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A review of the suspended sediment budget at the confluence of the Paraná and Paraguay Rivers

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Abstract:

In this paper, the sediment budget at the confluence of the Paraná–Paraguay Rivers is updated on the basis of new suspended sediment concentration data, obtained during the 1990s at carefully located cross-sections, after the construction of several large reservoirs. With these data, it was possible to estimate that the suspended sediment load transported by the Upper Paraná River had decreased by 60% due to the influence of the dams. This decrease occurred in spite of the influence of climate change across the Upper Paraná and Paraguay basin, which increased the precipitation and surface runoff. As a consequence of these anthropogenic and natural processes, the Bermejo River (the main source of wash load to the system) accounts for an increasing proportion of the sediment transport along the middle and lower reaches of the Paraná River. The Paraná River currently transports about 120×10^6 t $year^{-1}$ of wash load, with nearly 90% of this being supplied by the Bermejo. The contribution from the Bermejo is now about 35% larger than its contribution during the 1970s, when it accounted for approximately 60% of the sediment load of the Paraná River. These changes that have occurred over the last 30 years have enhanced the natural asymmetrical distribution of solid and water discharges in the Paraná River basin.

KEY WORDS sediment load; Paraná basin; wash load; reservoirs; climate change

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INTRODUCTION

The water and sediment discharges from a fluvial system represent important environmental indices, reflecting the interaction between precipitation inputs and the drainage basin characteristics, and the resultant of the many associated processes operating within the basin and the impact of anthropogenic activity on those processes. Studies of fluvial sediment loads are required to provide an improved understanding of geomorphologic processes, land erosion, water quality–sediments relationships, sedimentation rates in reservoirs, waterways, ports and the ecological integrity of rivers. The Paraná River, the Paraguay River (its principal tributary) and the Bermejo River that joins the Paraguay near its mouth are the three main rivers that control the functioning of the Río de la Plata basin. In the Upper Paraná River basin that embraces a large portion of south Brazil (891 000 km^2 $\approx 32\%$ of the total basin), 130 dams have been built and these have greatly changed the fluvial landscape. Only 250 km of the natural channel of the Paraná River between the mouth of the Paranapanema River and the Itaipú dam (Brazil—Paraguay) remains undammed. Between Argentina and Paraguay, the Yaciretá reservoir was built, 500 km downstream from Itaipú (Figure 1). These two dams are the largest in the Río de la Plata basin. This paper uses data on the water and sediment discharge of the river system, collected before and after the impoundment of the large Itaipú and Yaciretá reservoirs, to investigate changes in sediment and water discharge within the Rio de la Plata basin associated with climate change and dam construction.

METHODOLOGICAL ASPECTS

Data collected at the beginning of the 1970s, before the construction of the Itaipú and Yaciretá reservoirs construction, were reported by Drago and Amsler (1988). Recent data, for the 1990s, were obtained from the Water Resources Secretariat of Argentina. In the case of the Bermejo River, these new data were collected at El Colorado, 150 km upstream of its confluence with the Paraguay River and 210 km upstream of its confluence with the Paraguay and Paraná Rivers. For the Paraná River, the measurements were made at Itatí, 40 km upstream of the confluence with the Paraguay River and 180 km downstream of the Yaciretá reservoir (Figure 1). Although neither of these sampling cross-sections was located at the same sites where the measurements were made in the 1970s, the sediment discharge data can, nevertheless, be meaningfully compared, to investigate changes in water and sediment flux between the two periods.

The bulk of information presented in the paper corresponds to the December–May period of the sampled

