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Suspended sediment at a cross section of the Middle Paraná River: concentration, granulometry and influence of the main tributaries

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Abstract Based on data from our own and from other sources, the origin, magnitude, annual behaviour and granulometry of suspended sediments in the Middle Paraná River, were investigated. It was concluded that the River Bermejo through the Lower Paraguay supplies more than 60% of the suspended material carried by the Middle Paraná, and that the concentration peaks coming from that river, lag behind the highest Middle Paraná streamflows. The suspended sediments are composed largely of wash load, with high percentages of particles within the fine and very fine silts and clay ranges (<16 μm). The influence of the River Bermejo also confirms these aspects, since when the concentration peaks occur, the mean diameters, sorting and clay percentages are closely related to those which occurred 2063 km upstream in the Bermejo Upper basin. The total suspended yield in the Middle Paraná is not less than 100×10^6 t year^{-1}.

Répartition des sédiments en suspension dans une section du Paraná moyen: concentration, granulométrie et influence des principaux tributaires

Résumé L'origine, l'importance, le comportement au cours de l'année et la granulométrie des sédiments transportés en suspension par le Paraná moyen sont l'objet des recherches ici rapportées. Elles ont permis de conclure que plus de 60% de ces sédiments proviennent du Rio Bermejo (par le Paraguay inférieur), et que les pointes de concentration de ce fleuve arrivent après les crues du Paraná moyen. Les suspensions sont surtout le fait de charges de ruissellement (wash load) contenant de hauts pourcentages de limons fins et d'argiles (<16 μm). Cela confirme l'influence du Rio Bermejo, car la taille et le profil granulométrique des suspensions ainsi que les pourcentages d'argile associés aux concentrations maxima correspondent étroitement à ceux que l'on trouve sur le cours supérieur du Bermejo, 2063 km plus en amont. Le débit solide total en suspension du Paraná moyen est supérieur à 100×10^6 t an^{-1}.

INTRODUCTION

The middle reach of the River Paraná, integrating one of the most important fluvial systems of South America — the Río de la Plata basin — is the subject of an ecological study by the Instituto Nacional de Limnología (INALI-CONICET) in order to assess the likely impact from the construction of large dams which are now being planned.

Based on concentrations and granulometry data of suspended sediments from the study, the magnitude, composition and variations of suspended material during the different river stages were investigated. The influence of the main tributaries — namely the rivers Upper Paraná and Bermejo-Paraguay — on the suspended sediments in the middle reach, was also studied, using data from other sources.

SAMPLING CROSS SECTIONS

The location of the cross section S9 where the authors' measurements were taken and locations of the cross sections where the data from other sources were obtained, are presented in Fig. 1. In the braided pattern of the Middle Paraná River, S9 forms a typical primary control point with a mean width of 600 m and a maximum depth of 22 m.

METHODOLOGY

The samples at cross section S9 were obtained fortnightly from October 1976 until January 1979; weekly during the flood of 1980 and monthly during the rest of the period till October 1981. Throughout 1976 and 1977, a pump-type sampler was used and an instantaneous-type was used for the remaining period. Three verticals were always sampled: one at the mid-channel with three sampling points (0.02 *d*, 0.5 *d*, 0.95 *d*) and the other two near the banks each with two sampling points (0.02 *d* and 0.95 *d*). The influence of this number of verticals and sampling points on the value of the mean total concentration at S9, could be estimated by comparing the results afforded by a few detailed samplings considering eight verticals each with five sampling points. This revealed that the sampling error for the estimated concentration (using three verticals) does not exceed ±5%. It is also relevant to observe that, due to the lack of a suitable current meter, it was not possible to measure current velocity near the bottom when the pump sampler was used, so its intake velocity could not be adjusted at that point.

At section S9, 557 samples were obtained each with a volume of 2–2.5 l. The concentration analysis in 388 of these samples was made by filtration using a glass filter of 1 μm pore size. The granulometry of the remaining 169 samples, corresponding to the 1976–1977 period, was established using the bottom withdrawal tube method. The resulting granulometric distributions covered a size range between 62.5 μm (ϕ 4) and 3.9 μm (ϕ 8) divided in grade-size classes of width ϕ/2. Applying a computational procedure

