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POTENTIAL EFFECTS OF A MAJOR NAVIGATION PROJECT (PARAGUAY–PARANÁ HIDROVÍA) ON INUNDATION IN THE PANTANAL FLOODPLAINS

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ABSTRACT

The Pantanal wetland of Brazil, a vast complex of seasonally inundated floodplains along the Paraguay River, is renowned for its outstanding biological resources. A proposed navigation project known as the Paraguay–Paraná Waterway (or Hidrovía) would deepen the Paraguay River channel to facilitate year-round navigation through the Pantanal. The possibility of decreases in river levels (stage) has aroused concerns in relation to the potential environmental impacts, however the poor understanding of the hydrological relationships between rivers and floodplains has hampered evaluation of these impacts. The present study evaluates the potential impact of river modifications on adjacent floodplains by examining the relationship between the Paraguay River stage and the extent of floodplain inundation. Satellite observations of flooded area (from passive microwave emission; monthly data for 1979–1987) are plotted against river stage from several stations throughout the region to show the stage–inundation relationships for eight subregions along the Paraguay River. Scenarios in which the Paraguay River stage is decreased from the 20th and 80th percentile values reveal large potential impacts on inundation. For stage decreases of 0.10 and 0.25 m, the total flooded area is reduced by 1430 and 3830 km^2 at low-water, and by 2410 and 5790 km^2 at high-water, respectively. The floodplains of the two northernmost subregions appear to be most susceptible to reductions in flooding, losing more than half of their flooded area with a 0.25-m decrease in the low-water stage. The ecological impacts of these reductions in flooded area may be particularly severe at low water, when the few areas that typically remain flooded throughout the dry season serve as important refuges for aquatic animals. These results underscore the need for better understanding of the hydrology of the integrated river floodplain systems in the Pantanal before river channel modifications are carried out. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: navigation; floodplains; inundation

INTRODUCTION

The Pantanal wetland is a vast complex of seasonally inundated floodplains along the upper Paraguay River, located mostly in Brazil with smaller areas in Bolivia and Paraguay (Figure 1). The region is widely recognized for its outstanding biological resources and is considered a priority for Brazilian and international conservation efforts (Mittermeier *et al*., 1990). A recently proposed 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 in relation to the potential environmental impact on adjacent floodplains (summarized by Hidrovía Panel of Experts, 1997). The Paraguay River is the major river draining the floodplains of the Pantanal, and the seasonal inundation of much of the region has often been attributed to the inability of the river and its tributaries to carry the seasonal increase in runoff. Therefore, an important consideration regarding channel modifications in this region is the possibility that the channel

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capacity will be increased, leading to more efficient conveyance of flood waters, decreases in river levels, and hence, reduced extent and duration of floodplain inundation (Ponce, 1995).

Seasonal inundation of tropical floodplains is a predominant force determining the structure and function of these ecosystems, and changes in the extent and duration of inundation can produce a myriad of ecological consequences, leading to the degradation of the overall integrity of the ecosystem (Junk, 1997). Plants and animals in the floodplains cope with, and are often highly adapted to, the seasonal alternation between flooding and desiccation, and thus might appear resilient to hydrological variability. Individual species have distinct ranges of tolerance, however, and subtle differences in inundation patterns often produce striking spatial variability in species abundance and diversity, as evidenced by the typical patchy distribution of vegetation in the floodplains of the Pantanal (Prance and Schaller, 1982; Dubs, 1992). In addition, both aquatic and terrestrial organisms in floodplain environments may endure considerable stress at some point during the seasonal cycle, and this natural stress may make populations more vulnerable to additional stress factors resulting from anthropogenic changes (Beissinger, 1995).

