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Hydraulic and morphological characteristics of middle and upper reaches of the Paraná River (Argentina and Brazil)

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Abstract

The Paraná River basin is a 2,600,000-km^2 South American fluvial system, most of which is in Brazil and Argentina. The channel is about 4000 km long, the mean annual discharge is 17,000 m^3 s^{-1}, and the annual sediment load is more than 150,000,000 tons. The basin of the Paraguay River, its main tributary, covers about 38% of the Paraná basin. This paper compares the upper and middle channels of the Paraná. Hydraulic, morphological and sedimentological features of the Paraná River upstream and downstream of the confluence with the Paraguay were analyzed in order to evaluate the changes in these variables. The effect of the Paraguay on water and suspended sediment discharges was examined. The Paraguay River contribution explains most of the variation in channel conditions upstream and downstream of the confluence. The channel pattern, however, remains braided. The high bed load of the Paraná River in proportion to the total sediment discharge (21% in the upper course, 25% in the middle course) determines the similarity in drainage.

Keywords: Paraná River; Channel morphology; Downstream changes; Drainage pattern

1. Introduction

The Rio de la Plata Basin (Fig. 1) is the second largest catchment in South America with an area of 3.1 × 10^6 km^2 of which 45.6% is in Brazil, 29.7% in Argentina, 13.2% in Paraguay, 6.6% in Bolivia and 4.8% in Uruguay (OEA, 1971). The Rio de la Plata is formed by three large fluvial systems: Paraná, Paraguay and Uruguay (Fig. 2). The Paraná Basin, including that of the Paraguay River (2.6 × 10^6 km^2), covers about 80% of La Plata catchment. The Paraná Basin (Fig. 3) includes the following units (Iriondo, 1988): Andes Mountains, Chaco–Pampa Plain, Eastern Plains, Jurassic–Cretaceous Highlands and Brazilian Shield.

The main drainage channel of this large territory is the Paraná River formed by the confluence (Brazil, latitude 20°S) of Paranaiba and Grande Rivers (Fig. 2) which runs roughly south as far as the Rio de la Plata Estuary (Argentina, latitude 34°S). From its divide in the Brazilian Highlands to the mouth near Juncal Island in the Rio de Plata Estuary, the Paraná is 3965 km in length (Fig. 4).

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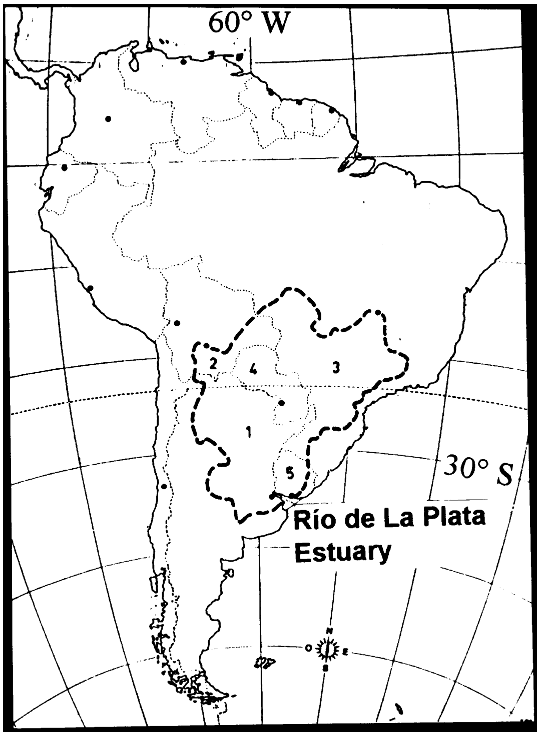

Fig. 1. Rio de la Plata Basin: (1) Argentina, (2) Bolivia, (3) Brazil, (4) Paraguay and (5) Uruguay.

The most important change in the longitudinal profile of the Paraná occurs at the former Sete Quedas Falls (currently Itaipu Dam and Reservoir), where the water surface altitude drops 180 m over a reach of 60 km (Fig. 4).The Sete Quedas Falls have been formed along the fractures and by differential erosion of the Serra Geral Formation basalts, probably during the Pliocene (Maack, 1968; Stevaux, 2000).

The main tributary of the Paraná is the Paraguay River. At the confluence, the annual discharge of the Paraná River increases from 11,983 to 16,941 $m^3 s^{-1}$ (Secretaría de Energía, 1994), and the suspended sediment discharge is from 5.1×10^6 (Amsler and Drago,1999) to 118.7×10^6 tons $year^{-1}$ (Orfeo, 1995). This sediment load includes an input of nutrients (chiefly phosphorous) transported with the sediment through the Bermejo River from the Andes (Carignan and Neiff, 1992). Likewise, the Paraguay brings down free-floating vegetation (called "camalotes" or "aguapés") that determines an increment of sediment retention in the floodplain wetlands. This vegetation retains the inorganic sediment either supplied by the river during floods or resuspended during low flow (Poi de Neiff et al., 1994). In some ponds on the floodplain, the roots of water hyacinth (*Eichhornia crassipes*) retain an average of 200–300 g m^{-2} of suspended sediments during low water and a maximum of more than 2000 g m^{-2} during the flood period (Poi de Neiff et al., 1994). The mechanisms of the retention and transport of the fluvial sediment are not well known at present but seem to have great influence on the geomorphology of the floodplain.

The confluence of the Paraguay and Paraná rivers is an important location in the hydrosedimentology, chemistry and biology of the river system. The objective of this paper is to analyze the major hydraulic, morphological and sedimentological features of the Paraná River upstream and downstream of the confluence with the Paraguay River in order to evaluate the influence of this major tributary on the mainstream.

2. Study areas

Two representative areas of the Paraná River in the upper and middle reaches were selected. The Porto Rico area (Brazil) at the upper Paraná reach is at the border of the states of Paraná, São Paulo and Mato Grosso do Sul (22°43′ 32″S and 53°10′ 30″W), 2340 km from the mouth and 1641 km from the divide of the Grande–Paraná River System. This area (Fig. 5) is located 18 km downstream of the Porto Primavera Dam, 6 km from the mouth of the Paranapanema River and about 200 km upstream of the Itaipu Dam. This is the last reach of the Upper Paraná River before channel modification. At this point, the catchment area is 670,000 km^2, the region has a tropical–subtropical climate with an annual temperature ranging from 10.3 to 33.6 °C with an average of 22 °C and an annual precipitation of 1220 mm.