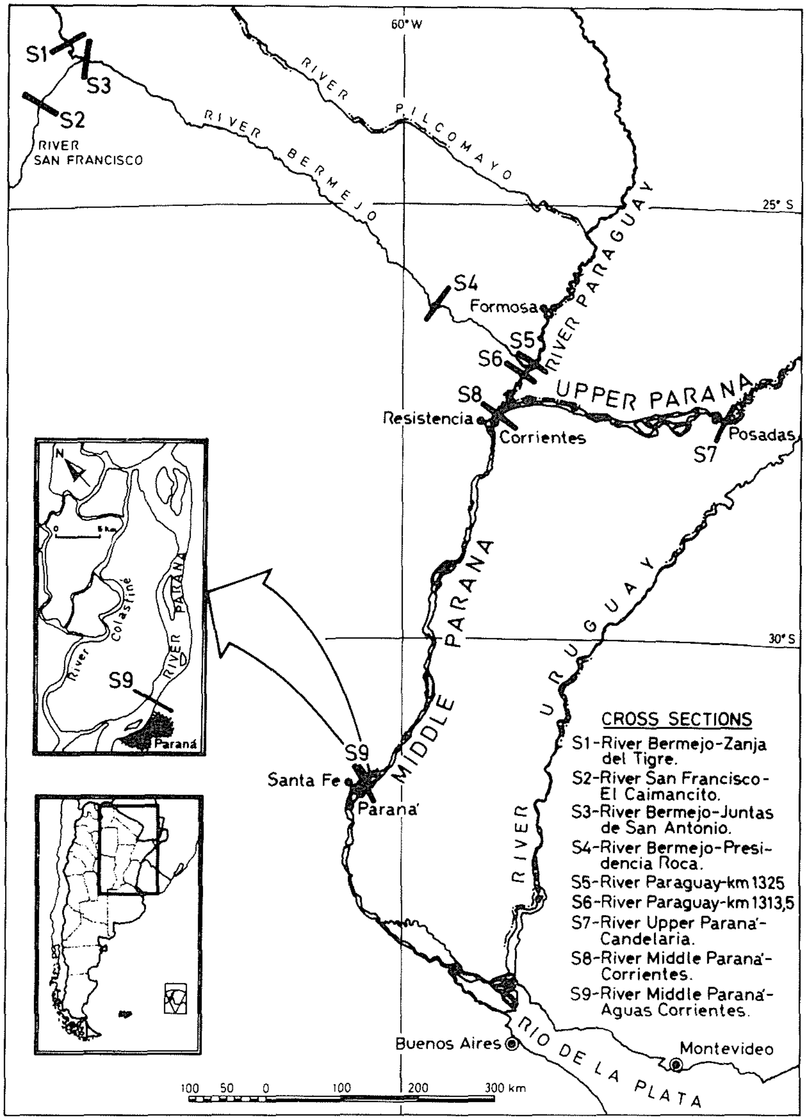

Fig. 1 Location of sampling cross sections.

which uses the moment method, the mean diameters and standard deviations for each distribution were computed. The rating curve existing for the S9 section afforded the streamflow data for each sampling.

The suspended sediment and discharge data for the other cross sections were obtained from the following sources: Programa para el Mejoramiento de la Navegación del Río Paraná – ARG 31 (UNESCO-MOSP) (unpublished original data), Agua y Energía Eléctrica (1966, 1977, 1987) and Scartascini (1971). This information is concerned with the December–May period of several years (1971–1974), since it is in these months that the maximum solid and liquid discharges are carried by the fluvial system. The suspended sediment samples were obtained with an instantaneous sampler at a number of verticals and sampling points selected according to the scheme suggested by WMO (1974). At all sections, mean concentrations were calculated using the cross-sectional distributions of water discharge.

RESULTS AND DISCUSSION

Influence of the River Bermejo on the Middle Paraná River

The River Bermejo 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 materials carried by the latter river (Soldano, 1947; Cotta, 1963). The authors' analysis has led to the following conclusions:

(a) The highest solid discharges supplied by the Upper Bermejo basin coincide with the streamflow peaks (Cotta, 1963) (Fig. 2(a)). The fact that peak concentrations apparently precede the maximum water discharges for the periods 1961–1962, 1965–1966 and 1968–1969 is an artefact caused only by the form of representing the data. For the 1968–1969 period, for example, in which there were suitable daily data, it was possible to verify clearly the coincidence of both peaks.
Downstream of S3, the resulting solid discharge arrives at the River Paraguay almost unchanged after travelling more than 1300 km. With the concentration values of several measurements carried out at S4 and at the River Bermejo outlet (Fig. 1; Table 1), corresponding to the December–May period, the mean suspended sediment concentrations at the River Bermejo outlet was computed as 6499 mg l^{-1}. Based on the mean monthly concentrations for the same period but at S3 (Fig. 2(a)), a mean concentration was computed as 5915 mg l^{-1}, only 9% lower.
The only existing data on the granulometry of the River Bermejo suspended sediments (Fig. 2(b)), show that when the maximum solid discharges occur, the percentages of the finest suspended particles (<8 μm) increase markedly, thus giving rise to a lowering in d_{50} and to an improvement in sorting.
This behaviour, clearly defined for the 1961–1962 and 1962–1963 periods, also holds for the River Bermejo downstream of S3, because the relationship between the sediment yields (t $month^{-1}$) through S1 and S2, reaches an average ratio of 5:1.

