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HYDROLOGICAL AND GEOMORPHOLOGICAL CHARACTERISTICS OF THE HYDROSYSTEM OF THE MIDDLE PARANÁ RIVER

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RESUMO - CARACTERÍSTICAS HIDROLÓGICAS E GEOMORFOLÓGICAS DO HIDROSSISTEMA DO RIO PARANÁ MÉDIO

Neste estudo se explica a dinâmica geomorfológica do canal principal do Rio Paraná Médio e de suas áreas alagáveis, juntamente com os tipos de formas do seu leito. Se discute a relação entre o regime do Rio Paraná e seus sedimentos suspensos. Além disto, se apresenta a classificação dos principais tipos de lagos aluvionais e o grau de conexão entre os componentes lóticos e lênticos. Entre os canais secundários e os lagos aluvionais, se estabelecem tanto conexões diretas como indiretas. O sistema de comunicação com o regime do Rio Paraná apresenta quatro fases hidrológicas: fase de isolamento, fase de comunicação com águas de canais naturais na enchente, fase de inundação ou transbordamento e fase de comunicação com os canais naturais na vazante. Esta interação lótica-lêntica produz uma mistura anual entre as águas correntes e as águas paradas, e constitui um fator importante na evolução do hidrossistema do Rio Paraná Médio e na determinação de suas características físicas, químicas e biológicas.

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ABSTRACT - HYDROLOGICAL AND GEOMORPHOLOGICAL CHARACTERISTICS OF THE HYDROSYSTEM OF THE MIDDLE PARANÁ RIVER

The geomorphological dynamics of the Middle Paraná main channel and its fringing floodplain, together with the channel bedforms types is explained. The relationship between the Paraná water regime and the suspended sediments is stressed. The classification of the main types of alluvial ponds and the degree of connection between lotic and lentic componentsare also mentioned. Direct as well as indirect connections between the anabranches and floodplain ponds exist. The communication system with the Paraná regime shows four hydrological phases: isolation phase, bankfull rising-water phase, overbanks phase, and bankfull falling-water phase. This lotic-lentic interaction causes an annual mixture between running and "standing" water, and is a primary factor in the evolution of the Middle Paraná hydrosystem and in its physical, chemical and biological behavior.

INTRODUCTION

The Paraná River system is an important water source and contributes 77% of the total annual discharge of the Río de la Plata Basin (3.7 km x 10^6 km²), with a discharge of c. 500 million m³ yr^{-1}.

There is a wide range in the climatological and geological parameters of the Paraná River Basin. In southeastern Brazil, the Upper Paraná drains an area of the tropical Brazilian Shield and the Paraná Tholeitic Basalts. Its major tributary, the Paraguay River, also drains a portion of the tropical Brazilian Shield before joining with the Paraná. The Bermejo River, a large tributary of the Paraguay, drains areas that extend westward into the

Andean Mountains and supplies the major portion of the dissolved and suspended load to the Río de la Plata (DEPETRIS & GRIFFIN, 1968; DEPETRIS, 1976; DRAGO & AMSLER, 1988). The Middle and Lower Paraná drains the eastern portion of the loess mantled Argentine Pampa Plains.

The Paraná is usually separated into three physiographic reaches: Upper, from its source to the Paraguay confluence; Middle, from the confluence to Diamante City (Argentina); and Lower, from Diamante City to the Río de la Plata. Due to recent man-made changes, however, the Paraná might now be divided in two reaches: the highly impounded Upper system from source to Itaipú Reservoir, and the unimpounded remainder Middle and Lower Paraná system.

This article deals with the geomorphological and hydrological features of the Middle Paraná hydrosystem.

RESULTS AND DISCUSSION

WATER REGIME AND SUSPENDED SEDIMENTS

The Paraná River has a length of 3.780 km and drains 2.600.000 km², the second largest catchment of South America. The reach between its confluence with the Paraguay River and Diamante City (Argentina) is known as the Middle Paraná. It is 707 km long (Fig. 1).

Owing to the great latitudinal extension of its drainage basin (from 15° to 34° S), the Paraná River receives water supplies of catchments with different pluvial regimes. Nevertheless it has a characteristic continuity in its hydrologic regime. Important tributaries, such as the Iguazú and Paraguay Rivers, the latter with a clear inverse hydrological behavior (low waters in summer and floods in autumn-winter), do not alter significantly the water level hydrographs along its main stem. This fact

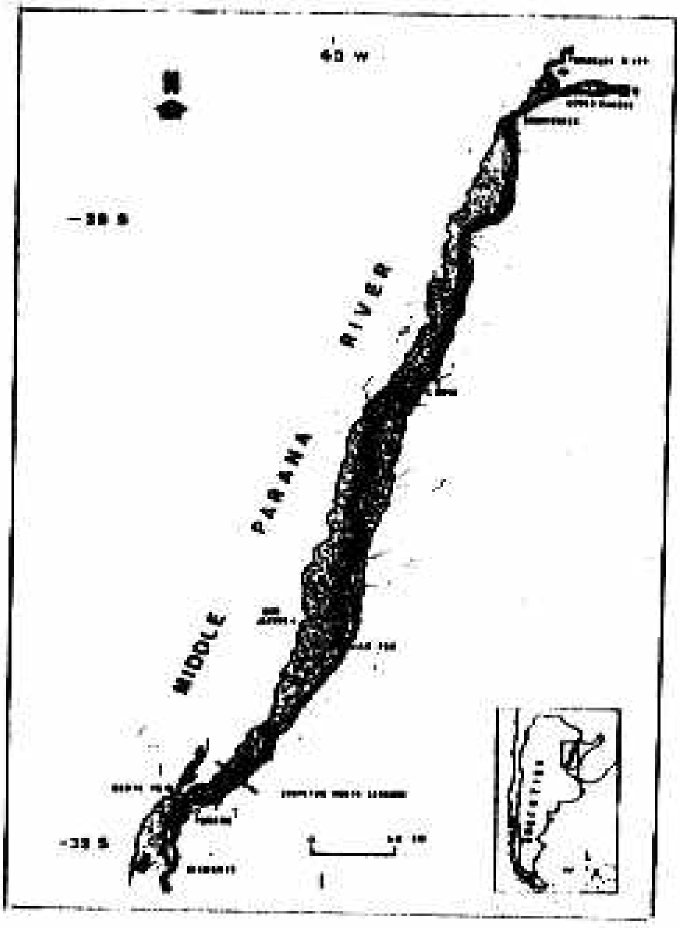

Figure 1 - The fringing floodplain of the Middle Paraná River between the Paraguay River outlet and Diamante City (Argentina).

is reflected in the middle reach of the Paraná River (Fig. 2), that presents the following features:

i) A high water period, with maximum levels in February-March, as a consequence of annual rains fallen during September-February, which impresses its regime on the Paraná River.

ii) A low water period, that begins at the end of autumn, with minimum levels in August-September. Sometimes this period extends to the end of the year.

iii) A minor water level peak in autumn (June), determined by the flood of the Iguazú River.