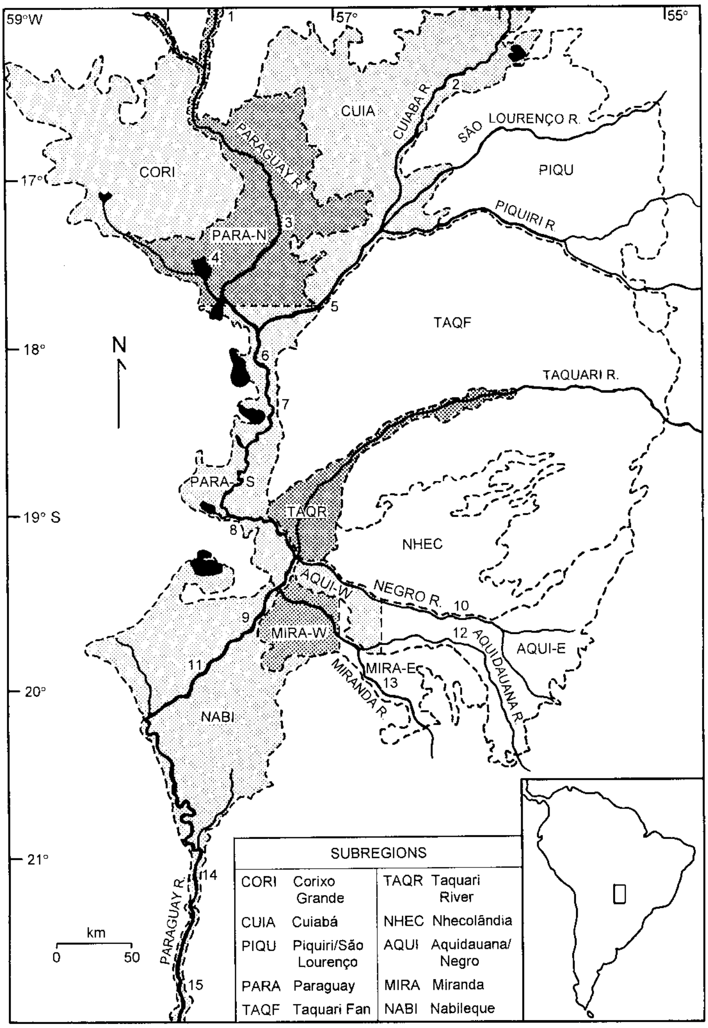

Figure 1. Map of the Pantanal showing the subregions and river stage stations considered in the present study. The shading indicates the subregions that are potentially affected by the water level of the Paraguay River and hence were included in this study. River stage stations are numbered as follows: 1, Cáceres; 2, Retiro Biguaçal; 3, Porto Conceição; 4, Bela Vista do Norte; 5, Porto Alegre; 6, Amolar; 7, São Francisco; 8, Ladário; 9, Porto Esperança; 10, Fazenda Rio Negro; 11, Forte Coimbra; 12, Porto Ciriaco; 13, Ticão de Fogo; 14, Barranco Branco; 15, Porto Murtinho.

The maintenance of the integrity of floodplain ecosystems in the Pantanal is important for current economic activities in the region. The floodplains provide productive natural pastures for cattle as a result of the seasonal floods, and ranching has long been the main economic use of the seasonally inundated land (Allem and Valls, 1987). Ecological tourism is becoming increasingly prominent, and much of the renowned wildlife of the Pantanal is dependent on floodplain environments (Mittermeier *et al*., 1990). Sport and commercial fishing are also important activities on the Pantanal, and the floodplains are essential to most fish species because they provide spawning grounds and food sources, even for species that spend much of their life-cycles in the rivers (Welcomme, 1985).

The channel modifications that would be required for the Hidrovía include dredging of shallow reaches, excavation of rock outcrops and straightening of some curves. As part of the environmental impact analysis of the Hidrovía project, the effects of the channel modifications on river levels were evaluated using one-dimensional flow-routing models (TGCC, 1996). The results generally indicated decreases in average river levels, but these predicted decreases were small (<10 cm). This modeling has recently been challenged however, in part because of the lack of information on river floodplain exchanges of water in the Pantanal (Dunne, 1997). Despite its poorly understood environmental impacts, the project remains under consideration.

The present study examines the relationship between water levels in the Paraguay River and the extent of inundation on the adjacent floodplains with the objective of estimating the potential impact of water level reductions on the floodplain ecosystems. Satellite observations of the inundated area derived from passive microwave emission are combined with government records of river stage measured throughout the region to generate empirical predictive models of the relationship between river levels and floodplain inundation. These models are used to produce scenarios of the changes in inundated area that may result from decreases in river levels. These scenarios reveal that river channel modifications associated with the Hidrovía project could strongly impact the inundation of floodplains in the Pantanal.