(b) Regarding the suspended sediment concentrations of the River Paraguay, there are great differences between the reaches upstream and downstream of the River Bermejo outlet during its high water period (Table 1, columns 5 and 7; Fig. 3). The differences in water discharge between the Rivers Paraguay and Bermejo (10.4:1; column 9), give rise to an important dilution of the Bermejo suspended sediment concentrations (from 6499 to 624 mg l^{-1} if the streamflow ratio is used

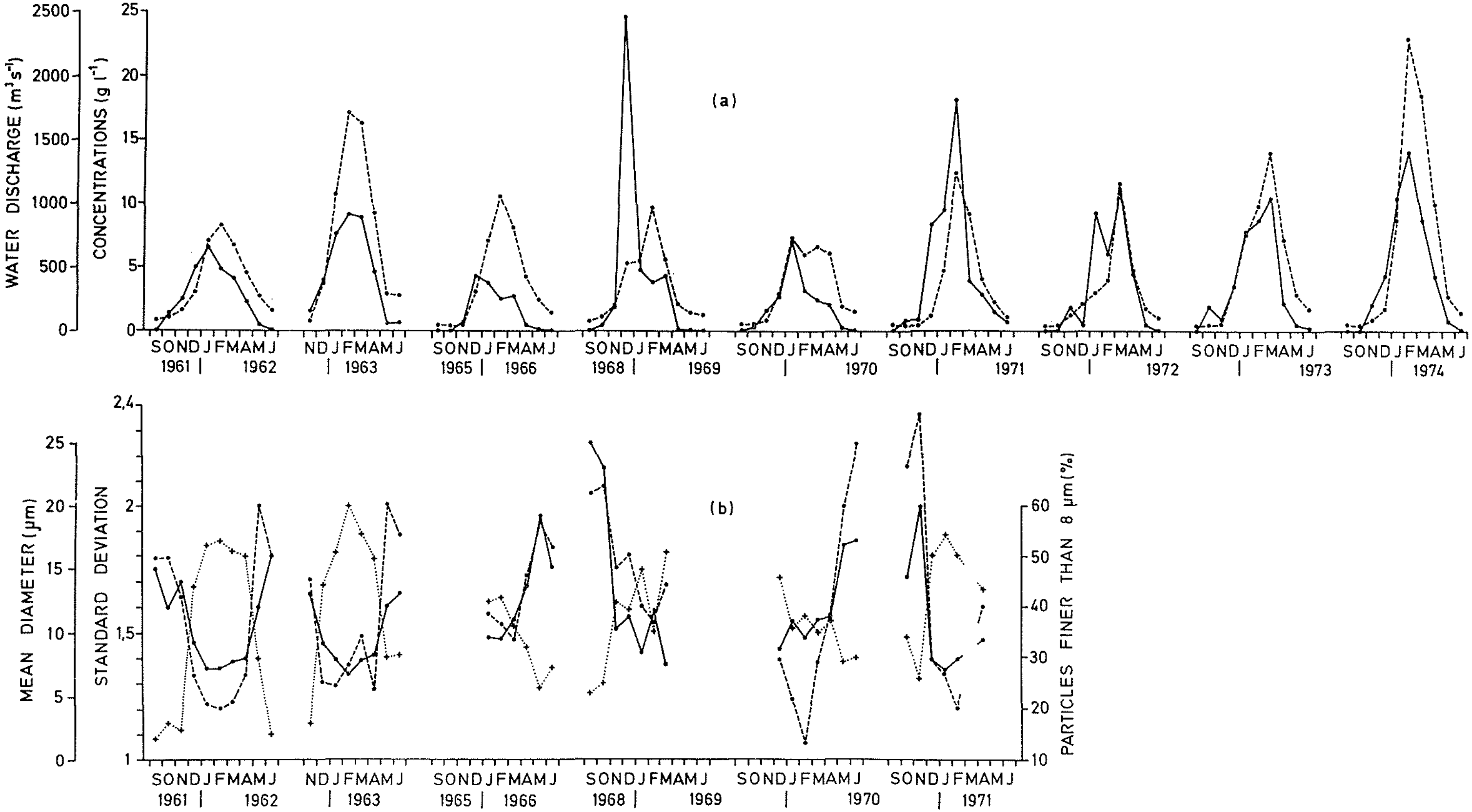

Fig. 2 River Bermejo. (a) Water discharge (-----) and suspended sediment concentration (——) at S3; (b) mean diameter (——), standard deviation (-----) and particles finer than 8 µm (·····) at S2.

Table 1 *Streamflows and concentrations in the Rivers Paraguay and Bermejo. (--): without data*