In the middle reach, an area near Corrientes City, Argentina (27°30′ S, 58°50′ W) was chosen due to its nearness to the confluence between the Paraguay and Paraná Rivers (Fig. 6). At this section (about 30 km downstream of the confluence), the surface drainage is 1,950,000 km^2 and is affected by a subtropical climate

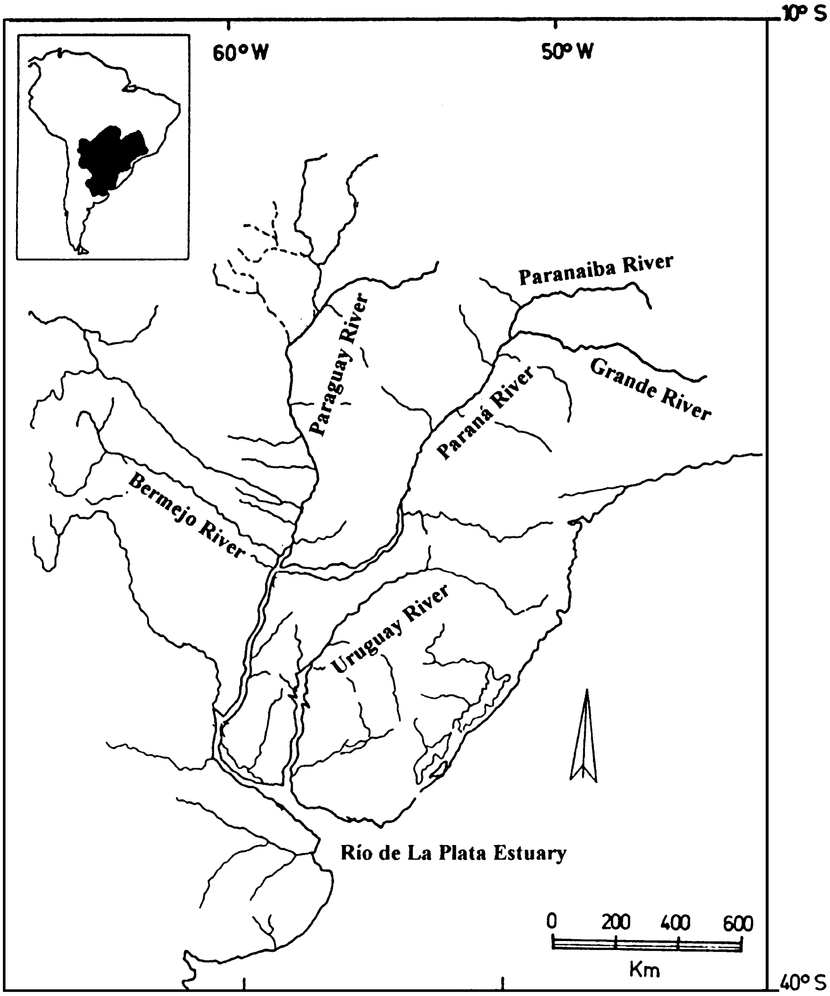

Fig. 2. Main fluvial systems of the Rio de la Plata Basin.

regime with 21.3 °C of mean annual temperature and 1290 mm of mean annual rainfall.

3. Methodology

In order to compare the selected stretches of the Paraná River, the following variables were selected: (1) annual water discharge, (2) suspended load, (3) bed load, (4) suspended sediment concentration, (5) grain size of bed sediments, (6) bedforms, (7) channel width, (8) floodplain width, (9) bar development and (10) channel morphology.

Annual discharge figures were taken from the data recorded and statistically analyzed at Porto São José and Corrientes fluvial stations. The suspended load was calculated using annual discharge and mean annual suspended solid concentration. Bed load discharge was obtained from the Colby (1964) empirical method. Determination of the suspended solid concentration and the grain-size analysis were carried out in laboratory. The first one was obtained by filtering using preweighed cellulose acetate filters of 0.45-μm pore size. The water samples of about 500 ml were collected using an instantaneous horizontal sampler located 0.5 m below the water surface. The bed sediment was collected with a surface bed sediment sampler. Grain-size analysis was carried out by sieving (Ingram, 1971). Echo-sounder surveys were carried out to produce

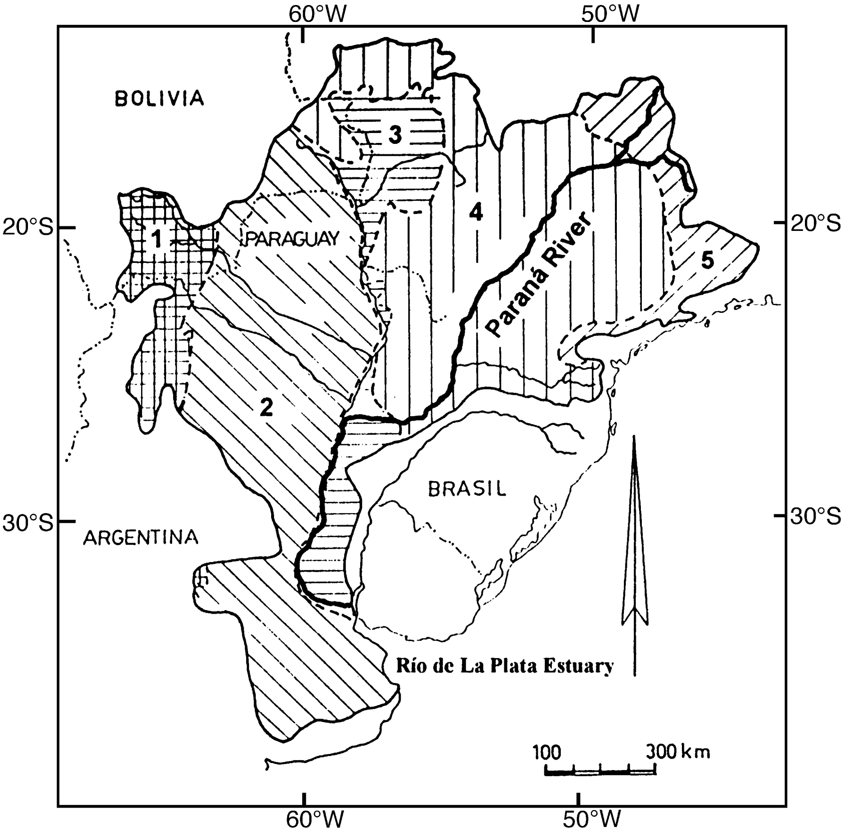

Fig. 3. Geological regions of the Paraná Basin (adapted from Iriondo, 1988): (1) Andes Mountains, (2) Chaco–Pampa Plain, (3) Eastern Plains, (4) Jurassic–Cretaceous Area and (5) Brazilian Shield.