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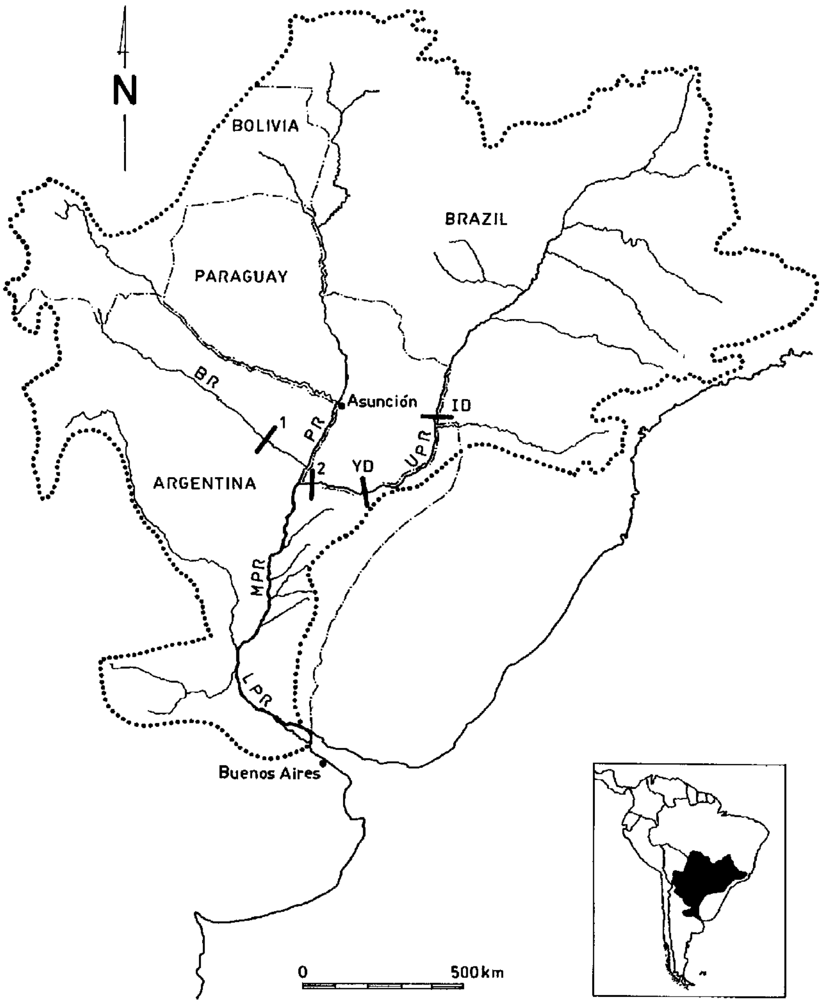

Figure 1. The Paraná River basin showing: (1) the El Colorado measuring station and (2) the Itatí measuring station. YD, the Yaciretá dam; ID, the Itaipú dam; BR, the Bermejo River; PR, the Paraguay River; UPR, the Upper Paraná River; MPR, the Middle Paraná River; LPR, the Lower Paraná River

years (Tables I and II), since it is found that maximum water and sediment discharges in the study rivers occur in these months only.

RESULTS AND DISCUSSION

The Bermejo River influence

The paper by Drago and Amsler (1988) provides baseline information on the hydrosedimentological behaviour of the Middle Paraná River in terms of both the magnitude and origin of the suspended sediment load and the contributions of its main tributaries, namely, the Upper Paraná and Paraguay Rivers. These authors showed that in the downstream of the confluence of the Upper Parana and Paraguay Rivers, suspended sediment concentrations increased by more than 130% on average, during the period of maximum sediment discharge (Figure 2). The high sediment loads supplied by the Bermejo River to the Paraguay mainstream, 60 km upstream its confluence with the Paraná, account for this fact. The Paraguay upstream from the Bermejo mouth and the Upper Paraná do not transport sufficient suspended sediment to explain this increase. One of the conclusions of the analysis undertaken by Drago and Amsler (1988) was that around 60% of the suspended sediment concentration values associated with the Middle Paraná River could be attributed to the sediment delivered by the Bermejo River.

The Andean headwaters of the Bermejo River supply the large amounts of wash load transported downstream. Heavy rains occur frequently during the summer, between October and April, giving rise to the highest sediment loads between December and February, when three to six storms per month occur. The results are high flows with high total suspended sediment concentrations (largely wash load) of up to 100 g l^{-1}. This fine sediment is transported in suspension from the Bermejo headwaters to the Middle Paraná main channel, and accounts for the increased suspended sediment concentrations described above.

Since the situation reported by Drago and Amsler (1988), using data collected 30 years ago, several important changes, both natural and anthopogenic, have occurred in the basin, changing the sediment transport regimes of its principal sub-basins.

