Holocene the paleochannels reconnected to the Paraná floodplain through avulsion processes (Iriondo, 1979). One of the most ancient areas of the Middle Paraná River is a fringing floodplain located in the south between the Coronda River (a secondary channel) and the Middle Paraná River (Figure 5c). The Coronda River connects a complex network of shallow floodplain ponds. Alluvial deposits created by periodic floods limit connection of the ponds with the main channel, except where the valley narrows.

3.3.4 Natural biogeochemical processes in a floodplain river

Dissolved (DOC) and particulate (POC) organic carbon dynamics have been described for the Paraná River. DOC/POC ratios

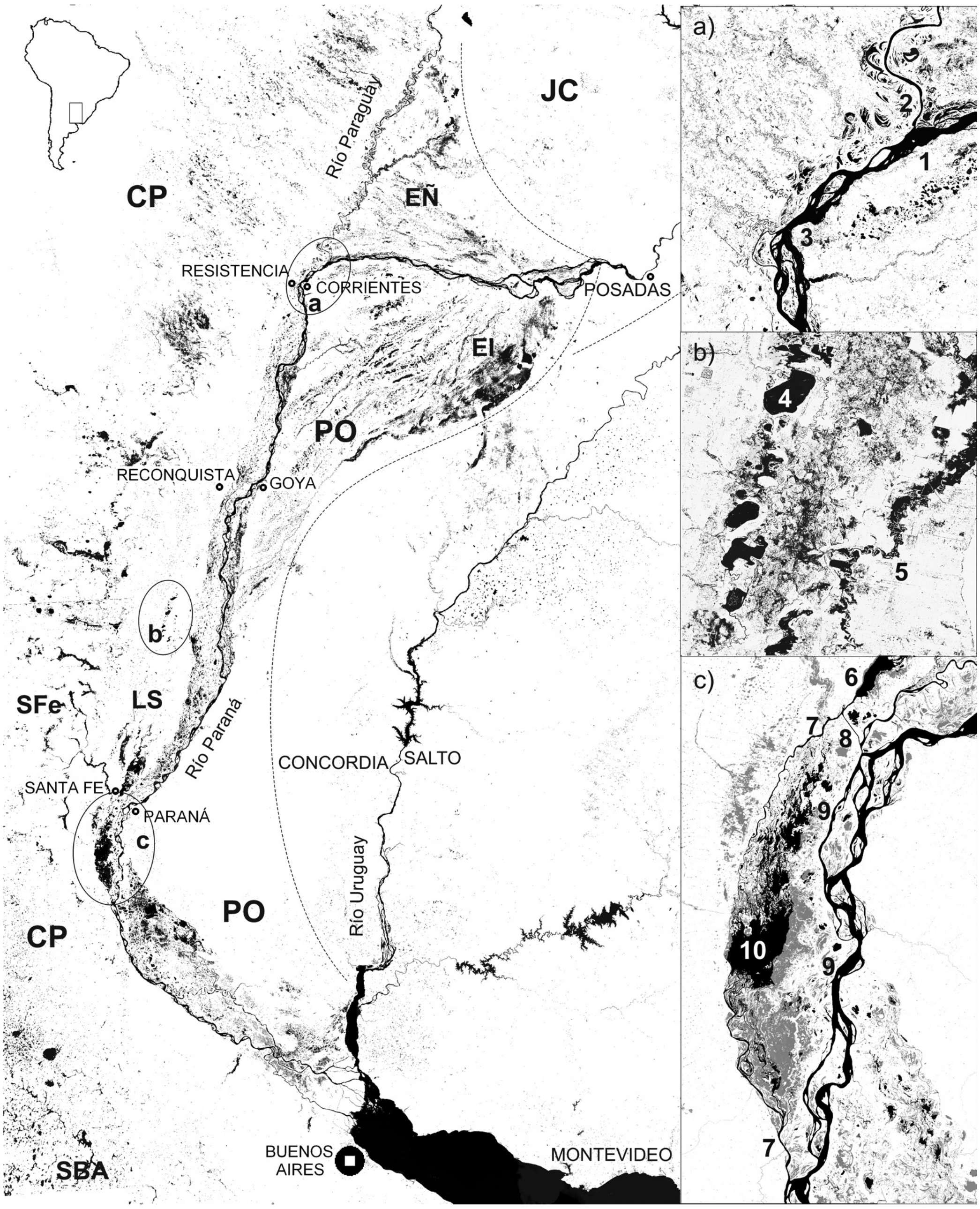

Figure 5 Middle Paraná system and associated basins describing primary foodplain characteristics. PO: Oriental plains. JC: Geological Province Jurásic-Cretácic of the Upper Paraná. CP: Chaco-Pampean plain. EI: Ibera wetland. EÑ: Ñambucu wetlands. LS: Los Saladillos Amargo and Dulce systems. SFe: Salado River basin in Sante Fe Province SBA: Salado River basin in Buenos Aires Province. (a) Paraná and Paraguay River junction and area of valley constriction. (b) Isolated ponds of the Saladillos system. (c) Coronda River system. (1) Paraná River. (2) Paraguay River. (3) Valley constriction. (4) Isolated ponds of the Saladillo Amargo River. (5) Saladillo Dulce River. (6) Setúbal lake. (7) Coronda River. (8) Santa Fe Canal port channel. (9) Natural levees in the Paraná River. (10) Coronda Lake.

vary from 2 to 8 (mean 4.4) depending upon hydrological year and size fraction of POC measured. Mean values of DOC, POC, and total organic carbon for the 1981–1984 period were estimated as 9.3, 2,1 and 11.4 mg/l, respectively (Depetris and Paolini, 1991). However, DOC can increase up to 35 mg/l during ENSO (EL Niño Southern Oscillation) phenomena. Allochthonous production of organic matter is greater than autochthonous production in the main channel, but the relative importance of allochthonous POC decreases during floods when flows enter the floodplain. DOC concentrations in the floodplain appear related to water level changes with low and high DOC concentrations appearing during low and high water discharges, respectively (Depetris and Cascante, 1985). Increases in DOC can also be associated with decomposition of POC stored in flooded soils. In addition to bulk organic matter dynamics, dissolved amino acids and dissolved carbohydrates increase during floods exemplifying the complex organic matter transformations that may be ecologically significant in flood plain rivers (Depetris and Paolini, 1991). Flood pulses may not only stimulate productivity of the floodplain because of high concentrations of suspended solids carrying adsorbed nutrients (Bonetto *et al.*, 1989), but may also trigger responses by phytoplankton and zooplankton communities (Bonetto, 1975) and increases in fish biomass (Bonetto *et al.*, 1969; Bonetto *et al.*, 1970). As the flood pulse recedes, floodplain DOC, POC, and floating aquatic and semi aquatic macrophytes may represent a valuable source of exported organic matter and nutrients for main channel communities.