The absolute water level fluctuations in the upper

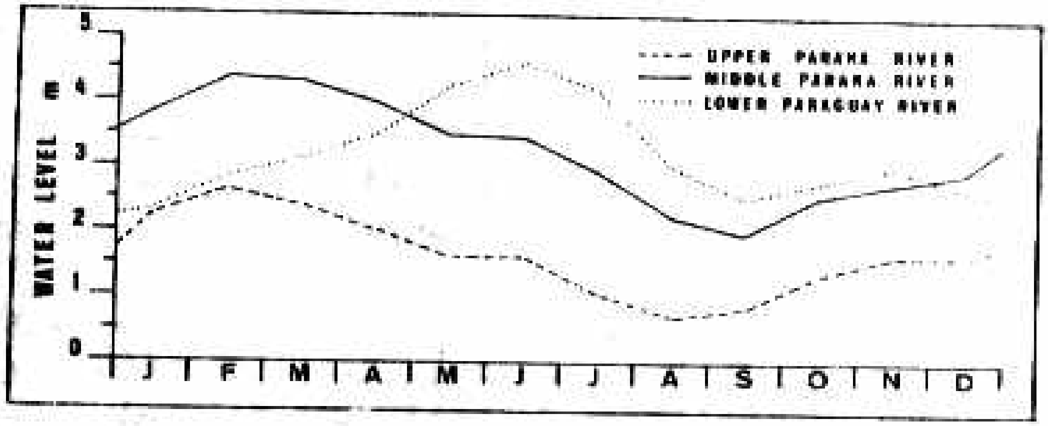

Figure 2 - Water level curves of the Upper Paraná River (at Posadas City, Argentina) and Middle Paraná River (at Corrientes City, Argentina) downstream from outlets of the Iguazú and Paraguay Rivers, respectively. Note that the water level regime of the Lower Paraguay River (at Formosa City, Argentina) does not alter behavior of the Middle Paraná River at Corrientes City. The mean annual discharges of the Paraná and Paraguay Rivers at the confluence are 13.684 $m^3 s^{-1}$ and 4.186 $m^3 s^{-1}$ respectively.

and lower sections of the middle reach, are respectively 9.39 m (in Corrientes City, Argentina) and 8.36 m (in Paraná City, Argentina).

The flood-wave translation varies according to the hydrological state of the stretch, from 5 to 20 days (SOLDANO, 1947). During high waters, measured velocities attained 35 km day^{-1}, 20 days being the aproximate renewal time of the stretch (unpublished data). The maximum and minimum water discharges are 60.000 $m^3 s^{-1}$ to 4.000 $m^3 s^{-1}$ respectively, with an annual average discharge of 16.000 $m^3 s^{-1}$. The magnitude and variation of the water discharges are strongly determined by supplies from the Upper Paraná.

The Bermejo River supplies large volumes of suspended sediments to the Lower Paraguay River and thence to the Middle Paraná, exerting a great influence on the character of the suspended material carried by the latter river. At the confluence of the Paraguay and Upper Paraná Rivers, the ratio of water discharges reaches an average of 3.86:1; nevertheless the suspended sediment concentrations in the Paraná River increase more than 100% downstream from the confluence: the mean concentration values are 114 mg l^{-1} in the Upper Paraná, 576 mg l^{-1} in the Lower Paraguay and 250 mg l^{-1} in the Middle Paraná for the period of maximum suspended sediment discharge (DRAGO & AMSLER, 1981).

The concentration peaks in the Middle Paraná River lag behind the highest streamflows, this delay fluctuating between 22 and 39 days (DRAGO & AMSLER, 1988). Maximum suspended loads are transported in April (Fig. 3). The differences between the regimes of the Upper Paraná and Bermejo account for the lag, since the highest streamflows of the Upper Paraná arrive at the Paraguay mouth before the peak concentrations coming from the Bermejo.

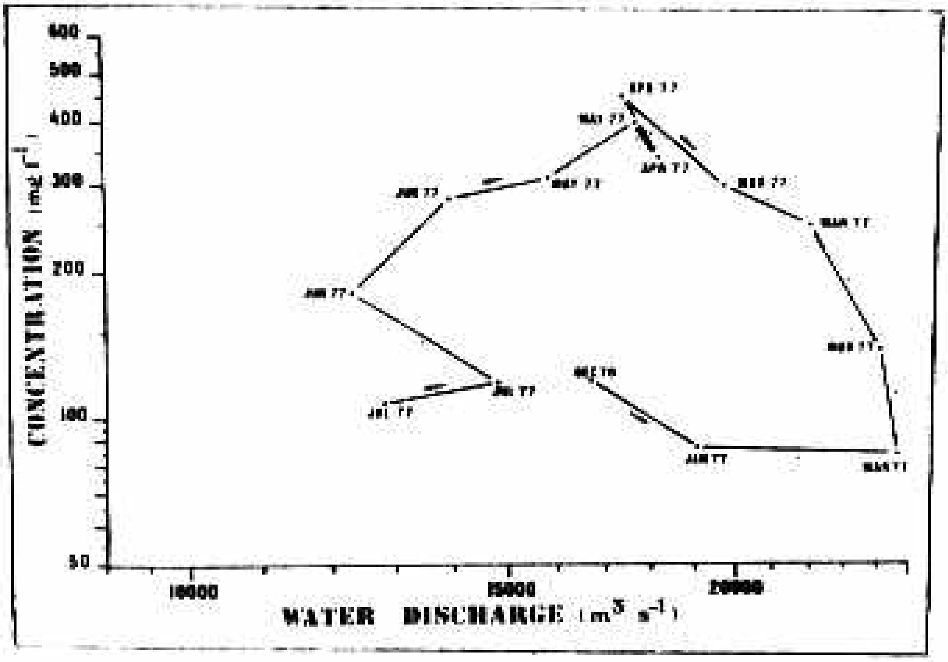

Figure 3 - Middle Paraná River, Aguas Corrientes cross-section (Paraná City, Argentina). Anticlockwise cycle observed between the suspended sediment concentrations and water discharges during the flood of 1977.