Date	RIVER PARAGUAY				RIVER BERMEJO		Streamflows ratios		
	Streamflows ($m^3 s^{-1}$)		Concentrations ($mg\ l^{-1}$)		Streamflows ($m^3 s^{-1}$) (Q_3)	Concentrations ($mg\ l^{-1}$)			
	Upstream Bermejo mouth-S5 (Q_1)	Downstream Bermejo mouth - S6 (Q_2)	Upstream Bermejo mouth-S5	Downstream Bermejo mouth-S6			Q_1/Q_3	Q_2/Q_3	Q_2/Q_1
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
28-30/04/71	4 971	5 382	97	577	411	6 383	12.09	13.09	1.08
3-4/05/71	4 947	5 450	--	--	503	--	9.83	10.83	1.10
5-6/05/71	4 990	5 527	83	378	537	3 119	9.29	10.29	1.11
11-12/05/71	5 036	5 357	--	--	321	--	15.69	16.69	1.06
13-14/05/71	5 013	5 376	--	--	363	--	13.80	14.80	1.07
17-18/05/71	5 091	5 300	--	--	209	--	24.36	25.36	1.04
20/05/71	--	--	--	655	--	--	--	--	--
27-28/05/71	5 068	5 454	--	--	386	--	13.13	14.13	1.08
13-14/12/71	1 561	1 894	--	--	333	--	4.69	5.69	1.21
20-22/12/71	1 627	2 100	--	--	473	--	3.44	4.44	1.29
10-11/01/72	--	--	89	187	--	--	--	--	--
10-11/02/72	1 332	1 665	102	831	333	3 747	4.00	5.00	1.25
20/12/72	--	--	--	432	--	--	--	--	--
25-26/01/73	4 220	5 052	68	813	832	4 591	5.07	6.07	1.20
27/02/73	--	--	--	--	879	9 978	--	--	--
28/02/73	--	--	--	--	855	10 393	--	--	--
13/03/73	--	--	--	--	885	8 900	--	--	--
15/03/73	--	--	--	--	923	9 799	--	--	--
23-24/03/73	3 094	4 160	76	--	1 066	--	2.90	3.90	1.34
22/01/74	--	--	--	--	725	7 435	--	--	--
8-9/02/74	2 216	2 682	131	780	466	3 869	4.76	5.76	1.21
2-3/04/74	3 102	3 458	65	565	356	4 918	8.71	9.71	1.11
19-20/04/74	3 553	3 928	88	543	375	4 855	9.47	10.47	1.11

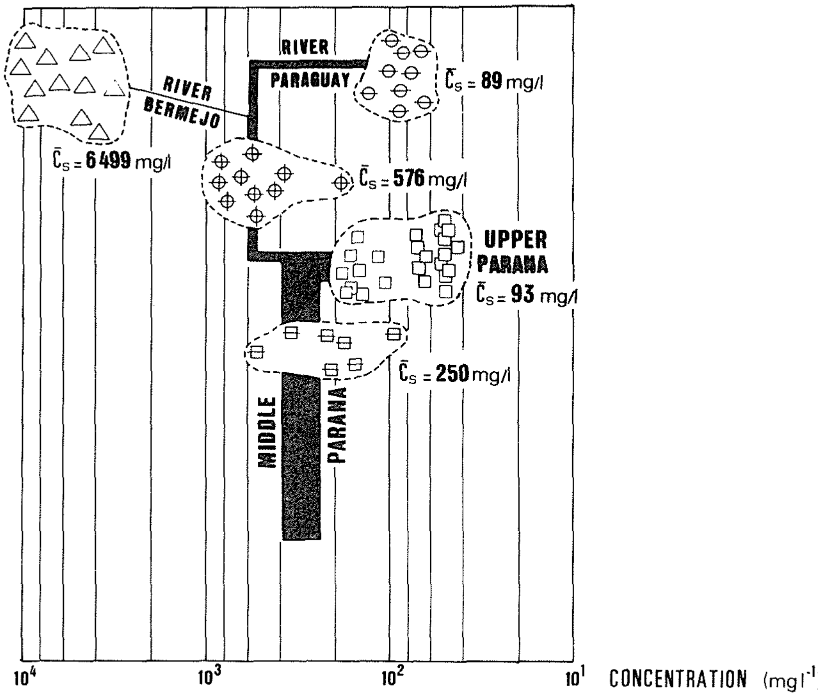

Fig. 3. Suspended sediment concentration changes along the hydrosystem studied during the period of maximum solid discharges. $\bar{C}_s$*: Mean value for each group of concentrations.*

for the computation).

(c) At the confluence of the rivers Paraguay and Upper Paraná the ratio of water discharges reaches an average of 3.86:1 (Table 2).
Regarding the sedimentological behaviour of the Upper Paraná, Scartascini (1971) showed for the April 1970–March 1971 period that maximum concentrations coincide with the highest streamflows. The mean concentration for the December–May period was 93 mg l^{-1} (Fig. 3). His data also showed that the clay percentages reached a minimum of 38.3% during January 1971 (maximum streamflows) and during the rest of the year they were not less than 50%, reaching a maximum of 61%. In all cases, the mean diameter of suspended sediment distributions ranged between 3 and 8 μm.