FLOODPLAIN INUNDATION IN THE PANTANAL

Seasonal inundation of floodplains in the Pantanal can occur in three ways: (1) overbank flow of river water across natural levees and onto lower-lying floodplains when channel capacity is exceeded; (2) a 'backwater effect' in which drainage from the floodplain and tributaries is impeded by the surface profile of the Paraguay River; and (3) pooling of local rainfall on gently sloping land where drainage to river courses is delayed. The first two causes of flooding have the potential to be affected by river channel modifications and hence are the subject of the present study. Pooling of local rainfall often occurs in areas distant from river channels and can be independent of river levels. Local rainfall is the predominant source of floodwaters in some of the more elevated parts of the Pantanal, such as the Taquari alluvial fan, as evidenced by the timing of flooding as well as the chemical composition of the floodwaters (Hamilton *et al*., 1998a).

In floodplains close to the Paraguay River inundation is driven largely by the river and its major tributaries. The timing of seasonal inundation in these areas reflects control by the river. Maximum flooding correlates well with river stage, which peaks several months later than the local rainfall in the central and southern Pantanal because of the delayed passage of the flood wave through the region (Hamilton *et al*., 1996). The chemical composition of the floodwaters in these areas generally reflects that of the parent river (e.g. Calheiros and Hamilton, 1998; Hamilton *et al*., 1998a).

The backwater effect can result in the decoupling of river discharge and water levels (Meade *et al*., 1991). The restricted capacity of the Paraguay River channel to convey floodwaters maintains water in the adjacent floodplains and slows or stops the inflow of tributaries, causing them to overflow onto their floodplains. The backwater effect can be propagated far up-river along the tributaries because of their small elevational gradients within the Pantanal. Thus, the source of the floodwaters may be local rainfall, tributaries, or the Paraguay River itself, but the depth and extent of flooding can be controlled by the backwater effect of the Paraguay River. The backwater effect is important in maintaining water on the floodplain during the dry season, when relatively little exchange of water between the river and floodplain may occur and local rainfall and runoff have essentially ceased. It is hypothesized that natural geomorphological barriers in the river channels cause the backwater effects in the Pantanal (EDIBAP, 1979). Along the Paraguay River, these barriers include occasional bedrock outcrops, as well as erosion-resistant soil hardpans (Ponce, 1995), some of which have been identified as points where the channel must be deepened or widened to facilitate navigation.

The Pantanal basin is geomorphologically complex, being comprised of several coalesced alluvial fans (Klammer, 1982), and various authors have distinguished subregions with distinct geomorphological, hydrological, and ecological characteristics. Hamilton *et al.* (1996) identified ten subregions on the basis of geomorphological maps produced from Side-Looking Airborne Radar images (RADAMBRASIL, 1982), with additional information obtained from LANDSAT images and field observations. Each of the ten subregions has a unique pattern of seasonal and interannual variation in flooded area, as shown by the passive microwave satellite observations of inundation reported by Hamilton *et al.* (1996). In general, the flood pulse travels from north to south across the region, and in the southernmost parts of the Pantanal the peak flooding occurs during the local dry season, when the source of the flood waters is largely overbank flow from the Paraguay River.

METHODS

The subregions identified by Hamilton *et al.* (1996) have been modified to provide better resolution of the floodplains where inundation is potentially controlled by the Paraguay River (Figure 1). In this analysis, the Piquiri, Taquari Fan and Nhecolândia subregions are excluded because of their distance from, and elevation above, the Paraguay River. I have also excluded the eastern portions of the Miranda subregion (east of 57°00′W longitude) and the Aquidauana/Negro subregion (east of 56°45′W longitude), since these areas are more hydrologically isolated from the Paraguay River. The Paraguay River subregion was split into northern and southern halves at 17°45′S latitude (at Lake Gaíba).

The observations of floodplain inundation are derived from satellite measurements of the passive emission of microwave radiation. Sippel *et al.* (1994) and Hamilton *et al.* (1996) describe the sensor system, global data sets and development of algorithms to estimate inundation area in the Pantanal. The difference between the horizontally and vertically polarized emission at 37 GHz provides a sensitive indicator of the presence of surface water. Unlike optical remote sensing systems such as LANDSAT, observations of passive microwave emission at 37 GHz are available throughout the year because they are affected little by cloud cover, and the presence of surface water affects the emission even when the water is largely obscured by overlying vegetation canopies.