3.3.5 Biodiversity and flood pulses

Many important biological processes associated with flood pulses that contribute to natural biodiversity have been described for the Middle Paraná River. Distribution and abundance of floodplain plants, a critical component of the organic matter cycle, strongly depend on the natural hydrological regime of the river (Lewis *et al.*, 1987; Neiff, 1978; Neiff, 1990a). Flood pulses trigger plant development, influence nutrient dynamics, provide substrate for invertebrates, provide refugia for fish larvae, and increase habitat complexity (Figure 6). Many floodplain lakes are dominated by *Eichornia crassipes* which increase in biomass from August to March (Neiff and Neiff, 1984). Plant growth is higher in connected floodplain lakes than in isolated lakes demonstrating the effect of floods on plant response (Neiff *et al.*, 2001). According to Neiff *et al.* (1994) up to 30% of the phosphorous requirement of aquatic vegetation is adsorbed from inorganic matter filtered out and retained by their roots. Macrophyte beds have a large underwater root surface area where organic matter can be processed (Lewis *et al.*, 1990) and that also increase potential floodplain phytoplankton production by increasing localized hydraulic residence time (Neiff, 1990b). However, macrophyte beds can also reduce phytoplankton production by competing for nutrients, physically filtering them out, or by increasing phytoplankton settling. Large amounts of plant biomass is exported to the main channel when water recedes.

Migratory fish enter floodplain lagoons to feed as water levels rise during the flood pulse. Fish community biomass is dominated by detritrivores (Winemiller, 2004) exemplified by *Prochilodus lineatus. P. lineatus* juveniles remain in lagoons and floodplain channels for two years before recruiting to the main channel (Figure 6). This species is critical to river functioning for three reasons. First, it comprises more than half of the fish biomass in permanent habitats of the floodplain reaching biomasses up to 4000 kg/ha (Bonetto *et al.*, 1970). Second, its larvae are a critical component of the food consumed by larvae of large ichthyophagous species that rear in the floodplain. Third, as adults they ingest fine organic matter and flock detritus from the bottom and on the surface of submerged plants (Fugi *et al.*, 1996; Marchese and Drago, 1992), contributing substantially to organic matter recycling in the system.