The suspended sediments of the Middle Paraná are composed largely of wash load (more than 60%), with high percentages of particles within the fine and very fine silt and clay ranges (<16 μm). The Bermejo River also influences the composition of suspended sediments, since when concentration peaks occur, the mean diameters, sorting, and clay percentages are closely related to those which occur 2.063 km upstream in the Bermejo Upper Basin. The total suspended yield in the Middle Paraná is over 100 x 10^6 t yr^{-1} (DRAGO & AMSLER, 1988).

FLUVIAL GEOMORPHOLOGY

The braided channel of the Middle Paraná presents broad expanses, over 8 km wide, and narrows of 400 m (node points); at mid-water, maximum depths reach 45 m and can dwindle to shallows of only a few meters.

In a river as highly charged with sediment as the Middle Paraná, the bed and bank morphology changes drastically under different flow regimes. Deposition of sediment in one point causes scour in another point. Thus the thalweg tends to wander continuously from one position to another withing the river banklines. This is generally characterized by two distinct types of movements: gradual and continuous transverse movements, and sudden shifts from one position to another. Fig. 4 shows the magnitude of the movement of the thalweg from a stable reference point. For example, the shiftings observed in cross-section A are always lower than 35 m yr^{-1} (Fig. 4 and 5), and the thalweg remains nearly constant in location. This fact shows the stability of the cross-section due to its condition of primary control point, originated by the low erodibility of the left bank and by the low degree of erosion and deposition on the border of the floodplain.

Cross-section B (Fig. 4 and 5) shows a sharp

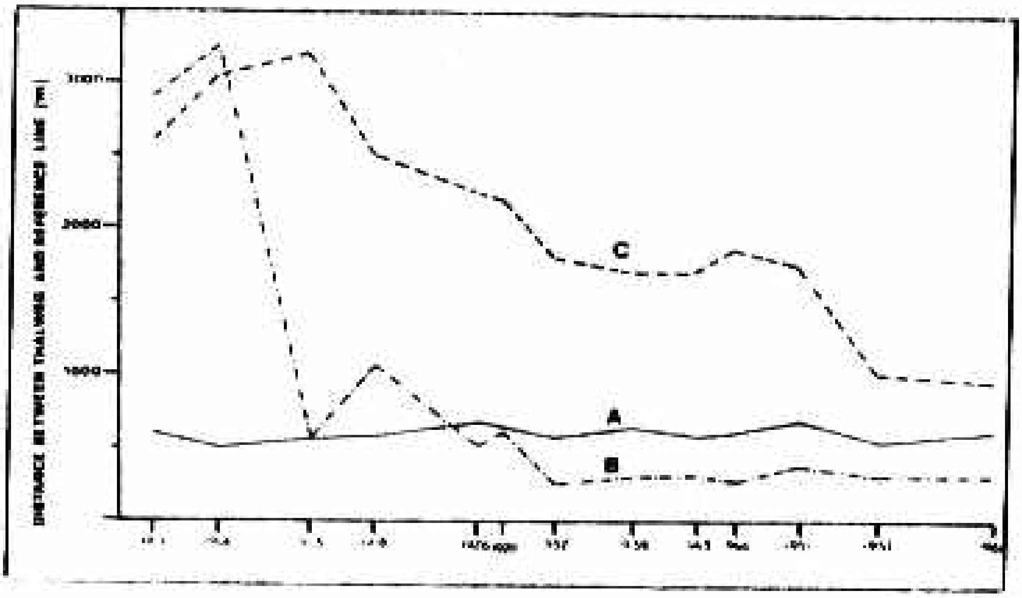

Figure 4 - Middle Paraná River. Shiftings of the thalweg in three cross-sections located in a reach of 13 km long.

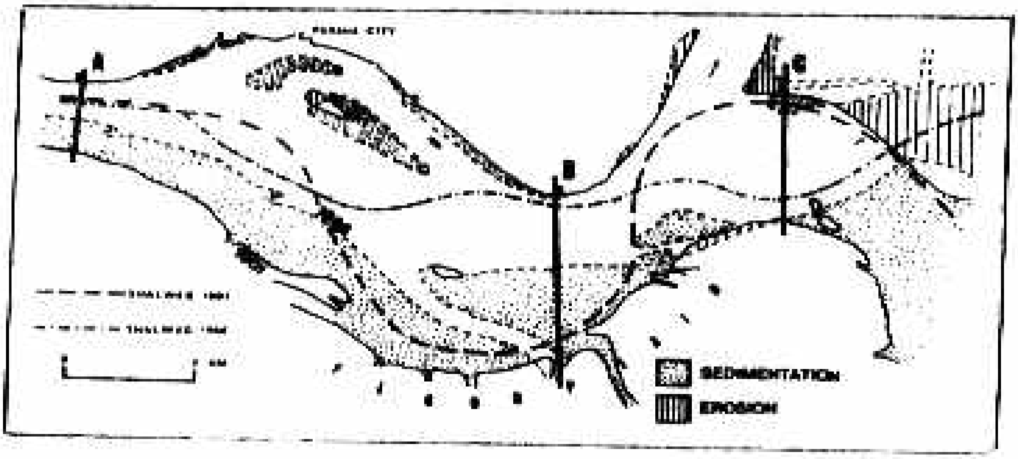

Figure 5 - Middle Paraná River. Comparative bankline changes, shifting of the thalweg and principal sites of deposition and erosion during the period 1901-1966. A, B and C: cross-sections studied.

change between 1906 and 1913, with shiftings of the thalweg over 350 m yr^{-1}, originated by the continuous progress of the floodplain border and by the stability of the other bank, composed of sandstones and limestones. Since 1926 a primary control point formed on that cross-section; therefore it became stable and very little movement of the thalweg has taken place since that time.