bathymetric profiles used in bedforms analysis. Channel and flood plain widths were measured from aerial photographs and satellite images. The channel was classified following Friend and Sinha (1993). The samples (suspended sediment and bed sediment) were taken during both low and high water levels. In some cases (for instance, annual sediment variations and sediment mineralogy), the results obtained were complemented with the additional data from previous studies.

4. Results and discussion

4.1. Upper Paraná River

4.1.1. Water regime and suspended sediments

The hydrographic gauge at Porto São José, which is in operation since 1964, records a mean annual discharge of 8912 $m^3 s^{-1}$ ranging between 6501 and 13,294 $m^3 s^{-1}$ (Fig. 7), with extreme values of 33,740 $m^3 s^{-1}$ (in 1983) and 2550 $m^3 s^{-1}$ (in 1969). The

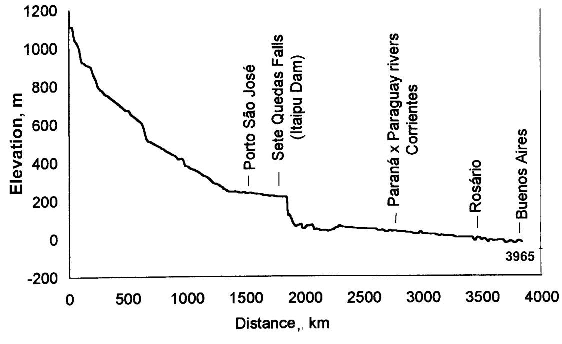

Fig. 4. Longitudinal profile of the Paraná River.

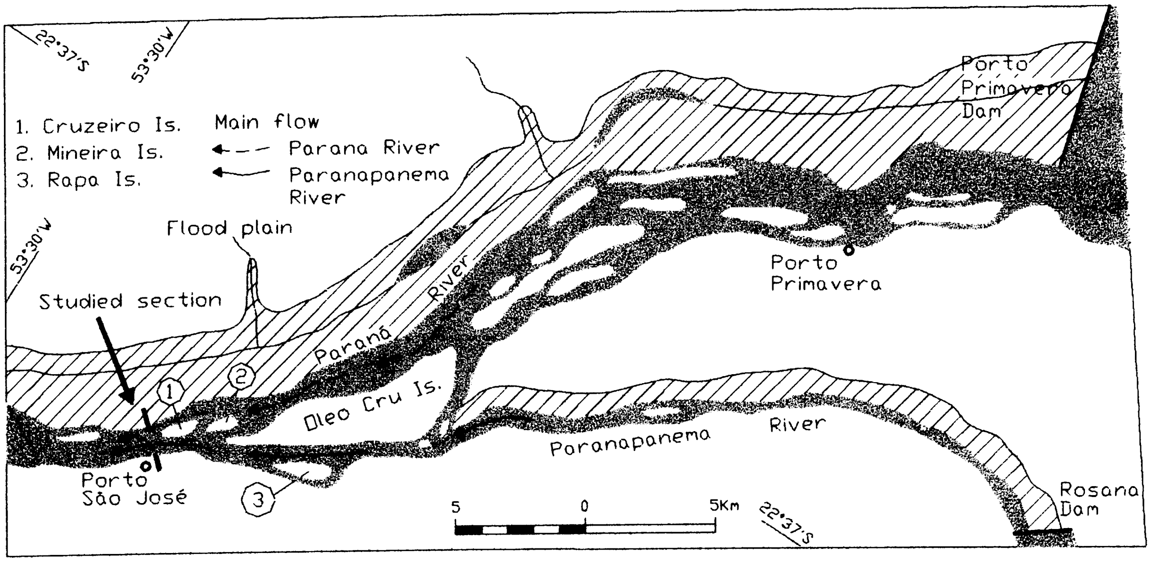

Fig. 5. Study area of the Upper Paraná River.

maximum flow velocity varies from 0.6 to 0.9 m s^{-1} in the tributary channels to 1.4 m s^{-1} in the main channel measured during the flood season (Table 1).

Although most of the Paraná and its tributaries are dammed, the river carries a suspended load concentration at the Porto Rico section (Fig. 8) varying from 6 to 30 mg l^{-1} (Stevaux, 1994), corresponding to 14.85×10^6 tons year^{-1}. The discharge and suspended load present a relatively good correlation although local rain during December and January can promote a lead of 22–39 days in the beginning of suspended load wave over the flood wave (Stevaux, 1994; Drago, 1990). Quartz, mica and kaolinite are the commonest minerals in the suspended load.

4.1.2. Bed load and channel morphology

The channel at Port São José has an asymmetrical section with a thalweg shifted towards the left margin. It is 1200–4500 m wide with the depth varying from 6 to 8 m in the shallower parts to 13–17 m in the thalweg. The channel slope along the thalweg at Porto São José is about 0.096 m km^{-1}.

The largest bedform observed is a sandwave that is about 1000 m long and 5–7 m high although dunes and megaripples are the most common bedforms. Longitudinal bedform migration along the thalweg is about 67 m month^{-1} (Stevaux, 1994).

The bed load material is essentially quartz (95%) with a little mica (3–4%) and heavy minerals (traces). The grain size is medium to fine sand (55–60%) with less amounts of fine (10–15%) to coarse (20–30%) sand. The bed load sediment discharge is empirically estimated at 4.04×10^6 tons year^{-1}, constituting about 21% of the total load (Itaipu Binacional, 1990).