Flood pulses also regulate distributions and abundances of other aquatic communities. Benthic macronvertebrates abundance appears to be controlled by connectivity between main channel, secondary channels, and lakes (Marchese and Drago, 1992). Benthic macroinvertebrate diversity increases from the main channel to the upper limit of the floodplain (Domitrovic, 1993) and a similar pattern was observed by (Junk *et al.*, 1989) for the phytoplankton community.

4 Discussion

4.1 Reference conditions for river restoration

Comparative analysis of large rivers has historically been based on a qualitative, synthetic world-wide framework of river characteristics (e.g. Depetris and Paolini, 1991; Welcomme, 1985), or it has been restricted to a few specific variables such as carbon or minerals transport (Degens, 1982; Degens and Ittekot, 1985; Degens *et al.*, 1983; Degens *et al.*, 1985; Degens *et al.*, 1987). By using a multivariate approach, we were able to expand existing frameworks to include climatic, hydrological, chemical, and geomorphologic characteristics. By integrating and analyzing this information over large time and space scales, we were able to demonstrate that the Mississippi and Middle Paraná Rivers are generally similar at basin scales. This finding is complemented by general qualitative descriptions of both systems. Additionally, both systems have a history of monitoring and scientific study so that considerable data are available for these two systems. The availability of study results and monitoring data for these two rivers separates them from other larger rivers that have not been as well studied. The Mississippi and Middle Paraná Rivers exhibit interesting similarities at large scales, but more importantly also differ substantially in their histories of water resources development. The Mississippi River exhibits major impacts associated with extensive water resources development whereas the Middle Paraná River does not. This basic similarity in certain characteristics, but difference in water resources development history provides an experimental setting where the system-wide effects of management actions can be directly measured.

Further evaluation of the two systems at finer scales shows that each is comprised of substantially different sub-regions. The spatial heterogeneity of the Middle Paraná River is greatest of the two rivers because it falls on a tectonic boundary (Iriondo, 1979). This heterogeneity can be exploited for Mississippi River restoration in several ways. For example, relict shallow pools that are connected by secondary channels during high flow periods of the mid Middle Paraná River share similarities to the dam and pool structure of the Upper Mississippi River. Study of natural processes and functions in the relict pools of the mid-Middle Paraná River may provide concepts and identify management actions that can be applied to restore natural processes and functions to the navigation pools of the Upper Mississippi River in a way that does not require the removal of dams. Additionally, the extensive network of channels and fringing wetlands in the Middle Paraná River may provide information that can be used to better understand and manage the extensive channels and wetlands of the northern reaches of the Upper Mississippi River. In the Upper Mississippi River, maintenance of water elevation for navigation has permanently connected the main channel to its backwaters because the seasonal drawdown has been eliminated. Further evaluation will likely identify other sub-regions or specific sites in the Paraná River that can help guide restoration of the Mississippi River or other large floodplain rivers.

An understanding of natural processes in relatively healthy rivers is the knowledge foundation upon which quantitative tools