In this study, monthly observations of inundation area for a 9-year period (January 1979–August 1987) derived by Hamilton *et al.* (1996) from measurements made by the Scanning Multichannel Microwave Radiometer (SMMR; Nimbus-7 satellite) are analyzed. Global SMMR observations are available for approximately 6-day intervals, and are compiled separately for day and night (local equator crossings at noon and midnight). The daytime observations were ranked within each month and the second-lowest value (out of four or five) was selected, thereby yielding one observation per month (Choudhury, 1989). This screening served to eliminate outlying values that might have resulted from atmospheric scattering by heavy rainfall, or from temporary pooling of water on the land surface after heavy rainfalls. The original 0.25° latitude-by-longitude satellite observations were aggregated into the modified subregions shown in Figure 1 using the same methods as in Hamilton *et al.* (1996).

The flooded area estimates reported by Hamilton *et al.* (1996) include both seasonally flooded land and permanent open-water bodies (mainly lakes). Open water comprises less than 2% of the overall Pantanal region, but is a more significant fraction of the total area in some subregions (Table I). Open-water area is not included in the flooded area estimates used in this study.

The river stage data are from stations along the Paraguay River throughout the Pantanal as well as along the major tributaries (Figure 1), and correspond in time with the satellite observations. At the time

Table I. Characteristics of the subregions potentially affected by the stage of the Paraguay River, and of the river stage sites that best predict their inundation

Subregion	Total area (km^2)	Open water (km^2)	River stage site	*n*	20th percentile stage (m)	80th percentile stage (m)
Corixo Grande	11 479	243	Porto Conceição	70	4.20	5.10
Cuiabá	14 406	213	Porto Conceição	70	4.20	5.10
Paraguay River, North	9592	865	Bela Vista do Norte	104	3.80	5.40
Paraguay River, South	6666	580	Ladário	104	2.50	5.05
Taquari River	2927	22	Ladário	104	2.50	5.05
Aquidauna/Negro, West	1300	22	Porto Esperança	104	2.45	5.05
Miranda, West	2165	33	Porto Esperança	104	2.45	5.05
Nabileque	13 662	210	Barranco Branco	104	4.20	7.45

For each subregion, the table gives the total area (as depicted in Figure 1), the open-water area (mainly permanent lakes), the stage measurement site and the number of stage measurements that were available for that site (*n*; monthly means), and the stage values at the 20th and 80th percentiles for the available stage data.

at which the data were gathered, most of these stations were operated by the Brazilian firm Hidrologia S.A., under contract to the Departamento Nacional de Obras Sanitárias (DNOS); the Brazilian Navy also collected data at several sites. Monthly means were calculated from the daily stage observations for comparison with the monthly satellite observations of inundation area.

The river stage site showing the best relationship with flooded area for each subregion was selected based on Pearson product-moment correlations between the monthly flooded area estimates and the mean monthly stage data for sites within, or close to, the subregion. Cross-correlation functions were computed to check for time lags between stage and flooding, but the contemporaneous correlation was superior for all subregions. Some stage data for the period of satellite observations were missing for the selected stage sites, but all had at least 70 months, and for six of the eight subregions there were stage data for the appropriate sites corresponding to all 104 months of satellite observations.

The relationship between stage and flooded area was described graphically using an iterative smoothing procedure known as Locally Weighted Scatterplot Smoothing (LOWESS) (Chambers *et al.*, 1983; Hirsch *et al.*, 1993). Compared to linear or curvilinear regression models, LOWESS is superior for describing complex, non-linear relationships, which might be expected between stage and flooded area in floodplains of variable geomorphology. LOWESS also provides a better characterization of the data at the extremes of the range of observations, which is important for the present study. Compared to smoothing using a running mean, LOWESS is preferable because it is less sensitive to outliers. The LOWESS curve is fit to the center of the local data by a weighted least squares procedure, in which the strongest weights are applied to the closest points and the weights become progressively weaker with distance to a user-defined limit. The limit is defined by a 'tautness' criterion (F), which is the proportion of the total data to be included in the weighting procedure and determines the smoothness of the resulting curve (Wilkinson *et al.*, 1996). In the present study, all of the LOWESS curves were produced using $F = 0.5$, and the computations were performed using SYSTAT Version 5.0 software.