4.1.3. Alluvial valley morphology

The Upper Paraná River has a multi-channeled pattern with a large number of islands and sand bars (lateral and midchannel bars). A strong asymmetry in the location of the river within the alluvial plain exists, most of the flood plain being developed on the right and ranging in width from 4.2 to 8.5 km (Table 1). On the left, the river continuously erodes the Mesozoic sandstone of the Caiuá Formation, suggesting a tectonic control on fluvial dynamics (Stevaux, 1994). The asymmetry in the channel section and the geometry of alluvial deposits support this hypothesis.

Two terraces can be observed along the Upper Paraná River. The first lies about 25 m above the present water level and is excavated on non-fluvial Cenozoic deposits. The second, which is located 10 m above the water level, is formed by Late Pleistocene sediments of the Paraná River (Stevaux and Santos, 1999).

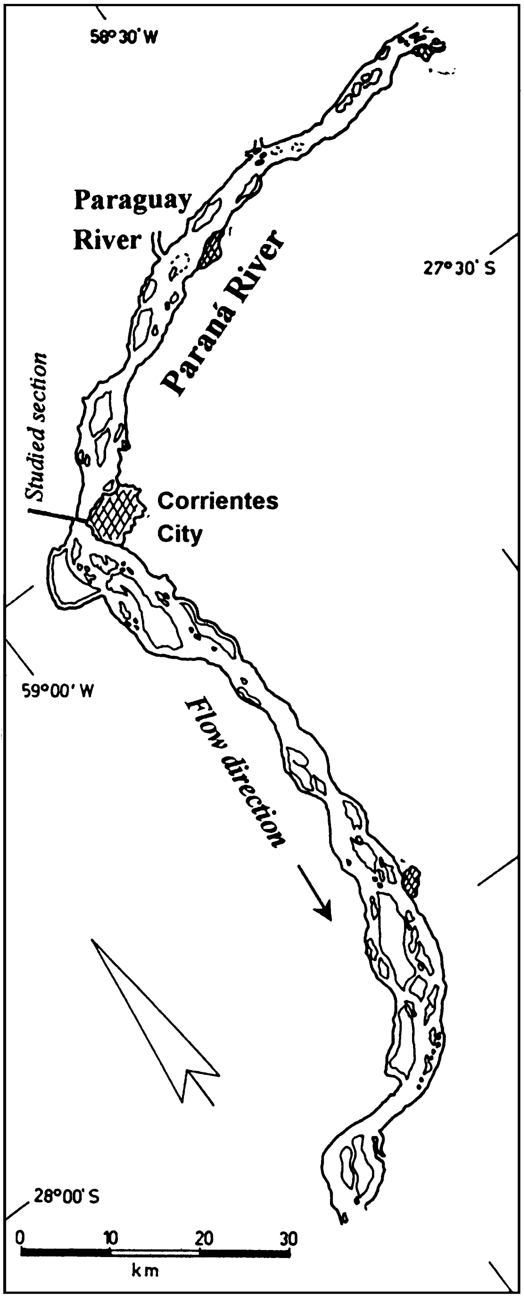

Fig. 6. Study area of the Middle Paraná River.

During normal floods, the water enters the floodplain through secondary and abandoned channels. This type of flood is gradual and slow flowing with no effective unidirectional flow over the flood plain. Water, however, may overflow the natural levee system and some crevasses may occur in extreme floods where the flow is more intensive, and temporary channels with associated splays may occur, or abandoned channels may be reactivated (Stevaux, 1994).

The Upper Paraná channel is characterised by large braided reaches (8–30 km long) separated by shorter nodal reaches (single-channel reaches) of 1–3 km. The channel morphology is controlled by a series of Mesozoic SE–NW geological lineaments that continue to be active until the present (Stevaux, 1994; Araujo et al., 1999).

Braided reaches display islands, sand bars and a series of minor channels. The vegetated surfaces of the islands lie 3–4 m above the medium water level and are flooded only during major floods (at an average interval of 7 years). These are erosive forms and have a complex sedimentary history related to Holocene climate changes (Stevaux, 2000). The bars are short-term depositional forms with a deposition–erosion cycle of 1–7 years. Both lateral and mid-channel bars occur in the channel (Santos and Stevaux, 2000). Minor channels carry higher sinuosity (1.18–1.25) than the main channel of the Paraná.

4.2. Middle Paraná River

4.2.1. Water regime and suspended sediment

Near Corrientes City, the Paraná River has an average annual discharge of 16,941 $m^3\ s^{-1}$ (Secretaría de Energía, 1994) with summer floods (February

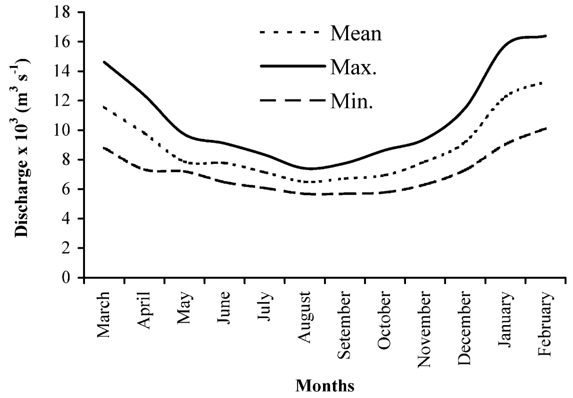

Fig. 7. Mean annual discharge of the Paraná River at Porto São José (Brazil): 1964–1994.