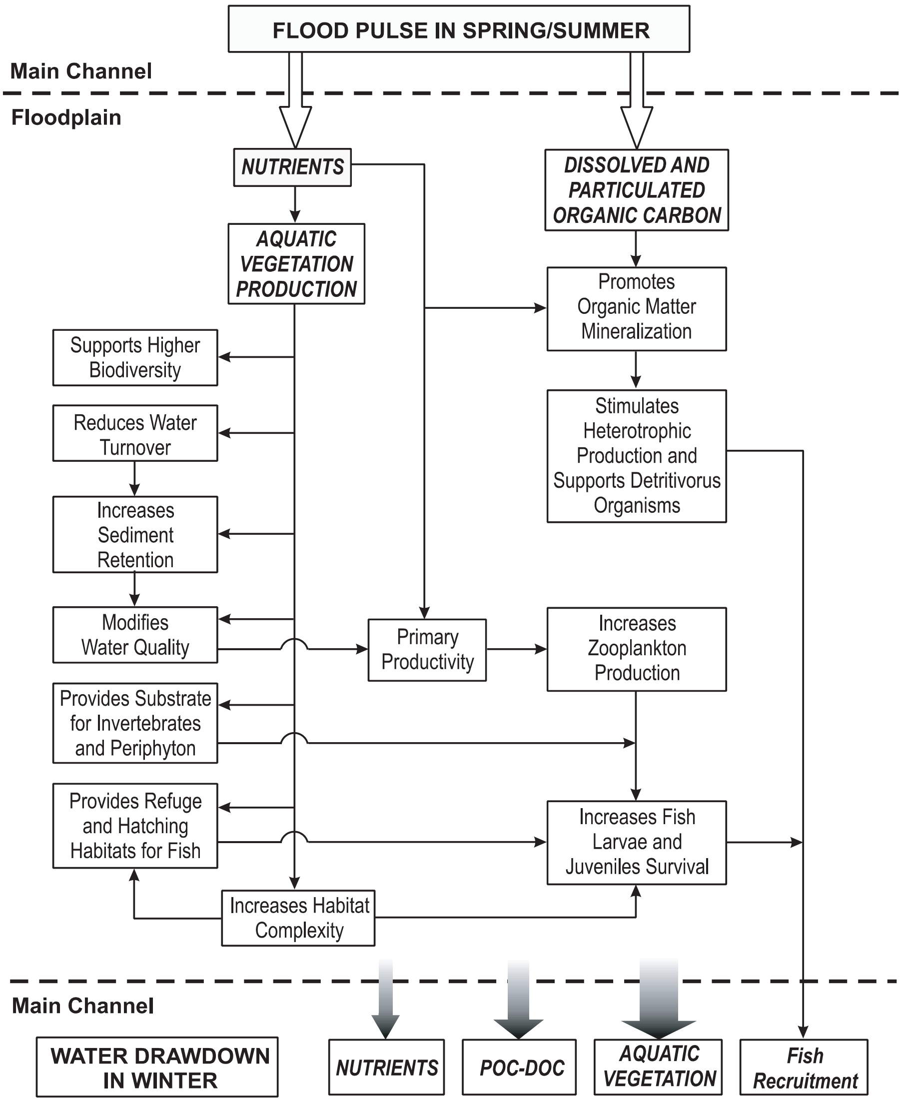

Figure 6 Ecological processes in the Paraná River related to aquatic vegetation in the floodplain. Empty wide arrows indicate water movement into the floodplain through pulses. Filled wide arrows indicate the water movement into the main channel transporting organic matter, nutrients and aquatic vegetation.

can be developed to guide large river restoration. Using large floodplain rivers that are relatively similar as references for each avoids the common problem of extrapolating process-based knowledge between fundamentally dissimilar river systems. Without this understanding it is not possible to identify blends of processes that are sustainable, support biodiversity, and benefit society. Together, the Mississippi River of North America and Middle Paraná River of South America offer an unique opportunity to 1) test and expand concepts about large rivers, 2) develop reference conditions for the Mississippi River, 3) provide a knowledge base that can be used to develop and test qualitative restoration tools and protocols, and 4) contribute to the development of a mathematically rigorous "virtual" reference to guide the design of specific management actions.

The use of a physical reference (such as the middle Paraná River) that is sustainable, supports biodiversity, and exhibits processes that appear relatively unimpaired is the optimum template to guide restoration of a highly impaired system (such as the Mississippi River). Such a reference minimizes the uncertainty inherent in developing a historical reference from isolated, poorly documented historical data or from use of reference conditions extrapolated from smaller rivers or large rivers of unknown similarity to the target river. Additionally, there may exist many natural analogues (such as the naturally occurring serial pools of the Paraná River) that can be used to better manage features of the Mississippi River that must be maintained as long as the commitment to provide navigation remains. Without such a reference, there is the danger of managing for impaired or inappropriate processes that distort interaction among key system components that shape ecological integrity (Figure 7).