Cross-section C (Fig. 4 and 5) shows a different behavior. The channel has both banks built out exclusively by alluvial sediments, with a gradually wandering talweg, because one bank is cutting and the opposite is building out at a similar rate. The maximum shifting detected in this cross-section was 107 m yr^{-1} (1951-1957).

Thus, shiftings of the thalweg are strongly related to the building or retreating of the floodplain border and to the movements of the sand bars and islands, especially when they are attached to the floodplain border.

The dynamics of erosion and deposition in the main channel of the Middle Paraná are shown in Fig. 6, where are represented the volume changes of the reach studied, which has a surface area of 73 km². During 1901-1913, there was a

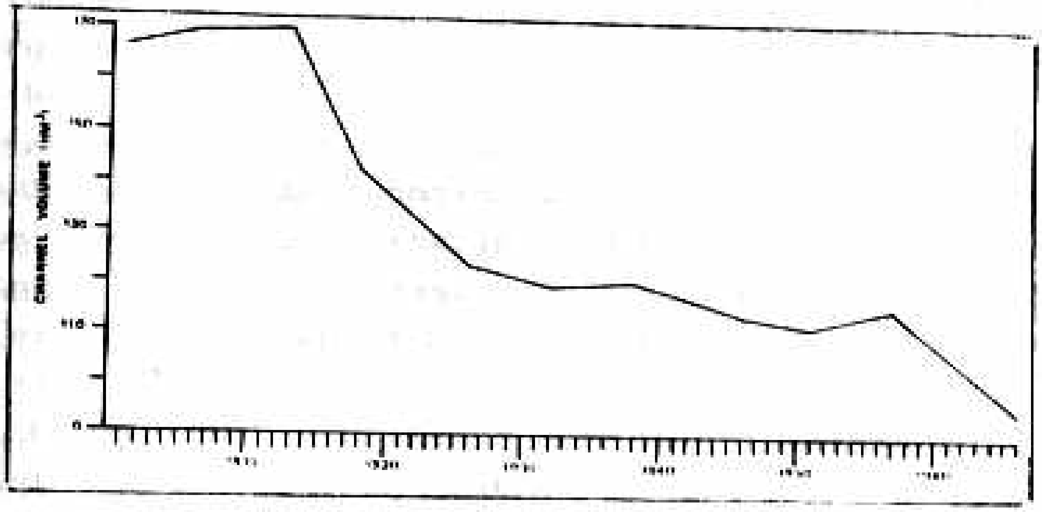

Figure 6 - Middle Paraná River. Channel volume changes due to the processes of erosion and deposition in a stretch of 13 km along the main channel.

small increase of the volume, indicating a prevailing erosion. Since 1913, a progressive decrease of the channel volume started, showing a clear tendency to silting of the reach. Therefore, 71 hm³ of sediments were deposited in the reach during 66 years, with an annual average sedimentation of 2×10^6 t yr^{-1} and an annual maximum deposition of 9×10^6 t yr^{-1} (DRAGO, 1977a).

These features clearly demonstrate that the principal sites of deposition or erosion are founded in the thalweg or on the floodplain border, being the areas where the greatest morphological changes are detected (Fig. 5). In Fig. 7, a conceptual model of the relationships among the different geomorphological elements is provided.

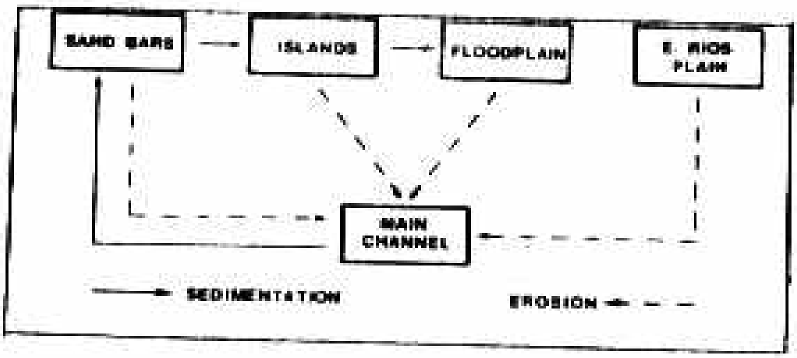

Figure 7 - Middle Paraná River. Conceptual model of the interrelationships among the different geomorphological elements in the alluvial valley.

It has been long recognized that loose, granular bed material generates characteristic forms under aqueous current. Considerable controversy exists regarding terminology applied to the various types of bedforms. The major cause of this controversy lies in the different scales of features observed in flume studies and field investigations (COLEMAN, 1969). Bedform terminology is unusually difficult in a river system such as the Paraná, where the wave heights of bedforms range from a few centimetres to over 10 m. Four groups could be identified

(DRAGO, 1977b; Fig. 8):

1) Ripples. The term "ripples" is applied to those forms that have a wave height ranging from a few centimetres to 0.30 m. The form of the ripples in plan view is ephemeral and generally changes drastically within a few hours. The most common type is the linguloid ripple. On some of the broad sand flats surrounding the islands, straight-crested ripples are common and are generally superimposed on the upstream face of larger bedforms.

2) Megaripples. These have wave heights ranging from 0.30 m to 1.5 m. In plan view megaripples are generally linguloid or lunate in shape. The depths over their crests vary from 3 m to 14 m.

3) Dunes. They range in wave height from 1.5 m to 7.5 m. The depths over the crest vary from 1.5 m to 18 m and the wave lengths are variable, ranging from 61 m to 520 m. They are the most common active bedforms in the thalweg of the Middle Paraná. Dunes cause quite a disturbance in the flow, producing large boils on the water surface. Even in quite deep water, the presence of dunes is apparent from boils on the water surface.