Table 1

Hydraulic, morphologic and sedimentological variables of the Paraná River

Variable	Upper course	Middle course
Liquid discharge × 10^3 ($m^3\ s^{-1}$)	Annual mean: 8.9 Range: 10.9–7.1	Annual mean: 16.9 Range: 37.8–10.7
Current velocity (surface) ($m\ s^{-1}$)	Range: 0.6–1.4	Range: 0.7–1.6
Suspended sediment concentration ($mg\ l^{-1}$)	Average: 18 Range: 6–30	Average: 286 Range: 18–554
Total sediment discharge × 10^6 (tons $year^{-1}$)	18.8	158.4
Suspended discharge × 10^6 (tons $year^{-1}$)	14.8 (78.6% of the total)	118.7 (74.9% of the total)
Bed load discharge × 10^6 (tons $year^{-1}$)	4.04 (21.4% of the total)	39.7 (25.1% of the total)
Bed load size	Sand (medium to fine) (55–60%)	Sand (medium) (60–80%)
Bed load dominant mineral	Quartz (95%)	Quartz (90%)
Bedforms	Dunes and megaripples	Sand waves, dunes and megaripples
Channel width (km)	Range: 1.2–4.5 (maximum: 15.5)	Range: 1.9–4.7 (maximum: 9.0)
Channel depth (m)	Range: 6–17	Range: 15–20
Width/depth ratio	Range: 200–264	Range: 126–235
Channel slope ($m\ km^{-1}$)	0.096	0.085
Channel elements	Islands and bars	Islands and bars
Floodplain width (km)	Range: 4.2–8.5 Maximum: 20.3	Range: 12.6–20.7 Maximum: 26.1
Sinuosity	Range: 1.05–1.15	Range: 1.04–1.21
Braid-channel ratio	Range: 1.73–5.82	Range: 1.75–6.28
Channel pattern	Braided	Braided

and March) and spring low water levels (Fig. 9). The maximum discharges in the period of 1904–1994 occurred in autumn–winter (June–July) with values higher than 50,000 $m^3\ s^{-1}$ (Fig. 9). The highest daily discharge during this period was 60,215 $m^3\ s^{-1}$ (July 23, 1983) in the main channel (Secretaría de Energía, 1994) and 66,000 $m^3\ s^{-1}$ considering the floodplain overflow (Neiff et al., 2000). The flow velocity (average) is 0.7 $m\ s^{-1}$ during the low water level and 1.6 $m\ s^{-1}$ during the high water period (Table 1).

Floods, when water levels remain below 49.3 m above the sea level, are locally considered as ordinary

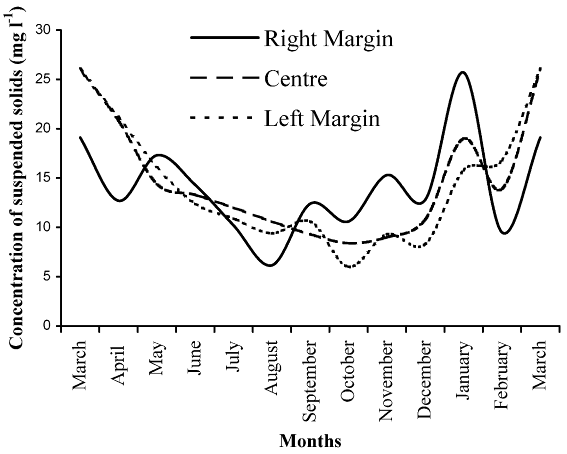

Fig. 8. Suspended solid concentration of the Paraná River at Porto São José (Brazil): 1993–1994 (from Stevaux, 1994).

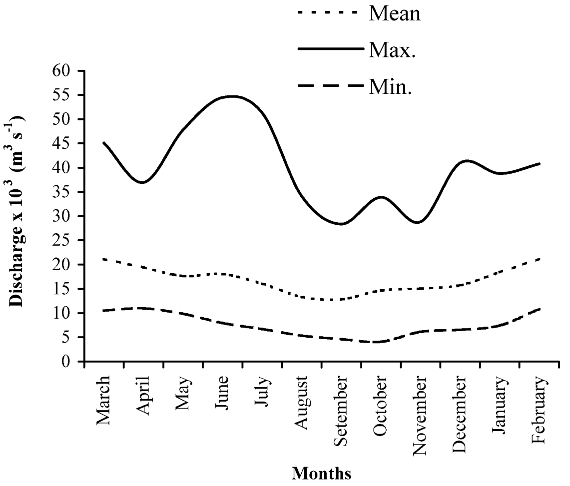

Fig. 9. Mean annual discharge of the Paraná River at Corrientes City (Argentina): 1904–1994.

floods. When the river exceeds that elevation, an extraordinary flood begins (Neiff et al., 2000). Extraordinary floods occurred with greater frequency during the second half of the 20th century (more than 62% occurred after 1970) (Neiff et al., 2000), probably due to the present global climate change.

In this section, the concentration of the suspended load is extremely variable below the confluence with the Paraguay River. The Paraguay carries large volumes of sediments from the Andean region brought by the Bermejo River and afterwards transported by the Paraná as far as its delta. The spatial and temporal variations of sediment discharge of the Paraná River downstream of the Paraguay confluence seem to be caused by: (1) the difference in discharge between both rivers (Paraná: 16,941 m^3 s^{-1} and Paraguay: 3770 m^3 s^{-1}), (2) the confluence angle between the two channels and (3) the difference in sediment size and concentration.

The mean concentration of the suspended solids varies between 18 and 554 mg l^{-1} during low and high water, respectively (Table 1). Bonetto and Orfeo (1984) determined the monthly suspended solid concentration in a cross-section at Corrientes from March 1981 to March 1982 (Fig. 10). These measurements were taken at three points along the section (left and right margins and center). Influenced by the Paraná–Paraguay system, the right margin presented higher values of suspended solid concentration (maximum of 1221 mg l^{-1} and annual average of 439 mg l^{-1}), whereas the left margin presented lower values (maximum of 88 mg l^{-1} and annual average of 33 mg l^{-1}). The asymmetrical distribution of the suspended solids remains constant during the entire annual hydrological cycle and continues for about 400 km downstream of the confluence (Bonetto and Orfeo, 1984). Although differences in the suspended solid concentration between the left and right margin occur throughout the annual hydrological cycle, both the highest values and greatest differences are associated with the flood period of the Bermejo (March and April).