The greatest value of contrasting analyses of the Middle Paraná (connected to its floodplain) and Mississippi (generally not as connected to its floodplain) Rivers is the opportunity to quantify and describe the importance of flood pulses to system-level restoration. Flood pulses and associated ebbing are critical components of the integrity of floodplain-rivers (Poff *et al.*, 1997; Bonetto and Waiss, 1980; Power *et al.*, 1995; Junk and Wantxen, 2004) because they: (1) create habitat heterogeneity by modifying

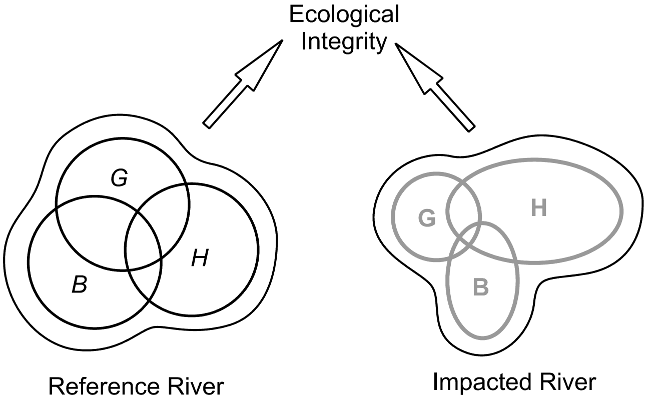

Figure 7 Conceptual framework for reference and impacted rivers based on geomorphology (G), hydrology (H) and biology (B). Circle intersections represent interactions among components and difference in shape implies change from original conditions caused by river regulation and human disturbances distorting overall ecological integrity.

erosion and deposition patterns and enhance the persistence of ecological communities (Bayley, 1995), (2) regulate fish community assembly patterns and regional diversity levels (Arrington and Winemiller, 2004; Poully and Rodriquez, 2004), (3) drive nutrient dynamics in the floodplain by affecting sediment chemistry, nutrient diagenesis, and microbial ecology (Junk, 1985; Baldwin and Mitchel, 2000), and (4) are important sources of carbon stored as periphyton, macrophytes, terrestrial forest, and organic litter that cannot be distributed within the river without a flood pulse (Neiff, 1990a; Hedges *et al.*, 1986; Junk, 1970; Junk, 1986; Klinge *et al.*, 1990).

Predictable large-scale flood pulses and associated ebbing are the primary forces determining the evolution of large river fishes (Naiman *et al.*, 2002). Flood pulses connect distant habitats, provide suitable spawning and feeding areas, offer refuge from unsuitable thermal conditions and predators, and are important corridors for migratory species (Sparks *et al.*, 1998; Depetris and Paolini, 1991). Biotic production is greater in river segments containing floodplains hydraulically connected to a main channel that exhibits natural flood pulses (Risotto and Turner, 1985). For example, acreage of bottomland hardwoods on the floodplain is important in determining overall fishery production (Risotto and Turner, 1985). Lakes isolated from the Mississippi main channel by levees had 64% less fish biomass that those connected to the floodplain (Bayley, 1995). Fish growth in littoral zones was correlated with high water levels from annual pulses (Gutreuter *et al.*, 1999). Natural hydrologic patterns favored native river fishes at the expense of exotic generalist fishes (Koel and Sparks, 2002; Petts, 1990b).

The Middle Paraná River, because it is still connected to its flood plain, is an important natural laboratory where floodplain river processes can be understood and described. It can be used to contribute to the knowledge needed to develop effective management actions and restoration techniques for highly impacted rivers (Lorenz *et al.*, 1997). For example, the unleveed mid- and lower-reaches of the Paraná River provide insight into probable natural conditions for some processes that existed in the Mississippi River prior to construction of extensive navigation improvements. Concomitantly, the present state of the Mississippi River is a negative reference for the Paraná River and illustrates what may happen to the mid- and lower-reaches of the Paraná River if unsustainable water resources development practices are followed.

4.1.1 Improved conceptual models

Data from large floodplain rivers are seldom used in development of concepts that describe river processes (U.S. Army Corps of Engineers, 2000) because their size and high-energy hydraulic environment make them difficult to sample and the temporal scales of some of their processes makes them difficult to assess. Therefore, restoration of large floodplain rivers cannot necessarily be guided by what is known about small rivers (Sparks, 1995) because of substantial differences in structure and process. The Paraná River provides an experimental site in which ecological concepts can be tested and assessed for their application to large floodplain rivers. Results of such studies can be used to confirm these concepts or to guide development of a revised conceptual template suitable for large floodplain river restoration.