(d) The high concentrations of the Lower Paraguay River fall notably downstream of the confluence with the Upper Paraná due to the differences in discharge between both rivers. Based on the ratios of streamflows given in Tables 1 and 2, it was estimated that the Middle Paraná should have a concentration of 215 mg l^{-1} at S8, thus increasing more than 130% the concentration of the Upper Paraná (93 mg l^{-1}). Similarly, it may be computed that the 6499 mg l^{-1} concentration of the River Bermejo represents the 60% of the concentration at S8. This value is quite similar to that (63%) determined by Depetris (1968) with data prior to 1962.
With the limited number of data measured at S8, an average

Table 2 Streamflow ratios at the confluence of the rivers Paraguay, Upper Paraná and Middle Paraná

Date	Streamflows			Q_2 / Q_1	Q_3 / Q_1	Q_3 / Q_2
	R. Paraguay ($m^3 s^{-1}$) (Q_1)	R. Upper Paraná ($m^3 s^{-1}$) (Q_2)	R. Middle Paraná ($m^3 s^{-1}$) (Q_3)			
29/04/71	5 382	11 267	16 649	2.09	3.09	1.48
4/05/71	5 450	10 924	16 374	2.00	3.00	1.50
7/05/71	5 527	11 267	16 794	2.04	3.04	1.49
12/05/71	5 387	13 122	18 479	2.45	3.45	1.41
15/05/71	5 376	14 736	20 112	2.74	3.74	1.36
18/05/71	5 300	13 031	18 331	2.46	3.46	1.41
28/05/71	5 450	10 206	15 660	1.87	2.87	1.53
14/12/71	1 894	9 056	10 950	4.78	5.78	1.21
21/12/71	2 100	10 796	12 896	5.14	6.14	1.19
13/02/72	1 665	14 418	16 083	8.66	9.66	1.12
27/01/73	5 052	14 736	19 788	2.92	3.92	1.34
24/03/73	4 160	15 927	20 087	3.83	4.83	1.26
11/02/74	2 682	16 906	19 588	6.30	7.30	1.16
3/04/74	3 458	22 306	25 764	6.45	7.45	1.16
21/04/74	3 928	16 559	20 487	4.22	5.22	1.24
			AVERAGES	3.86	4.86	1.32

concentration was obtained of 250 mg l^{-1} for the period 1971–1974 of the investigation (Fig. 3).

Middle Paraná River — cross section S9

Concentrations The authors' measurements at S9 during 1976–1981 allowed a first approach to the understanding of the relationship between the water discharges and concentration peaks. A distinctive feature is the lag of peak concentrations behind the highest streamflows (Figs 4(c) and 5). The lags were about 22 days for the 1978 and 1980 floods. At least one of the annual concentration peaks was always measured during April. The lack of coincidence between the maximum concentrations and highest discharges gives rise to hysteretic effects (Walling, 1974; Fig. 6).

To explain this behaviour some of the main facts presented so far are next summarized:

(a) The water regime of the Middle Paraná is essentially determined by the Upper Paraná, the influence of the River Paraguay being unimportant (Table 2).

(b) The concentration peaks of the Upper Paraná coincide with the highest streamflows, their maximum values being relatively low, about 200 mg l^{-1}