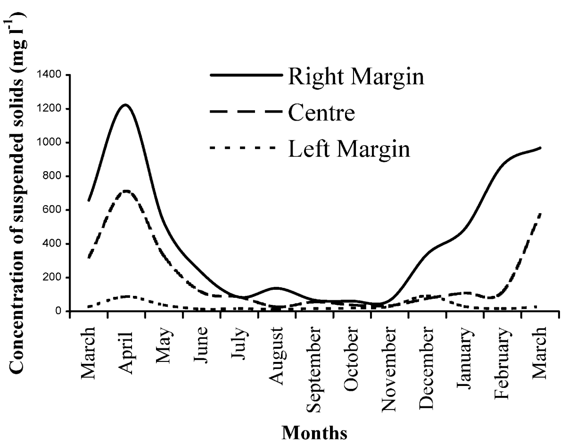

Fig. 10. Suspended solid concentration of the Paraná River at Corrientes City (Argentina): 1981–1982 (from Bonetto and Orfeo, 1984).

The clay mineralogy of the suspended solids also presents differences along the channel cross-section. Suspended solids near the right margin are composed of illite (60–80%) and low amounts of chlorite (5–30%), kaolinite (5–30%), interlayered chlorite–kaolinite or chlorite–smectite (20%) in varying combinations (Poi de Neiff et al., 1994; Orfeo, 1995). This clay mineral association, especially the illite proportion, is very similar to that of the Bermejo River (Bertolino and Depetris, 1992) and suggests an influence of this river on the Paraná River's suspended solid composition. On the other hand, the left margin presents a slight dominance of chlorite (30–50%) followed by kaolinite (30–40%), smectites (5–10%) and illite (0–30%) and suggests an influence of the upper course of the Paraná River (Depetris and Griffin, 1968; Orfeo, 1995).

Silt (61–66%) is the dominant grain size of the suspended load on the right margin and clay (79%) on the left one. Suspended load on the right margin also includes very fine sand (1–5%).

4.2.2. Bed load and channel morphology

The mean channel width of this stretch of the Paraná River ranges from 1.9 to 4.7 km (minimum: 1.0 km, maximum: 7.4 km). The channel with a slope of about 0.085 m km^{-1} comprises 20% of the alluvial valley total surface. Due to its nearness to the Paraná–Paraguay confluence, the middle Paraná cross-section presents an asymmetrical profile where two channels may be identified. The right channel has a width of 500 m and a depth between 15 and 18 m, whereas the left channel is 2000 m wide and 20 m in depth. The channels are separated by a flat shallow surface that is 1–2 m deep.

The bed load sediment in both channels is constituted of medium (60–80%) and fine (20–40%) sand.

On the average, the right margin presents a slightly coarser grain-sized sand (1.7 ϕ) than that of the left margin (1.9 ϕ). The interpretation of the cumulative frequency curves of the bed sediments (Visher, 1969) suggested that saltation is the dominant transport mechanism (96–99%) in these channels (Orfeo, 1995).

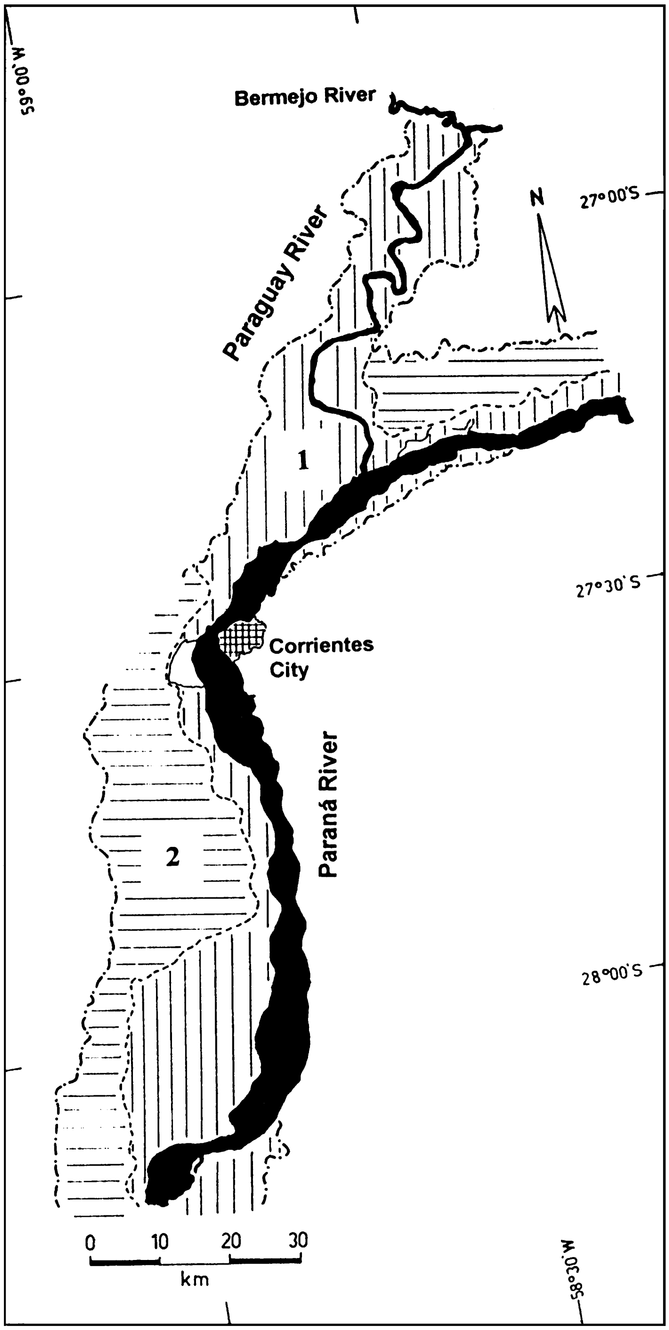

Fig. 11. Proximal (1) and distal (2) floodplain of the Middle Paraná River (Argentina).