4) Sand waves. These are the most spectacular type of bedforms, with wave heights ranging from 7.5 m to 15 m. The largest sand wave measured during the study period, had a wave height of 12 m, a wave length of 1.640 m and a depth over the crest of 8.5 m. Sand waves commonly have smaller bedforms superimposed on their backs. These smaller bedforms are generally megaripples, but occasionally larger forms are found (dunes). Large, turbulent boils break the surface downstream from the crestline. Boils are easily discernible from the air, because they are heavily charged with sediment and the dark color imposed by this sediment concentration stands out from the adjacent lighter-colored water.

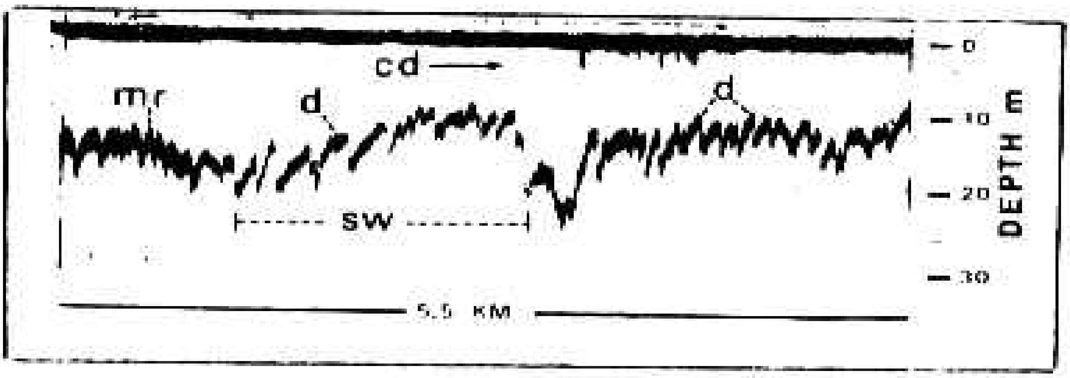

Figure 8 - Middle Paraná River. Echogram of longitudinal profile in a main channel showing typical and well-developed megaripples (mr), dunes (d), and sand waves (sw); cd: current direction

MIDDLE PARANÁ FLOODPLAIN

A braided channel is characterized by innumerable sand bars and mid-channel islands which separate the flow into several channels. Such a condition exists in the Middle Paraná channel, which is choked with sand bars and islands. The sand bars are generally diamond-shaped in plan view, and their long axes are oriented parallel to the average flow direction of the channel in which they form (DRAGO, 1977a). The angle of the upstream face is molded and determined by the variation in current flow direction in the vicinity of the island. The longer downstream faces of the islands generally have very low slopes, and the surface is covered with ripples and larger bedforms. During the high water period, the islands are inundated and in some cases they are completely removed by erosion, but commonly they suffer erosion on their upstream faces and deposition on their downstream ends. This process generally causes the island to migrate downstream. In most cases the total area of the islands remains aproximately the same from one flood to another, and only their positions and shapes change. In some instances, however, whole islands disappear or new islands form. The large number of bedforms observed on the surface of these islands when they are exposed, indicates that the sediment has moved as migratory dunes during flood. The sand bars are first colonized by aquatic and semi-aquatic grasses and subsequently by alder (*Tessaria integrifolia*) and willow (*Salix humboldtiana*) forests.

The processes mentioned above and the joining of the islands to the floodplain border, are important features in the building and in the increasing of the floodplain surface. Along its middle reach, the Paraná River has built a composite, fringing floodplain, covering an area of 13.063 km^2 (width range: 6-40 km). About 30% of this area is interspersed with permanent waterbodies, some of which are as large as 130 km^2 (Tab. 1). At the peak of the floods, they tend to merge into a continuous sheet of water that covers the whole floodplain, that is, the ponds are periodically engulfed by the Paraná River. At low river levels, processes such as the growth and decay of primary producers (mainly macrophytes), and the mixing and resuspension of bottom sediments, govern pond metabolism. According to JUNK (1980, 1982, 1983), such waterbodies are intermediate between closed lakes as accumulating systems and rivers as discharging systems; hence, they are not true

Table 1 - Mean general characteristics of a typical floodplain section of the Middle Paraná River at mid-water level.

Number of ponds by km^2	3
% of area covered by ponds	18
Mean shoreline development	1,6
Number of swamps by km^2	2
% of area covered by swamps	16,6
Mean shoreline development	1,3
Number of channels by km^2	2
% of area covered by channels	6
Drainage density (km/km^2)	2,2

lakes. For this reason I use the term pond for the waterbodies of the Paraná floodplain. They are remarkable, as compared with lakes, for their shallowness and absence of long periods of thermal stratification.

ORIGIN OF THE ALLUVIAL WATERBODIES

Owing to these river and floodplain dynamics, the thousands of floodplain ponds in the Middle Paraná vary considerably in shape and size. The ponds range in shape from dendritic to circular, with lengths from less than 100 m to more than 10 km. They are shallow, rarely exceeding 5 m depth at mid-water stage, and with regular bottom topography.

The evolution of these waterbodies is related to geomorphological, hydrological, and biological (e.g., palustrine and aquatic vegetation) factors. DRAGO (1976), taking into account the processes responsible for building, excavation, and damming, classified the Paraná floodplain ponds according to the following main types:

1) Obstruction ponds, formed by sediment deposition at the ends of abandoned and well-defined secondary channel stretches. They vary in their shapes from slightly to strongly curved, elongated, and narrow troughs. They are extremely common in the Paraná floodplain, due to the meander migration of the anabranches (e.g., oxbow and meander scroll ponds; Fig. 9).