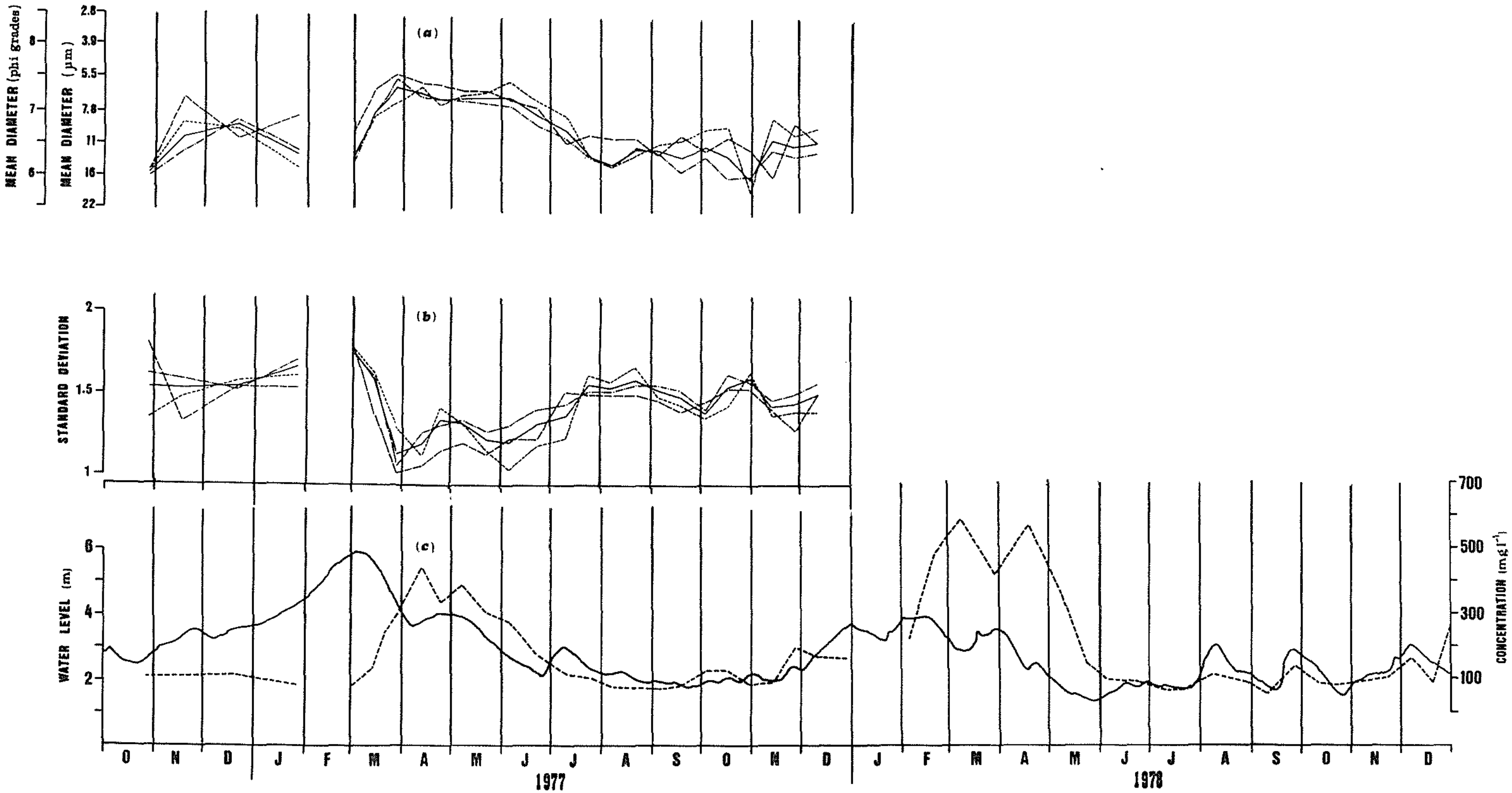

Fig. 4 Middle Paraná at S9. Fluctuations of (a) mean diameters, (b) standard deviations at mid-channel (-·-·-·-), right bank (-------), left bank (——-——) and for the complete cross section (——); (c) concentrations (-------) and water level (——) hydrographs.

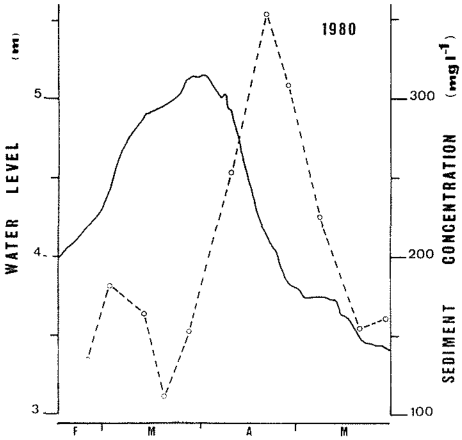

Fig. 5 Middle Paraná at S9. Concentrations (-----) and water level (——) hydrographs for the 1980 flood.

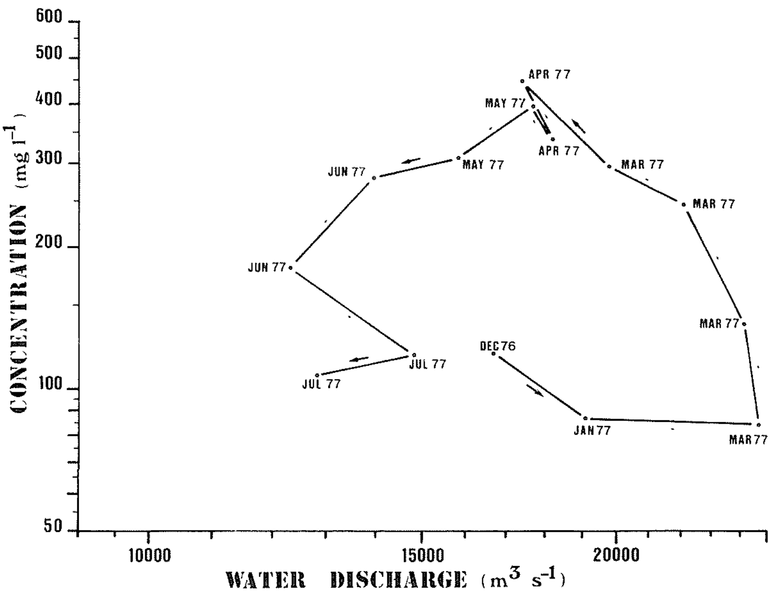

Fig. 6 Middle Paraná at S9. Relationship between concentrations and streamflows. Anticlockwise cycle for the 1977 flood.

(Scartascini, 1971).

(c) In the River Bermejo, the peaks of suspended sediment loads and the highest water discharges are essentially simultaneous events.

Considering the water level hydrographs for the December–May period of 1977, 1978 and 1980 at S4, S8 and S9 (Fig. 7), it can be observed that when the maximum water discharges from the Upper Paraná arrived at S8, the highest streamflows of the River Bermejo have not yet flowed through S4.