The LOWESS curves were employed to develop scenarios for average low-water and high-water conditions. For each local stage site, I calculated the 20th and 80th percentiles for the 9 years of river stage observations (Table I). These values were taken to represent typical low- and high-water conditions, and thus provide a conservative estimate of the changes that could occur. I used the LOWESS curves to estimate flooded area at low and high water under these typical conditions and under scenarios of decreased water levels. Decreases of 0.10 and 0.25 m were chosen arbitrarily because the actual decreases that would result from the proposed channel modifications remain unknown. These scenarios did not extend outside of the range of the observations, and thus extrapolation was not required. The curves were interpreted visually using enlarged plots.

RESULTS

The river stage sites showing the best correlation with flooded area in each subregion are listed in Table I. Among the stage sites identified in Figure 1, sites on the Paraguay River yielded the best predictive power in all cases. Scatterplots of the stage and flooded area observations for each subregion are depicted in Figure 2, which also shows the LOWESS curves. The smaller subregions show the poorest relationships between river stage and flooded area, with particular scatter above the LOWESS lines. Much of the scatter above the LOWESS lines in these and the other subregions can be explained by a clockwise hysteresis in the relationships. During the rising limb of the hydrographs, the floodplains may fill with water from local precipitation and overbank flow originating upstream a few weeks before the concomitant rise in river levels at the stage measurement stations, which are mostly located downstream of much of the flooded area.

Predictions of the decrease in flooded area that would accompany reductions in water level of the Paraguay River are shown in Table II (low water) and Table III (high water). Results are expressed as the flooded area that would remain, and as the percent change in flooded area in that subregion compared to no change in water levels. The results for the individual subregions are also summed to show the total decrease in flooded area within the subregions influenced by the Paraguay River.