2) Levee ponds, troughs entirely suttounded by levees, originated by the downstream evolution of channel bars and mid-channel islands. Each bar or island will be converted into a basin as soon as deposition closes the open ends. This basin remains as a central cavity that will form the new pond (Fig. 10a). Levee ponds may be also formed in the islands and sand bars of an internal delta and build up when a tributary flows into the ponds. They

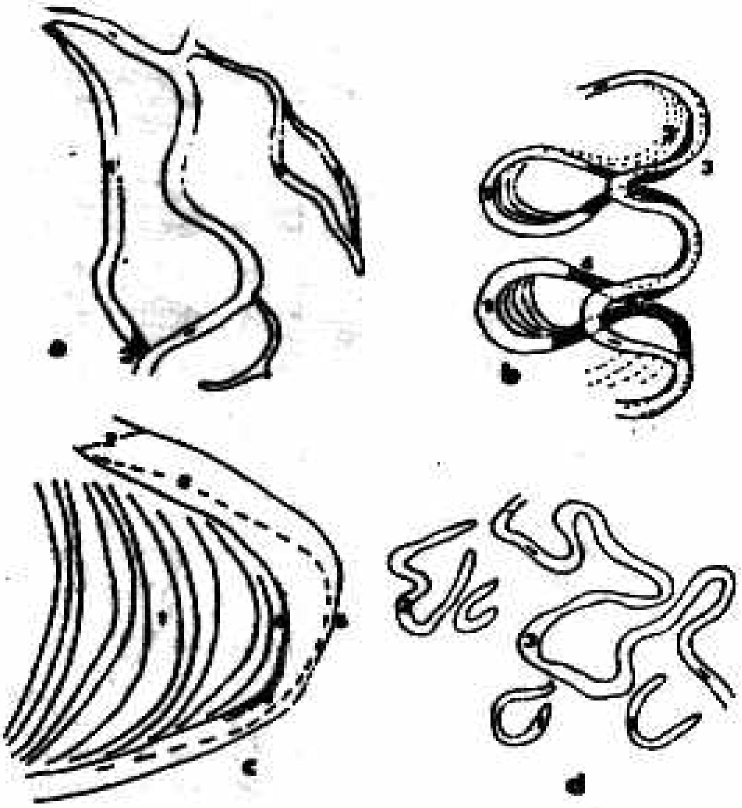

Figure 9 - Middle Paraná River floodplain. a: obstruction ponds (1) and the "sediment plugs" (2); b: stages in the formation of cutoffs and in development of new meanders, oxbow ponds (1), meander scrolls (2), point bars (3), "sediment plugs" (4); c: meander scroll ponds (1), river banks (2), thalweg (3), point bar (4) and cut bank (5); d: oxbow pond (1), multiple oxbow pond (2) and main river channel (3).

are triangular in shape.

3) Inter-bar ponds, formed when a large channel stretch is dammed at its ends by fluvial bars or islands. Their surfaces are large and dendritic (Fig. 10b).

4) Lateral expansion ponds, similar in origin to the preceding types, but owing to breaking of levees, the water drowned adjacent lowlands. They present a very particular basin shape, with the former channel connected to a lateral trough (Fig. 10c).

5) Annexation ponds, formed by a fusion of two or more waterbodies. Their shapes vary between subrectangular-elongated and dendritic (Fig. 10d).

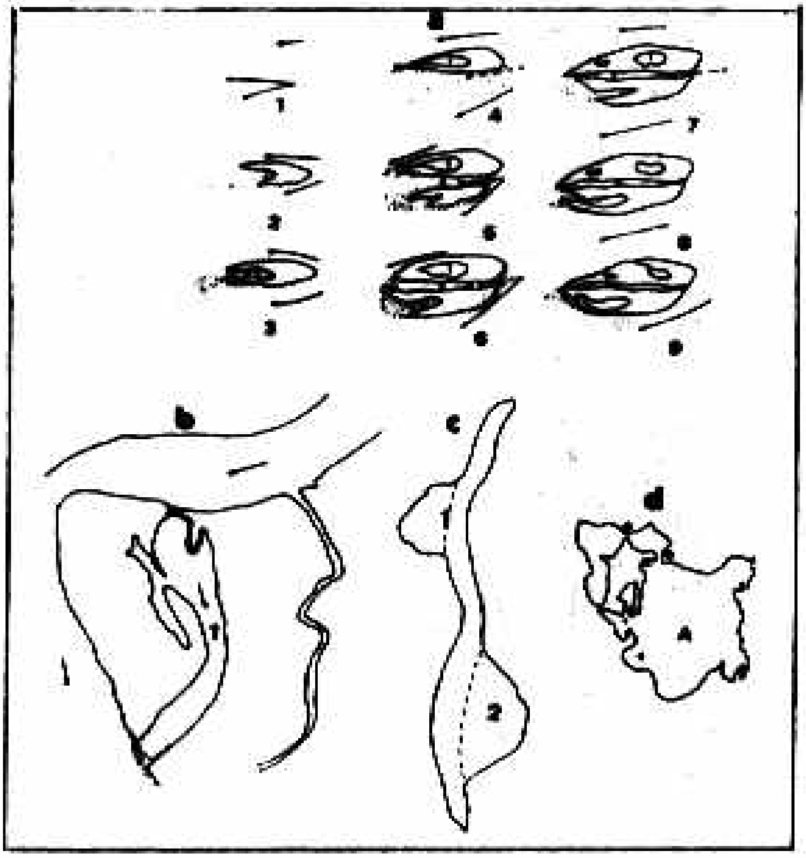

Figure 10 - Middle Paraná River floodplain. a: scheme showing the origin and evolution processes of the channel bars and islands and the origin of the levee ponds (1) and inter-bar pond (2); b: inter-bar pond in development (1); c: lateral expansion pond, the broken-line indicates the border between the eroded levee (1) and the lateral water expansions (2); d: annexation pond; arrows indicate the points of annexation to other waterbodies.

7) <u></u>

6) Overflow ponds, lying in smooth depressions originated by uneven aggradation or degradation during floods. They have irregular shapes and are situated near the main channels.

7) Swamps, lying in old pond troughs, filled by river sediments and organic materials. They are the final stage in the evolution of the Paraná floodplain ponds and may be associated with other waterbodies. They support dense growths of aquatic macrophytes, covering up to 100% of their surfaces.

DEGREES OF CONNECTION BETWEEN LOTIC AND LENTIC COMPONENTS

The floodplain geomorphology and the origin and evolution of its waterbodies will determine the degrees of connection between rivers and ponds. Generally, these communication systems become more complex with the increasing distance from the main channel (Tab. 2).

Table 2 - Middle Paraná River floodplain. Number of waterbodies and drainage density for different floodplain areas. A: near the main channel; B: far from the main channel.