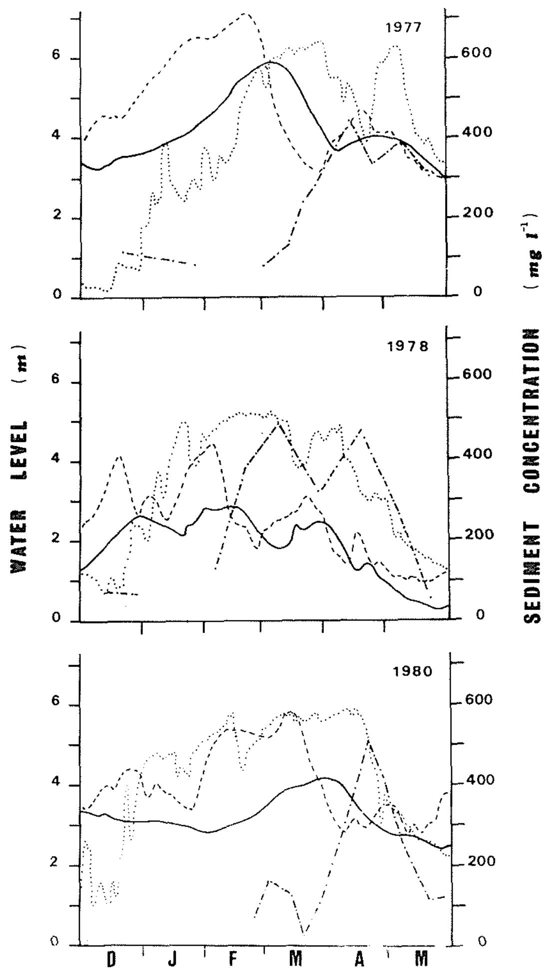

Fig. 7 Water level hydrographs at S4 (· · · · ·), S8 (------), S9 (——) and concentration hydrograph at S9 (-·-·-·) for the December–May period of 1977, 1978 and 1980.

This fact, in conjunction with what was stated in (c) above, explains why the suspended sediment wave arrives at the confluence of the rivers Paraguay and Paraná after the annual flood of the latter river and is detected at S9 with the delays referred to previously.

Granulometric features From the samples measured during 1976–1977 it was found that the Middle Paraná suspended sediments are composed largely of wash load (Table 3). The vertical distributions measured at both banks presented similar characteristics. Based on bottom sediment samples obtained along the Middle Paraná and at S9 during 1976–1981 (Bertoldi de Pomar, 1984), it was concluded that the 31.2 μm (ϕ 5) diameter is the limit between wash load and the suspended coarser fractions. This size is quite similar to that specified by Lelievre & Navntoft (1980), 37 μm, in their study

Table 3 *Middle Parana River at S9. Maximum and minimum percentages of wash load and clay fraction with the corresponding mean diameters and standard deviations (averages at the sampling vertical)*

Date	MID-CHANNEL			
	Mean diameter (μm)	Standard deviation	Wash load (%)	Clay fraction (%)
28/10/76	16	1.62	66	22
27/01/77	12	1.70	73	36
01/03/77	14	1.74	66	31
28/03/77	6	1.06	97	55
13/04/77	7	1.26	93	51
25/04/77	7	1.30	92	51
09/05/77	7	1.33	92	49
23/05/77	7	1.27	94	47
06/06/77	7	1.31	92	47
25/07/77	12	1.52	77	31
08/08/77	14	1.52	73	23
31/10/77	15	1.58	67	22
14/11/77	11	1.47	81	26

at S8.

Concerning the mean diameter values of the single granulometric distributions, Amsler & Drago (1984) showed that 60.8% of them fall within the fine silt range and that the frequencies for the coarsest mean diameters at mid-channel and banks are in close relation with the transverse distribution of water discharges at S9 (Table 4).

Regarding the fluctuations of mean diameters and standard deviations along the sampling period, Fig. 4 (a) and (b) shows that the finest and best-sorted suspended sediment is transported when the concentration peaks flow through S9. Simultaneously, the maximum wash load and clay percentages are detected (Table 3).

Fluctuations shown in Fig. 4 suggest that there exists a relationship between mean diameters and standard deviations (Fig. 8). It is one of the scatter plots suggested by Folk & Ward (1957) for granulometric distributions. According to the data arrangement in Fig. 8, it can be seen that there exists a best-sorted mode in the very fine silt range (about d = 5.5μm and σ_ϕ = 1.0).

Folk & Ward (1957) pointed out that the minima of best sorting reflected the modal size of sediments supplied from the source areas and that these values are strongly affected by the geological characteristics of those areas. This fact is clearly verified in this case since the minimum mean diameters and standard deviation at S9, reflect the suspended sediment

Table 4 Middle Paraná at S9. Percentage frequencies of the mean diameter distributions with the corresponding mode values at mid-channel, both banks, surface, bottom and entire section

	Medium silt (16 - 31 µm) (%)	Fine silt (8 - 16 µm) (%)	Very fine silt (4 - 8 µm) (%)	Principal/s mode (µm)
Left bank	2	61.3	36.7	9.3
Mid-channel	9.7	63.5	26.8	13.1
Right bank	4	57.2	38.8	12.3
Surface	4.2	58	37.8	9.3 8.1 7.04
Bottom	8.4	61	30.6	12.3
Section	6	60.8	33.2	12.3