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Table I. Concentrations and discharge measured in the Upper Paraná River at Itatí, during the 1990s

Date	Discharge (m^3 s^{-1})	Concentrations (mg l^{-1})		
		Fine fraction	Coarse fraction	Total
17 December 1993	12 963·5	32·7	18·1	50·8
27 January 1994	16 897·6	19·7	14·7	34·4
22 February 1994	18 060·6	8·5	15·6	24·1
24 March 1994	13 793·9	11·7	8·3	20·0
12 April 1994	12 237·0	101·0	114·9	215·9
24 May 1994	10 972·8	90·3	9·4	99·7
Averages	14 154·2	44·0	30·2	74·1
6 December 1994	14 385·3	7·1	6·9	14·0
27 January 1995	24 798·1	9·5	6·5	16·1
16 February 1995	18 253·6	9·6	6·9	16·5
24 March 1995	12 578·6	4·3	8·6	12·9
26 April 1995	17 224·1	11·7	6·8	18·5
23 March 1995	12 741·1	5·5	7·2	12·7
Averages	16 663·5	8·0	7·1	15·1
15 December 1995	11 987·5	6·9	9·0	15·9
22 January 1996	14 940·8	16·8	7·2	24·0
14 February 1996	16 976·3	16·3	9·5	25·8
5 March 1996	11 812·8	10·2	14·1	24·2
29 April 1996	12 994·8	6·6	7·8	14·4
28 May 1996	10 877·1	3·9	5·9	9·9
Averages	13 264·9	10·1	8·9	19·0
12 December 1996	13 052·3	7·2	15·5	22·7
31 January 1997	25 250·1	8·4	118·7	127·1
25 February 1997	28 838·0	16·1	10·3	26·4
26 March 1997	14 590·3	26·7	20·1	46·8
29 April 1997	11 568·4	5·4	11·6	17·0
28 May 1997	14 561·7	5·5	11·2	16·7
Averages	17 976·8	11·5	31·2	42·8
23 December 1997	20 038·3	1·8	7·2	9·0
29 January 1998	14 306·3	12·0	10·0	22·1
5 February 1998	18 517·6	1·8	4·5	6·3
24 March 1998	23 679·0	4·2	5·7	9·9
24 April 1998	30 061·3	19·0	9·2	28·2
2 May 1998	35 273·7	28·5	16·9	45·4
Averages	23 646·0	11·2	8·9	20·2
3 December 1998	12 769·4	6·7	12·0	18·7
13 January 1999	14 016·7	8·1	10·9	19·0
Averages	13 393·1	7·4	11·4	18·8
Total averages	16 906·8	16·4	16·9	33·3

Table II. Concentrations and discharge measured in the Bermejo River at El Colorado, during the 1990s

Date	Discharge (m^3 s^{-1})	Concentrations (mg l^{-1})		
		Fine fraction	Coarse fraction	Total
2 December 1993	628·8	8 174·9	2096·6	10 271·5
6 January 1994	586·9	8 641·8	2432·5	11 074·3
3 February 1994	1032·4	8 876·7	3501·3	12 378·0
1 March 1994	1169·4	10 976·4	4192·9	15 169·4
12 April 1994	447·3	48 32·7	2368·8	7 201·6
7 May 1994	321·1	3 740·8	731·3	4 472·1
Averages	697·7	7 540·6	2553·9	10 094·5
2 December 1994	311·7	4 143·6	480·3	4 623·8
3 January 1995	473·1	7 117·2	951·6	8 068·8
10 February 1995	1350·0	9 403·0	2710·0	12 113·0
3 March 1995	937·5	11 213·9	750·3	11 964·2
6 April 1995	1522·4	8 316·9	4236·2	12 553·2
11 May 1995	372·7	2 404·6	12·1	2 416·7
Averages	827·9	7 099·9	1523·4	8 623·3
5 December 1995	220·4	1 991·6	204·6	2 196·2
3 January 1996	235·4	2 193·0	95·6	2 288·6
2 February 1996	991·6	10 377·7	2694·0	13 071·7
7 March 1996	1292·3	11 553·6	9145·9	20 699·6
18 April 1996	395·0	4 594·1	832·2	5 426·3
2 May 1996	389·5	5 325·8	1122·4	6 448·2
Averages	587·4	6 006·0	2349·1	8 355·1
4 December 1996	186·7	2 623·5	273·1	2 896·7
3 January 1997	1036·1	9 764·5	1962·9	11 727·4
11 February 1997	1396·7	9 626·8	2533·0	12 159·8
7 March 1997	1547·4	13 455·7	3249·9	16 705·6
10 April 1997	808·6	8 304·2	1897·2	10 201·4
2 May 1997	364·0	3 534·0	389·5	3 923·5
Averages	889·9	7 884·8	1717·6	9 602·4
4 December 1997	54·7	329·3	12·8	342·1
7 January 1998	139·7	1 899·5	115·2	2 014·7
13 February 1998	409·9	5 964·3	642·9	6 607·1
3 March 1998	384·2	6 990·3	885·0	7 875·3
1 April 1998	1060·0	13 119·3	3405·4	16 524·7
7 May 1998	498·5	5 751·8	1920·0	7 671·8
Averages	424·5	5 675·7	1163·5	6 839·3
1 December 1998	199·0	2 204·8	533·7	2 738·5
6 January 1999	325·1	4 593·0	113·5	4 706·5
Averages	262·0	3 398·9	323·6	3 722·5
Total averages	659·0	6 478·9	1966·2	8 137·3