4.1.2 Use of a physical reference

Data collected on the world's few remaining large floodplain rivers is the only practical means of understanding the natural functioning of floodplains and, therefore, provides the most useful information for planning river restoration (Lewis *et al.*, 2000). At the system level, the Middle Paraná River offers an opportunity to guide Mississippi River restoration by providing an existing system on which normal behavior of a large floodplain river can be extracted. The value of a physical reference system that still has many relatively intact processes cannot be overemphasized. Such a system can provide insight into large floodplain river geomorphology, hydrology, and biotic adaptation at the natural scales necessary to understand bio-complexity and system behavior. For example, the Upper Mississippi River floodplain is a sink for FPOC during floods and a source of DOC during flood recession (Grubaugh and Anderson, 1989) suggesting that its organic matter dynamics may be similar to that of large South American river systems (Welcomme and Hagborg, 1977; Depetris and Paolini, 1991). At a sub-region or site specific scale, sufficiently detailed information may be collected from the Middle Paraná to guide development of restoration technologies or actions for the Mississippi River.

Snapshot comparisons made at time intervals between reference and target rivers can be used to infer the health of the target system and to identify critical processes that are sufficiently impaired to disrupt natural river functions. Snapshot comparisons can also be used to determine status of the impacted river at a allowed by sampling protocols. Comparisons made over long periods of time must supplement snapshot comparisons because flood plain rivers are non-equilibrium systems where ecological integrity depends upon a certain level of disturbances (Hamilton, 1999). Successful restoration must include a certain set of disturbances at scales sufficient to affect the main channel, backwaters, and floodplain for the river system to recover some of its natural values (Sparks *et al.*, 1998). Once impaired processes have been identified, they can then be studied in detail in both the reference and target systems to determine remedial actions necessary to restore natural functions to the target system. Management plans can be instituted that reverse the effects of impacts in an adaptive management context. Ecosystem health and integrity can be assumed when important processes in the impacted system appear to be generally consistent with reference conditions.

4.1.3 Opportunity to develop a virtual reference

Mechanistic models are increasingly used as mathematical surrogates for real ecosystems on which restoration measures can be tested and evaluated. However, mathematical models are inherently simplifications of real systems and must be calibrated by adjusting their coefficients until their predictions converge on observed values. This creates a dilemma for system modelers who attempt to create mathematical surrogates of impacted systems to develop and assess restoration alternatives. These models can only be calibrated to the impacted condition for which data exist. They cannot be calibrated to a restored condition because data to describe the restored condition do not exist. Therefore, there must be more uncertainty in the accuracy of the forecasts for the desired future condition than there is in the accuracy of the hind cast to historical conditions.

The availability of paired systems like the Middle Paraná and Mississippi Rivers provides a unique opportunity to develop and calibrate a single model to conditions representative of both restored and impacted systems, respectively. Once this model is dually calibrated to both systems, then it can be used with increased confidence in both systems because the hind cast conditions at one site are the forecast conditions at the other. The success of this dual calibration strategy will hinge on locating specific, comparable locales in both systems, but the spatial heterogeneity of the Middle Paraná River should present an abundance of opportunity sites.

Use of a virtual reference based on a dually calibrated mathematical model of impacted/unimpacted pairs of rivers one of which is relatively impacted and another which is relatively unimpacted, but in a different continent, may be the only method left for scientists to develop virtual reference conditions of sufficient detail to develop restoration alternatives. Therefore, the best strategy to ensure successful restoration is to either use a natural reference river as a template or to develop a sufficient understanding of the ecosystem so that functional and structural components can be modeled based on sustainable reference conditions. In the long term, having a pair of rivers such as the Paraná and Mississippi Rivers becomes a knowledge focal point about the behavior of two related rivers that can serve as the spring board to compare and contrast many of the world's great rivers.

4.2 Conclusions

We emphasize the importance of contrasting large floodplain rivers that are generally similar in many of their attributes but subjected to different disturbance histories. Using a relatively simple ordination technique on basin scale variables, we demonstrated that the Middle and Lower Paraná River of South America and the Mississippi River of North America provide such contrasting systems. In the future, it may be useful to expand the analysis to more detailed river reach-scale information or to identify specific paired sites by using more detailed variable sets such as hydraulic residence time, floodplain area, water quality patterns, nutrient contents, mean depth or channel width instead of the basin scale variables employed in this analysis.