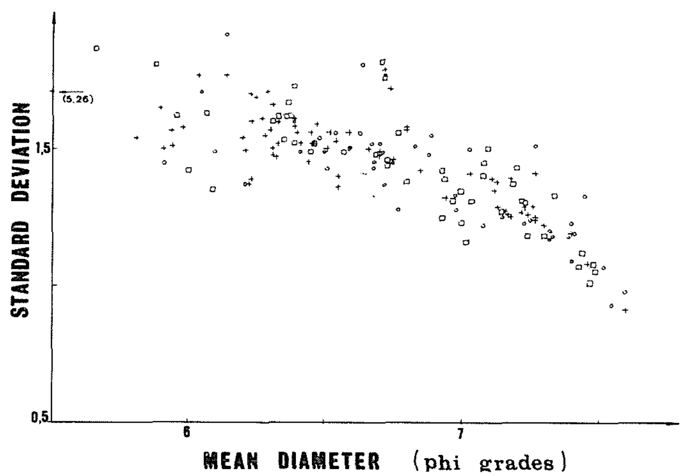

Fig. 8 Middle Paraná at S9. Relationship between mean diameters and standard deviations of granulometric distributions at mid-channel (+), right bank (□) *and left bank* (o).

features coming from 2063 km upstream, supplied by the Upper Bermejo basin (Fig. 2(b)). This sediment is largely composed of particles with size 8 µm. The well defined increases of clay fractions during the concentration peaks (Table 3) are also thus explained.

Reliability of the data at S9 for sediment yield estimates

Based on available hydrological information (Agua y Energía Eléctrica, 1987), the annual sediment yields at S3 were computed for the 1976–1981 period. These values should be approximately 60% of those measured at S9 latitude during the months of peak concentrations, since according to Drago & Vassallo (1980), the total concentrations do not change noticeably along the middle reach.

The results of the analysis are shown in Table 5; it is necessary to point out that the sediment yield at S9 was increased by 9.3%, in order to account for the sediment transported by the River Colastiné (LHA-UNESCO, 1974), the main secondary channel of the Paraná alluvial valley in the area (Fig. 1).

Table 5 *Comparison between the annual suspended sediment yields of the River Bermejo at S3 and the corresponding measurements at S9*

Year	S3 (t)	S9 + River Colastiné		
		Peak concentrations period (t)	Remaining period (t)	Total (t)
1976-1977	127 646 000	56 056 482	36 316 451	92 372 933
1977-1978	79 931 950	75 089 907	32 642 772	107 732 679
1978-1979	106 285 000	88 377 530	34 873 522	123 251 052
1979-1980	100 847 000	62 127 531	45 418 125	107 454 656
1980-1981	191 920 000	67 561 351	45 601 311	113 162 662

It is seen from Table 5 that when the maximum solid discharges occurred, the measured sediment yield was significantly lower that that supplied by the River Bermejo. Considering the evidence concerning the absence of a net deposition downstream of S3, it is believed that the sampling frequency at S9 was not fully adequate and that the maximum concentration peaks, therefore, were not sampled. In the light of these results, it is estimated that a sampling frequency of five days or less would have been necessary in the periods of the River Bermejo influence.

As the yields of the rivers Upper Paraná and Paraguay upstream of the Bermejo mouth, must be added to those at S3, it is roughly estimated that the Middle Paraná River would have been transporting more than 100×10^6 t $year^{-1}$ during 1976–1981.

CONCLUSIONS

(a) Downstream of the River Paraguay outlet, the suspended sediment concentrations of the River Paraná increase more than 130% on average for the examined periods of maximum solid discharges. The high sedimentary deliveries of the River Bermejo to the lower reach of the River Paraguay, account for this fact, since the Upper Paraná and the Paraguay upstream from the Bermejo mouth do not transport the necessary suspended loads to account for such an increase.

(b) The concentration peaks in the Middle Paraná lag behind the highest streamflows; this delay being about 22 days for two of the sampled floods. April would be the month when the maximum suspended loads are transported. 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 (Fig. 7).

(c) The suspended sediment in the Middle Paraná River is composed largely of particles within the fine and very fine silts and clay ranges (<16 μm), as is suggested by the low mean diameter values of the granulometric distributions at S9 (Table 3).

(d) When the concentration peaks coming from the River Bermejo flow through S9, the highest clay percentages, the minimum mean diameters (about 5.5 μm) and the best sorting occur, facts which relate closely to the character of the suspended sediment at S3, 2063 km upstream (Fig. 2(b)).

(e) The total suspended sediment yield at S9 is not less than 100×10^6 t year^{-1}. A sampling frequency of five days or less is recommended, in order to obtain reliable data for such estimates in the Middle Paraná River during the period of maximum sediment discharges.

(f) These conclusions regarding the origin, magnitude, annual behaviour and granulometry of suspended sediment in the Middle Paraná River apply essentially to the wash load, since the percentages of this fraction measured at S9 were never less than about 60%.

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