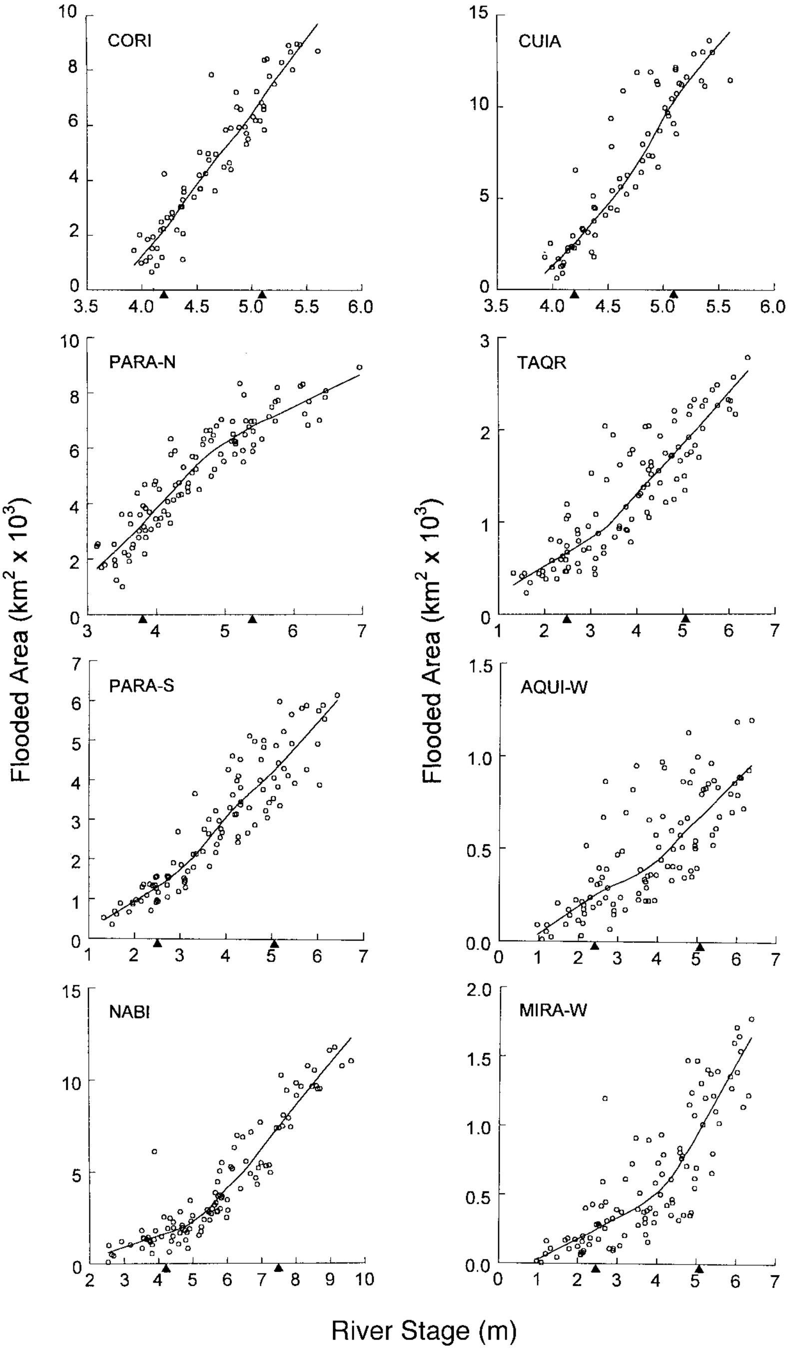

Figure 2. Relationships between river stage and flooded area for the eight subregions that are potentially affected by the stage of the Paraguay River. The curves were determined by the LOWESS smoothing procedure (see text for explanation). Triangles below the abscissa mark the 20th and 80th percentiles for the stage observations. Figure 1 provides the locations and full names of the subregions, and Table I lists the river stage sites

At low water, the sum of the predicted flooded areas for the individual subregions shows the total flooded area to be reduced by 1430 and 3830 km^2 for respective decreases in river stage of 0.10- and 0.25-m. At high water, the predicted reductions are 2410 and 5790 km^2 for respective decreases in stage of 0.10- and 0.25-m. The results of the scenarios for individual subregions show that these decreases are

Table II. Predicted decreases in flooded area for subregions along the Paraguay River at low water, based on the relationships between flooded area and river level in each subregion

Low water	Flooded area (km^2)			Percentage decrease	
Subregion	No change	Stage −0.10 m	Stage −0.25 m	Stage −0.10 m	Stage −0.25 m
Corixo Grande	2212	1757	1067	20.6	51.8
Cuiabá	2587	2128	1058	17.7	59.1
Paraguay River, North	3276	3002	2657	8.4	18.9
Paraguay River, South	1301	1230	1114	5.5	14.4
Taquari River	667	632	592	5.2	11.2
Aquidauna/Negro, West	257	241	219	6.2	14.8
Miranda, West	248	230	207	7.3	16.6
Nabileque	1672	1566	1472	6.3	12.0
Sum of individual subregions	12 219	10 785	8385	11.7	31.4

Estimates are provided for the present situation (no change in stage; 20th percentile stage value) and for hypothetical decreases in stage that may result from river channel modifications. Subregions are depicted in Figure 1, and the stage stations and 20th percentile stage values for each subregion are listed in Table I

not evenly distributed throughout the region, and that certain subregions would have more extreme reductions in flooded area. Flooded areas in the two northernmost subregions—Corixo Grande and Cuiabá—are reduced by more than half with a 0.25-m decrease in river levels during a typical low-water period. Decreases in flooded area on the order of 10–20% are also predicted for the other subregions with a 0.25-m decrease at low water.

At high water, the Corixo Grande and Cuiabá subregions are also the most strongly affected by reductions in river levels. The northern and southern Paraguay River subregions are predicted to be least affected by a decrease in river levels at high water, reflecting the deeper flooding in those areas.

DISCUSSION

The reductions in flooding predicted to result from decreased river levels are large and would have strong impacts on the floodplain ecosystem. Reductions in flooded area are largest during high water but are proportionately greater during low water (Table II), when they would be particularly critical for aquatic animals that depend on the few remaining flooded areas for refuge, including fishes, giant river otters, and

Table III. Predicted decreases in flooded area for subregions along the Paraguay River at high water. See Table II for explanation

High water	Flooded area (km^2)			Percentage decrease	
Subregion	No change	Stage −0.10 m	Stage −0.25 m	Stage −0.10 m	Stage −0.25 m
Corixo Grande	7067	6463	5632	8.5	20.3
Cuiabá	10 422	9375	7740	10.0	25.7
Paraguay River, North	6821	6664	6421	2.3	5.9
Paraguay River, South	4255	4150	3969	2.5	6.7
Taquari River	1872	1804	1731	3.6	7.5
Aquidauna/Negro, West	670	651	612	2.8	8.7
Miranda, West	961	910	830	5.3	13.6
Nabileque	7425	7061	6766	4.9	8.9
Sum of individual subregions	39 493	37 078	33 701	6.1	14.7

caiman. In the longer term, major changes in vegetation would be expected in areas where the average flooding period is reduced significantly, or flooding is eliminated. The reduced extent of inundation at high water, which ranges from 6-26% for individual subregions (Table III), would represent a significant loss of floodplain area at the regional scale.