	A	B
Number of ponds by km^2	0,11	2,53
Number of swamps by km^2	0,75	3,55
Number of channels by km^2	1,02	2,41
Drainage density (km/km^2)	0,95	3,20

The shallow waterbodies are filled annually during periods of rising water due to the river water inflow. During falling stages, the surplus pond water flows back into the river. At low stages, large portions of the ponds become dry. At high stages, the floodplain becomes inundated and the ponds may lose their identity. Thus, the floodplain ponds are strongly influenced by the seasonal fluctuations of the Paraná level, and they expand and contract according to the annual flood cycle. Some permanent waterbodies may be in communication with the main river or its anabranches during a great part of the year (Tab. 3).

Table 3 - Middle Paraná River floodplain. Annual periods of isolation and connection for two floodplain ponds separated by 7 km (time in days).

		1975	1976	1977
"Los Mataderos" pond	Isolated	18	0	17
	Connected	348	366	348
"El Negro" pond	Isolated	354	243	224
	Connected	11	123	141

During mean water stage, two kinds of connection between rivers and ponds can be distinguished (Fig. 11):

1) Direct connection, communication through to a mouth, ditch, or a short channel only. The river water fluctuations are quickly reflected in the ponds, and the communication channel has a reversible flow.

2) Indirect connection, communication through channels of greater length, with intermediate pond and/or swamp basins. The pond water level shows more irregular oscillations due to greater isolation from the main channel.

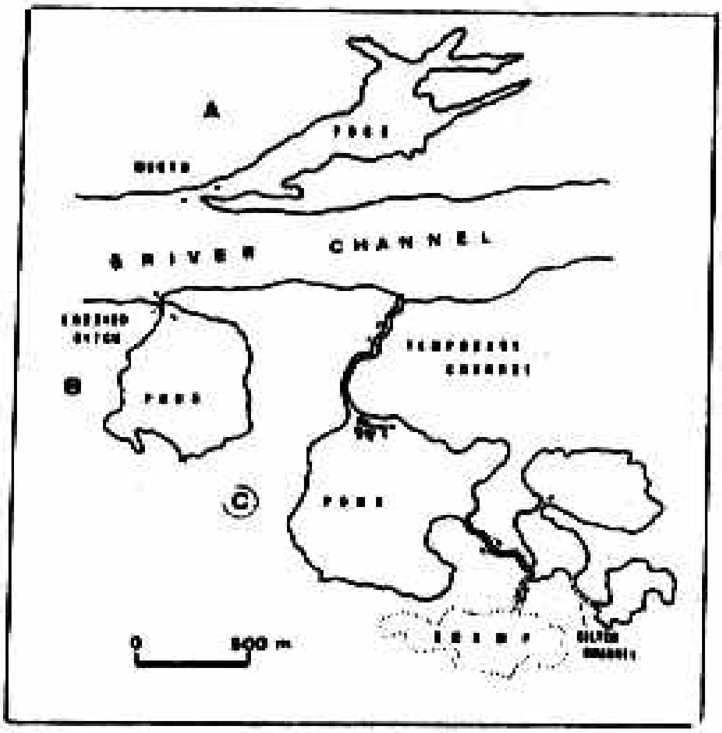

Figure 11 - Degree of direct connection during mid-water stage through mouth (A), an erosion ditch (B), a temporary channel with reversible flow (C). Note in (C) the internal delta built up in the largest pond and the other waterbodies with indirect connection with the main channel.

These different degrees of connection are reflected in the diverse hydrological behavior of the lentic waterbodies and in the quality of water they will receive from the Paraná River and its anabranches. Some physical and chemical characteristics of the river water show strong changes during its displacement across the lentic and lotic components of the floodplain (Fig. 12).

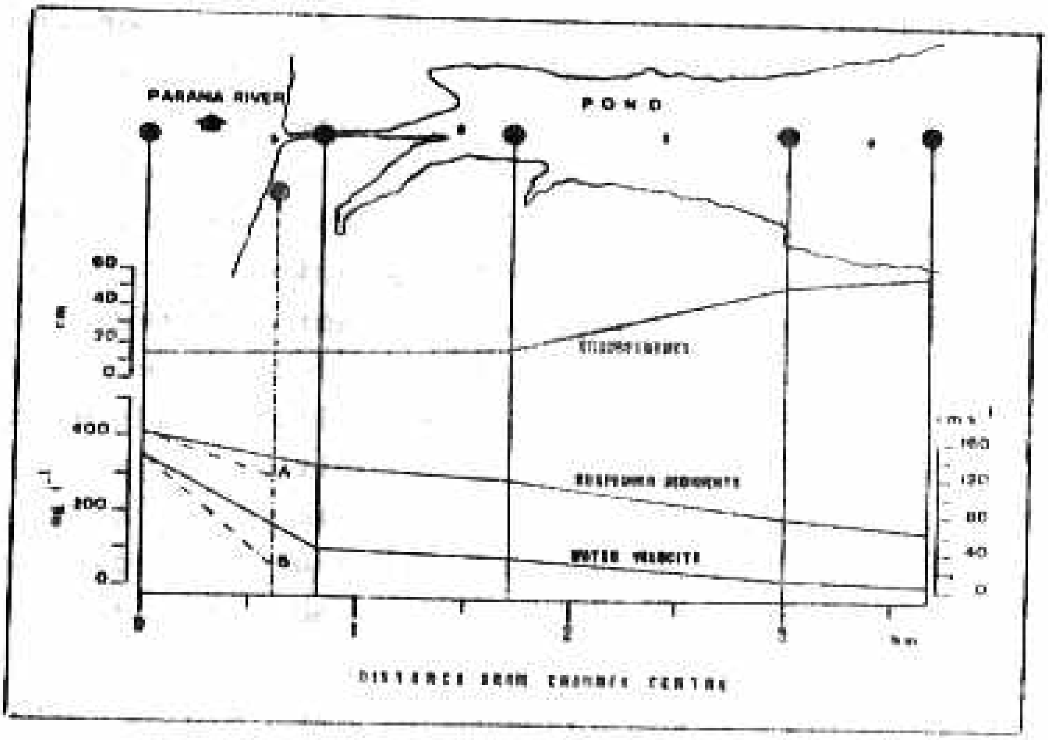

Figure 12 - Changes in transparency (Secchi disc), suspended sediment concentration and current velocity during the start of the over-banks phase (24-03-77). A and B: data measured on the flooded levee. Note the degree of direct connection between the Paraná River main channel and the floodplain pond La Cuarentena.