Using the new hydrosedimentological data collected from the El Colorado measuring station (Formosa Province, Argentina) on the Bermejo River (Table II), it is possible to compute an average total concentration of 8140 mg l^{-1} for the December–May period. This value is 25% greater than that reported by Drago and Amsler (1988, Figure 2). If the mean annual discharges of the river for the 1970s and 1990s are considered: 560 and 830 m^3 s^{-1} (the latter value was computed on the basis of a discharges series longer than that shown in Table II), the sediment discharge of the Bermejo River can be seen to have increased 85% during the period of the year with maximum sediment transport: from 3660 to 6750 kg s^{-1}. It is recognized that use of the load calculation procedure advocated by Piest and Miller (1977), for example, in combination with sediment rating curves, such as those shown in Figures 3 and 4, would have provided a more reliable estimate of the mean sediment discharges for the two periods, and that the last value is possibly underestimated. In this context, it can be seen that Figure 4 predicts a mean concentration of approximately 6500 mg l^{-1} for a Q_m of 560 m^3 s^{-1}, which is similar to the concentration recorded in the 1970s. For a Q_m of 830 m^3 s^{-1}, Figure 4 provides an estimate of the total suspended sediment concentration in the 1990s of approximately 10 g l^{-1}. The 50% increase in the mean water discharge between the 1970s and the 1990s is consistent with the evidence for changing flow regimes within the sub-basins of the Río de la Plata system during the same period documented by García and Vargas (1996, 1998). These authors attributed the increased water discharges to increased rainfall, as a reflection of climate

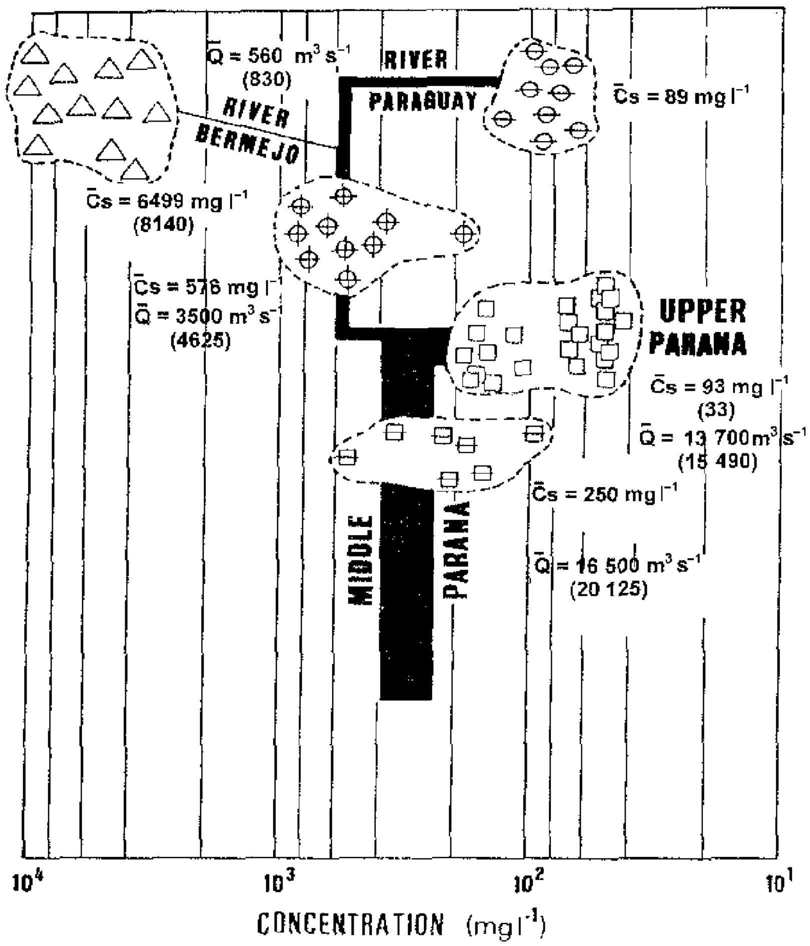

Figure 2. A comparison of water discharge and suspended sediment transport in the study rivers during the period 1971–1974, based on the data presented by Drago and Amsler (1988), with those for the period 1993–1999 (shown in brackets)