The scenarios offered in this study represent typical conditions during the past few decades. Since 1974, water levels in the Paraguay River have been higher than the mean for the past century, as revealed by the stage record for Ladário, which dates from 1900 (Hamilton *et al*., 1997). The long-term mean stage of the Paraguay River at Ladário is 2.66 m (1900–94), while for the 1979–87 period analyzed in this study the mean stage is 3.80 m and the 20th percentile stage is 2.50 m. Given that the impacts of reduced river levels on flooded area may be greatest at lower river stages, it would be expected that when dryer periods occur again in the future, the impacts of channel modifications on floodplain inundation would be even greater than these scenarios suggest. Prolonged dry periods spanning several years have occurred on several occasions during the period of record. Such dry periods would probably impede normal navigation and lead to the desire for further channel modifications beyond those now proposed, exacerbating the impacts on floodplain inundation.

The scenarios presented here are conservative because they use the 20th and 80th percentiles of river levels as the starting points. From an ecological perspective, the minimum and maximum stage levels might be more relevant. The minimum stage determines how much aquatic habitat persists through the dry season, and the maximum stage defines the boundaries of the floodplain ecosystem. I did not use the minimum and maximum stage for my predictions because the stage–inundation relationship is not as well-defined at the extremes, and in the case of low water, the scenarios would have required extrapolation below the range of observations for the 9-year period. Although statistical extrapolation is not advisable, examination of the curves in Figure 2 strongly suggests that the two northernmost subregions would be more likely to dry completely for at least one month at low water with a 0.25-m decrease in river levels. Even a brief complete desiccation of the floodplain at low water would result in the loss of critical floodplain refuges for aquatic animals, and the river channel may not suffice as a refuge if it is used regularly for navigation.

It is conceivable that flooded area and river level are independent of each other and controlled by some external factor such as local rainfall, but there is abundant evidence to support the conclusion that the major rivers control the extent of inundation on adjacent floodplains in much of the Pantanal. Hydrological studies of the region have consistently concluded that overbank flow and the backwater effect are the main drivers of inundation in the region (UNESCO, 1973; EDIBAP, 1979; RADAMBRASIL, 1982; PCBAP 1996). Flooded area in the southern Pantanal, as observed by passive microwave remote sensing, correlates well with river stage but is 3–5 months out of phase with the seasonal peak in local rainfall (Hamilton *et al*., 1996). The chemical composition of floodwaters in the subregions analyzed in this study generally shows that they originate from river water (either the Paraguay River or its major tributaries), rather than from local rainfall (Calheiros and Hamilton, 1998; Hamilton *et al*., 1998a,b).

The empirical models presented in this study provide only an approximate indication of the manner in which river channel modifications might reduce the inundation of the adjacent floodplains. The models describe the present hydrological system, but do not consider the mechanisms that may control inundation of the floodplains, and how they might be subject to change as the river channel is altered. Interactions and feedback among these mechanisms, which include groundwater exchange and evapotranspiration, as well as rainfall and riverine overflow, could result in fundamental changes in the hydrological dynamics of the system. Hydraulic models of flow-routing may be capable of demonstrating the effects of channel modifications in this kind of system, but at present their application to the Pantanal is severely limited owing to insufficient understanding of the hydrological linkages between the rivers and floodplains and the controls on floodplain inundation. A major new data collection effort spanning several years would be required to obtain the information required to adequately model the hydrology of such a vast region. Until such information is available, the empirical relationships between river levels and flooded area presented here provide the best available indication of the potential impact of river channel modifications on the hydrology of floodplain ecosystems. The results of the scenarios demonstrate how seemingly small decreases in river levels may result in large reductions in flooded area, and underscore the importance of understanding the hydrology of the river–floodplain systems in the Pantanal before major river channel modifications are carried out.

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