WATER REGIME OF THE ALLUVIAL PONDS

The connection degrees between the rivers and the floodplain ponds, together with the yearly water level fluctuations of the Paraná River, generate four hydrological phases in these alluvial ponds. The intensity of mixing between running and "standing" waters will be dependent on these phases, as described below:

1) Isolation phase, there is no communication between rivers and ponds, because the river waters are confined within the main channel and its side-arms. Usually, the means of connection (mouth, erosion ditch, or channel) dry up completely. If this phase is very prolonged, the shallowest waterbodies may also dry up completely, producing mass fish mortalities. Furthermore, conditions in the ponds may be influenced by meteorological factors such as air temperature, wind, and rainfall.

2) Bankfull rising-water phase, the river waters flow into the floodplain ponds without overspilling the levees and other higher flats. The annual supply of allochtonous material to the ponds begins with this phase.

3) Overbanks phase, further rises above the bankfull level result in overspill onto the plain. The floodwater spreads over the levees, flats, and waterbodies, and the ponds lose their lentic identity and attain their maximum depths. Organic and inorganic materials of the levees and flats come into suspension and are carried into the ponds. Mixing between running and "standing" waters reaches its maximum during this phase. The basin morphology and the proximity of some ponds to the main watercourses promote the temporary acquisition by them, completely or partially, of some lotic characteristics (e.g., current velocities over 0.9 $m\ s^{-1}$).

4) Bankfull falling-water phase, decline in stage below the overbanks level originates a flow from the ponds to the rivers. The running waters will again be confined progressively to the channel banklines, and the waterbodies will return to their lentic conditions.

The streamflow fluctuations and the communication systems between lotic and lentic environments will determine the duration and the time of the year of each phase. Clearly, the stage limits will not be the same for waterbodies with different origins and degrees of connection (Tab. 3). Hence, for the same river level it is possible to find both isolated and connected ponds. Furthermore, the persistence of a specific gauge height will determine the duration of the corresponding phase. Usually, in the Middle Paraná River the pond isolation periods are detected between July and December, while the flooding periods are between January and June. However, particular low or high-water peaks can deflect this typical regime pattern. Data obtained by DEAGO (1980, 1981) emphasize the importance of hydrological relationships between streams and ponds in the Paraná alluvial valley (Fig. 13). Fig. 14 shows the different annual stage regimes of two shallow waterbodies 7 km apart; one was isolated about 95% of the year and the other only 39%.

Data concerning the morphology and water regime of floodplain ponds in general, and those of the Paraná alluvial ponds in particular, are scarce, and hence our knowledge of such aquatic habitats is limited. However, with the available information, an outline of the main morphological and hydrological features of the Paraná floodplain waterbodies has been presented herein.

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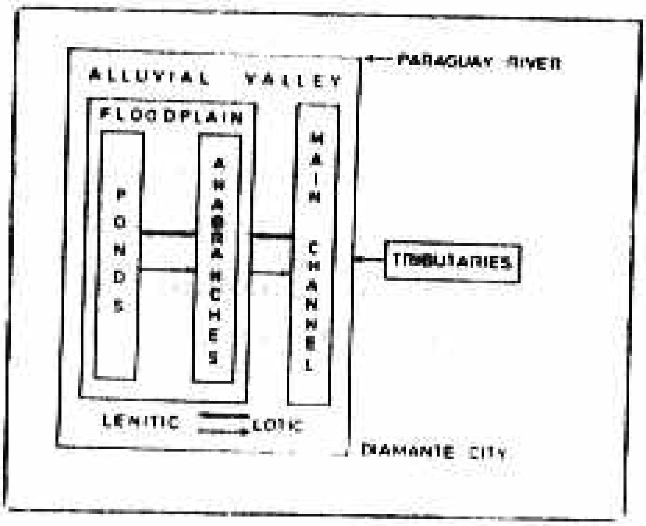

Figure 13 - Middle Paraná River. Hydrological relationships between streams and ponds in the alluvial valley.

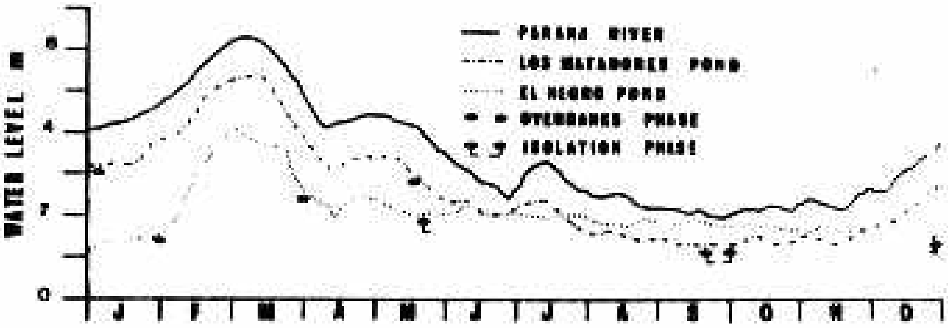

Figure 14 - Hydrological phases in two floodplain ponds of the Middle Paraná River during an annual cycle (1977). Note the different periods for the overbanks phase (January-May) and for the isolation phase (May-December) fot both ponds, separated by 7 km. Los Matadores Pond demonstrates a direct communication with the river, and El Negro Pond an indirect connection. Arrows indicate the different periods of overbanks and isolation phases for both waterbodies.

Closure, Fig. 1) will form a man-made lake over 300 km long, which will cover ca. 50% of the floodplain surface. This reservoir will affect the water-level fluctuations and sediment load of the water and will change the ecological conditions of the Middle Paraná River Valley. Therefore, additional and intensive studies of the aquatic habitats are needed in order to specify floodplain areas for protection.

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