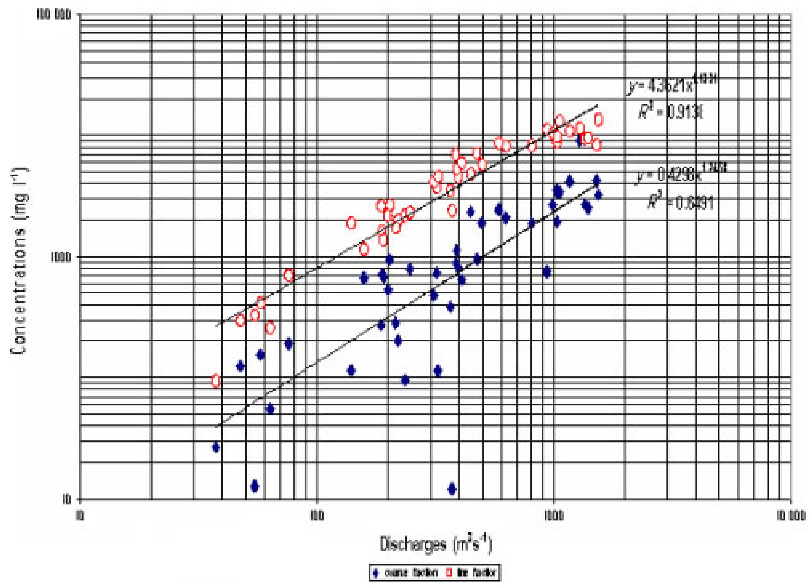

Figure 3. Sediment rating curves for the coarse ($d > 62{\cdot}5$ μm) and fine fractions of the suspended sediment load transported by the Bermejo River at El Colorado, based on the measurements undertaken in the 1990s

change across the Río de la Plata basin. Increased rainfall and water discharge within a basin with a high susceptibility to erosion, such as that of the Bermejo River, will inevitably give rise to an increase in sediment yield.

Upper Paraná

During the last 30 years, a number of important dams have been constructed and are now operational in the

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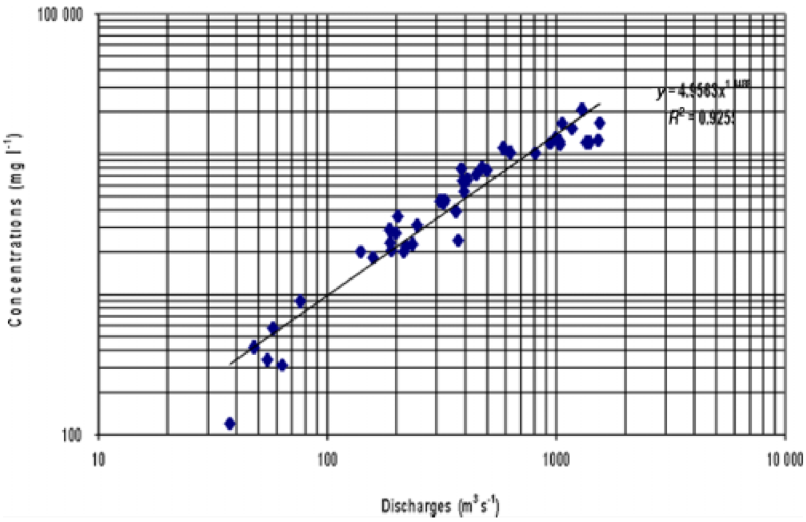

Figure 4. Sediment rating curves for total suspended sediment load transported by the Bermejo River at El Colorado, based on the measurements undertaken in the 1990s

Table III. Principal dams built in the Upper Paraná basin during the last 30 years

Dam residence	Beginning of operation	Retention period (days)
Promissaso (Tieté River)	1974	134
Agua Vermelha (Grande River)	1978	62
Nova Avanhadava (Tieté River)	1982	45
Itaipú (Upper Paraná River)	1982	40
Yaciretá (Upper Paraná River)	1992	~15