The Paraná River is not pristine, but the level of anthropomorphic disturbance that it exhibits is considerably less than that of the Mississippi River. The descriptions provided for the Paraná River indicates that its present condition may resemble the natural condition of the Mississippi River prior to the construction of major navigation improvements two centuries ago (Figure 8). Evidence for the middle Paraná River suggests that it exists at a state where natural system resilience would still allow it to return to a historical state. In contrast, the Mississippi River has seen such major geomorphic change associated with channel, floodplain, and watershed changes that it is unlikely to be restored to a historical condition or even to an intermediate condition using traditional rehabilitation and restoration actions (Figure 9).

The Mississippi River may serve as a negative reference for the middle and lower reaches of the Paraná River. Decisions about

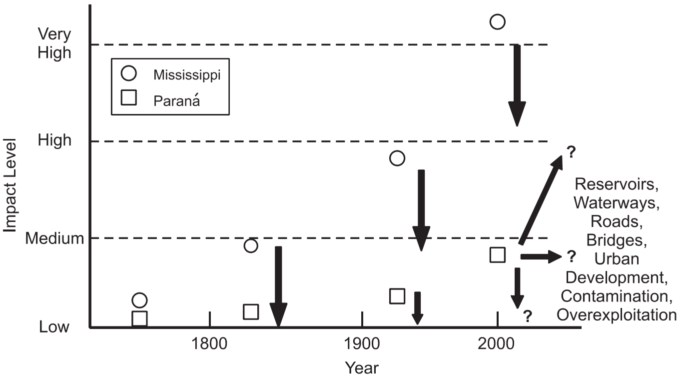

Figure 8 Comparison of summary environmental impact trajectories in the Paraná and Mississippi Rivers. Arrows indicate the recovery level that can be achieved by applying restoration or remediation techniques.

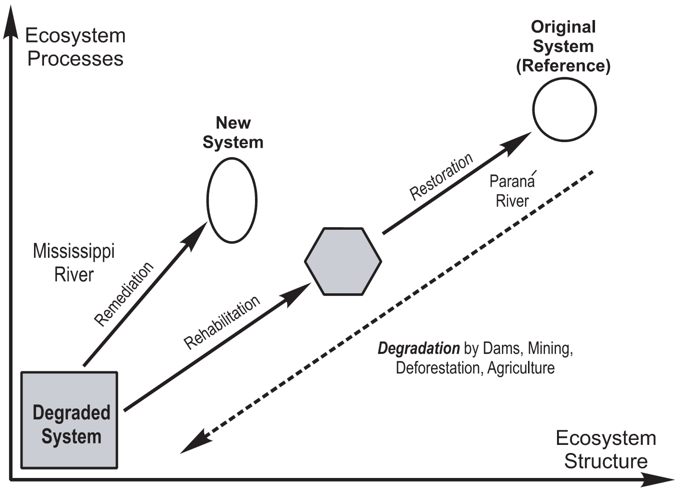

Figure 9 Conceptual framework for ecosystem integrity changes (function and structure) in the Paraná and Mississippi Rivers (modified from Rutherford *et al.* 2000).

construction of dams, water diversions, and extensive navigation improvements face water resources managers in the Paraná River Basin. The Missouri-Mississippi River system may represent the fate of the Paraná-Paraguay River system if unsustainable development plans are implemented (Gottgens *et al.*, 2001). For example, continental-scale navigation projects such as the Paraguay-Paraná Hidrovia Project may have a strong impact on adjacent floodplains because of changes in main channel water level (Michener and Hacuber, 1995). An even more ambitious Hidrovia network that would connect the Amazon, Orinoco and De la Plata basins is being considered. Based on experiences in the Mississippi River, such projects should be planned carefully to avoid the level of impact observed in the Mississippi River.

The Middle Paraná River still exhibits the single dominant feature that defines large floodplain rivers, a natural flood pulse that seasonally submerges a hydraulically-connected, fringing floodplain. Although flood pulse characteristics may vary among large rivers, its ecological effects are generally similar in terms of preserving habitat complexity and functional processes that sustain biodiversity. Understanding the function of flood pulse through study and recreating them through management action is a critical element of river restoration (Galat *et al.*, 1998; Rhoads and Herricks, 1996). These findings may assist in restoration of a system like the Mississippi River, which cannot be restored to a historical condition, but could be rehabilitated to a new state that supports natural processes and functions (naturalization *sensu*), but in blends for which there are no local historical analogues. Additionally, there may be opportunities for restoration, but in spatial patterns for which there is no historical analogue. Such rehabilitation activities for the Mississippi River will be challenging and more likely to be successful if the Paraná River could be used to provide guiding information.

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