Table 2
Attributes of studied bars (Middle Paraná)

Bar	Length (km)	Width (km)	Length/width ratio	Surface area (km^2)	Genetic type[a]		Position[b]		Orientation[c]	
					1	2	3	4	5	6
1	1.45	0.50	2.9	0.37	x		x		x	
2	0.65	0.10	6.5	0.05	x		x		x	
3	1.50	0.40	3.7	0.36	x		x		x	
4	4.20	1.45	2.9	3.61	x			x	x	
5	2.20	0.50	4.4	0.89	x			x	x	
6	6.90	2.60	2.6	9.13	x			x	x	
7	6.35	2.00	3.1	6.99	x			x	x	
8	1.75	0.60	2.9	0.72	x			x	x	
9	6.50	1.55	4.2	6.17	x			x	x	
10		4.20		23.71	x			x	x	
11	1.75	0.25	7.0	0.30	x			x		x
12	1.70	0.45	3.7	0.45	x			x		x
13	0.90	0.35	2.6	0.17	x			x	x	
14	4.20	1.30	3.2	4.01		x		x	x	
15	0.85	0.15	5.6	0.09	x		x			x
16	1.85	0.45	4.1	0.64	x		x			x
17	1.80	0.60	3.0	0.72	x		x		x	
18	1.00	0.25	4.0	0.17	x		x		x	
19	6.85	2.05	3.3	10.32	x			x	x	
20	11.80	3.55	3.3	22.20	x		x		x	
21	2.80	0.50	5.6	1.12	x			x		x
22	0.45	0.06	7.5	0.03	x			x		x
23	0.60	0.10	6.0	0.04	x			x		x
24	1.80	0.20	9.0	0.21	x		x		x	
25	10.80	3.15	3.4	15.65		x		x	x	
26	2.45	0.40	6.1	0.58	x			x		x
27	3.50	0.80	4.3	1.99	x			x		x
28	9.20	4.55	2.0	28.73		x		x	x	
29	1.80	0.70	2.5	0.85	x			x		x
30	3.25	1.50	2.1	2.71	x		x		x	
31	2.55	0.70	3.6	1.21	x			x	x	
32	0.95	0.40	2.3	0.24	x			x		x
33	3.60	1.10	3.2	2.52	x			x	x	
34	1.50	0.40	3.7	0.36	x			x	x	
35	0.90	0.40	2.2	0.21	x			x		x
36	3.25	0.70	4.6	1.42	x			x	x	
37	14.40	4.15	3.4	35.17	x			x	x	
38	11.55	1.80	6.4	11.38		x			x	
39	2.55	1.05	2.4	1.45		x				x
40	1.30	1.50	2.6	0.40	x				x	
41	1.40	0.25	5.6	0.25	x			x	x	
42	0.90	0.20	4.5	0.13	x			x	x	
43	0.55	0.25	2.2	0.07	x				x	
44	1.30	0.25	5.2	0.21	x				x	
45	0.55	0.10	5.5	0.04	x				x	
46	1.85	0.40	4.6	0.43	x				x	
47	6.55	2.30	2.8	8.49	x				x	
48	1.05	0.20	5.2	0.13	x					x
49	1.60	0.70	2.2	0.74	x			x		x
50	3.85	1.20	3.2	3.27	x				x	
51	5.35	1.85	2.9	5.78	x			x	x	
52	0.45	0.10	4.5	0.04	x					x

Bedforms are controlled separately by the dominant flow dynamics in each channel of the cross-section. The right channel carries bedforms generated by upper flow regime, dunes and sand waves 150 m in length and 3 m in height, but the bedforms of the left channel are ripples and megaripples.

Bed load sediments consist of stable minerals that resist weathering and transport. The most frequent light mineral is quartz (90%) with minor amounts of chalcedony, potassium feldspar and plagioclase. Heavy minerals are rare (1.2–1.5%) and are essentially composed of magnetic and non-magnetic opaque minerals (Passeggi, 1996).

4.2.3. Sediment transport

The amount of transported sediment may be estimated (Colby, 1964) by using the average annual discharge (16,941 $m^3 s^{-1}$), average annual suspended solid concentration (224 mg l^{-1}) and average grain size of the bed load (1.8 ϕ) in the studied cross-section. The annual transport of suspended sediment is estimated (Table 1) to be 118.7×10^6 tons $year^{-1}$, and the annual bed load discharge is 39.7×10^6 tons $year^{-1}$. Considering the total sediment discharge to be 158.4×10^6 tons $year^{-1}$, the bed load discharge represents about 25%. If the bed load proportion in relation with the total transported sediment and the low proportion of silt and clay (less than 5%) are taken into account, the channels may be classified as tractive type (sensu Schumm, 1977, 1981).

4.2.4. Alluvial valley morphology

The Middle Paraná River flows across a region composed of several structural blocks elongated in the N–S direction, most of them are tilted to the east. From the Paraná–Paraguay confluence, the Paraná flows 75 km on a sunken block, widening the floodplain from 13 to 45 km (Iriondo, 1988).

In the studied area, the Paraná River drains a plain without terraces. Its floodplain is divided into two parts according to their elevation above the water level. The proximal floodplain (35% of the alluvial plain surface) is lower (Fig. 11) than the distal floodplain (45% of the alluvial plain surface).

The floodplain is asymmetrical, practically only on the right side of the river (Fig. 11). The proximal floodplain is 8.1 km wide (average) and it is flooded every year. During extraordinary floods, the water reaches the distal floodplain, which on the average is 12.6 km in width, so that the entire flooded area measures 20.7 km in the average width (ranging from 9.6 to 26.1 km).

About 32% the of channel surface is occupied by bars (Table 2) with surface areas ranging from 0.04 km^2 (length: 0.45 km and width: 0.1 km) to 35 km^2 (length: 14.4 km and width: 4.1 km). These bars can be genetically grouped into *aggradation bars* (from the accumulation of load material) and *relict bars* (from the erosive processes that isolated portions of the alluvial plain into the channel) (Fig. 12). According to the subaerial exposition of the bar surface and the water level, the bars may be classified as *islands* (when they remain emergent during the ordinary floods) and *emerging bars* (flooded every year). With regard to their position in the channel, the bars may be classified into *midchannel* and *lateral* (Fig. 12). They may also be designated as *longitudinal* and *diagonal bars* (Orfeo, 1996) according to their orientation in the channel in relation with the main flow. Attached and complex bars were rarely present.

Bars also occur in sets responding to dominant flow dynamics in different stretches of the main channel. In each set, bars and minor channels support similar flow regime and evolve according to the width of the upstream main channel (Thorne et al., 1993; Yalin, 1977).

4.3. Channel pattern, both reaches

The upper and middle reaches of the Paraná River present a multi-channelled pattern, with many bars and islands. The studied reaches were divided into stretches of 10 km in length, each one with the

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Notes to Table 2:

[a] 1, aggradational; 2, relict.

[b] 3, central; 4, lateral.

[c] 5, longitudinal; 6, diagonal.

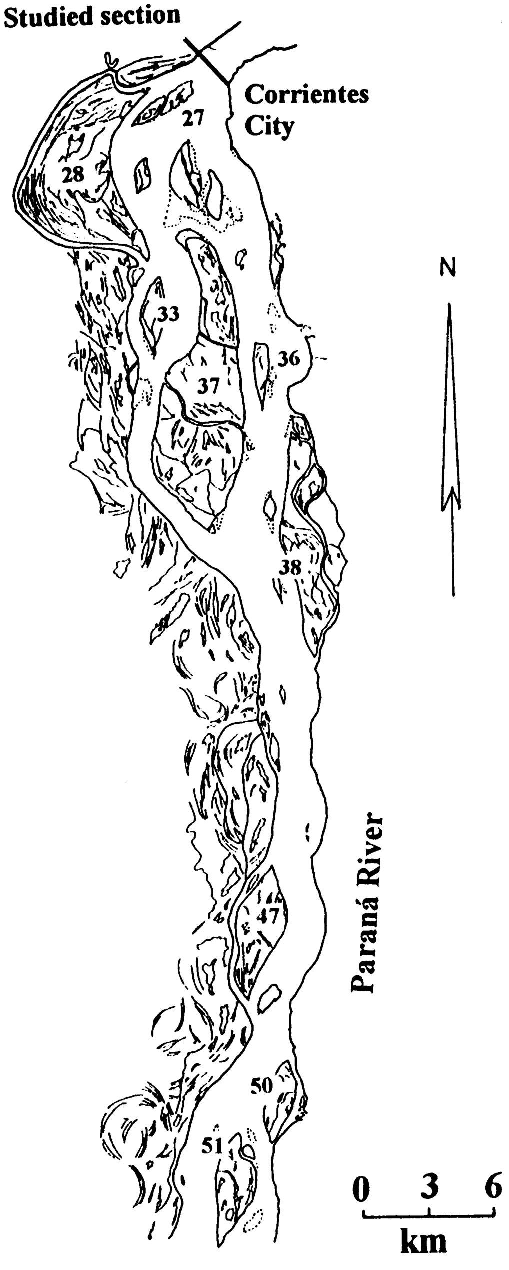

Fig. 12. Different types of bars in the Middle Paraná River (Argentina): aggradational, relict, central, lateral, longitudinal and diagonal (see Table 2).

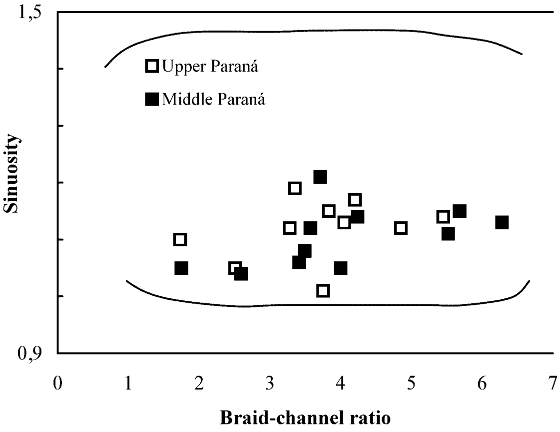

Fig. 13. Sinuosity and braid-channel ratio of the Paraná River. Lines mark the expected limits of braided pattern in natural rivers (sensu Friend and Sinha, 1993).

objective of analyzing the channel pattern according to sinuosity and braid-channel ratio (Friend and Sinha, 1993). Comparing these results with the generalized diagram obtained by Friend and Sinha (1993), both reaches show similar values (Table 1) and may be classified as braided (Fig. 13).

This braided pattern is strongly influenced by the high availability of bed load sediment relative to the suspended load sediment (Friend and Sinha, 1993). The type of sediment load is considered to be a more important control on channel shape than the total quantity of the sediment transported through a channel (Schumm, 1977). The mode of sediment transport as bed load or suspended load appears to be a major factor in determining the character of a stream channel. Alluvial rivers can be classified primarily as suspended load channels, bed load channels or mixed load channels according to the type of sediment load that moved through the channels. A bed load channel is one that transports more than 11% of the bed load (Schumm, 1977).

In this sense, the high proportion of the bed load in comparing it with the total solid load in the studied sections of the Paraná River (21% at the upper course and 25% at the middle course) (Table 1) may explain the similitude of the channel pattern in both sections.

5. Conclusions

The downstream increment of the main hydrological and sedimentological variables of the Paraná River has been observed. From Porto Rico (Brazil) to Corrientes City (Argentina), the annual mean river discharge increases from 8900 to 16,900 $m^3 s^{-1}$, the bed load from 4,000,000 to 39,700,000 tons $year^{-1}$, the concentration of the average suspended sediments from 18 to 286 mg l^{-1}, and the suspended sediment discharge from 14,800,000 to 118,700,000 tons $year^{-1}$. The bed load is medium sand in the Middle Paraná and medium to fine sand in the Upper Paraná. The grain size in the Upper Paraná River is strongly controlled by the sandy soil cover of its hydrological basin. This material originates from the aeolian well-sorted sandstone of the Caiuá Formation. The channel width of the Upper Paraná ranges between 1.2 and 4.5 km, while the same variable of the middle course is between 1.9 and 4.7 km. The floodplain is wider in the middle course (12.5–20.7 km) than along the upper course (4.2–8.5 km). The influence of the Paraguay River (the main tributary of the Paraná River) explains most of the modifications downstream this confluence, especially the changes in the discharge and suspended load. Nevertheless, the channel elements (bars and islands) and the channel pattern (braided) are very similar in both areas, suggesting that the bed load proportion of the Paraná River (21% at the upper course, 25% at the middle course) determines the comparable patterns in spite of the changes in other properties. In this sense, the Paraguay River contribution is comparatively limited and does not change the morphology of the Paraná River despite its strong high water and suspended sediment contribution.

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