Upper Paraná basin. Some of the more important dams are listed in Table III (A. A. Agostihno, personal communication). On the basis of the available data on total suspended sediment concentrations, during the period of maximum discharge, for the decade 1990–1999 (Table I), it is possible to compute an average total concentration of 33·3 mg l^{-1} for the Upper Paraná at its confluence with the Paraguay River. This value is 64% lower than the concentration reported by Drago and Amsler (1988) (Figure 2) for the same station. Considering the mean annual discharge in the Upper Paraná during the 1971–1974 period (13 700 m^3 s^{-1}), and that for the 1990s (15 491 m^3 s^{-1}), the total suspended sediment discharge transported by the Upper Paraná can be estimated to have decreased by 60% (from 1274 to 515 kg s^{-1}). This decrease in sediment load occurred in spite of the increased annual water discharge for the river, as a consequence of the changes identified by García and Vargas (1996, 1998), and referred to previously. Thus, it can be concluded that the large reservoirs built in the last 30 years account for the decreasing sediment load of the Upper Paraná River. Their capacity to retain sediment and reduce sediment loads must be seen as particularly important when it is recognized that the Upper Paraná basin includes some of the major areas of high population density and industrial activity in Brazil, and has experienced a major increase in human impact, including deforestation and intensification of land use. In the absence of the dams, sediment loads could be expected to have increased, as in the case of the Bermejo River. Another important fact appears when the composition of the present suspended loads transported by the Upper Paraná River is examined. It is seen that the coarse fractions (ds $\geq$0·062 mm) reach similar mean concentrations than the finer ones (17 and 16 mg l^{-1}, respectively; Table I). If it is taken into account that the coarse suspended fractions deposit normally completely at the entrance of large reservoirs, it is inferred that the 17 mg l^{-1} of coarse fraction transported downstream the Yaciretá dam by the Upper Paraná comes from the erosion of the bed itself along the reach (180 km long) before the confluence with the Paraguay. At the same time, it is noted that the usual percentages of wash load in the total suspended load transported by the principal basin rivers (see below) was markedly altered.

Mean annual solid discharges

As explained earlier, the Bermejo River supplies large amounts of wash load to the Middle Paraná River. Drago and Amsler (1988) reported wash load percentages ranging between 66 and 97% in the suspended load of the Middle Paraná River, with the largest values occurring during the December–May period, when the deliveries of the Bermejo River flow through the system. Prendes (1981) computed, based on the data measured before 1970, a mean value of 87×10^6 t $year^{-1}$ for the wash load in the Middle Paraná, 63% of it supplied by the Bermejo River.

With the data obtained during the 1990s at El Colorado and Itatí, it was possible to compute $109{\cdot}3 \times 10^6$ t $year^{-1}$ and $5{\cdot}1 \times 10^6$ t $year^{-1}$, for the wash load annually transported by the Bermejo and Upper Paraná Rivers, respectively. (These values were set at combining instantaneous sediment rating curves fitted at each cross-section, with 10 years long daily discharge series). Consequently, and under the assumption that the wash load delivered by the Paraguay River upstream of the Bermejo mouth do not exceed 5% of that fraction at the Middle Paraná

(Drago and Amsler, 1988), it was estimated an average of 120×10^6 t year^{-1} for the wash load transported annually downstream of confluence. That is, a value of about 35% larger than the one measured during the 1970s and with near 90% supplied by the Bermejo River.

CONCLUSIONS

The Paraná River basin may be divided into two main sub-basins which differ in their water and sediment yields, and in the anthropogenic action operating on each one.

The Upper Paraná sub-basin extends largely in Brazil draining 32% of the total area of the Paraná basin and contributing the largest streamflows to the system. It has the highest population densities and industrial concentrations of Brazil. Some consequences of these facts were the construction of more than 130 dams, increasing deforestation, soil degradation, urbanization, etc. Furthermore, the effects of the climate change increased both the precipitation and surface runoff. These features, usually associated with a rising in the sediment yield, were not detected in the Upper Paraná sub-basin according to the measurements available at the Paraná–Paraguay confluence. Actually, prior to the building of the largest dams at the beginning of 1970s, a mean solid discharge of 1274 kg s^{-1} was recorded that decreased to 515 kg s^{-1} at present. This fact would be the result of the 'trap effect' owing to the reservoirs built during the last 30 years.

The sub-basin of the Paraguay River shows a minor anthropogenic action because of its low demographic and industrial development. Another important difference exits since its main rivers are not damming up to now. This sub-basin supplies smaller water discharges to the system than the Upper Paraná one, but the largest sedimentary deliveries through the Bermejo River. This Andean tributary really governs the sedimentological behaviour of the Middle Paraná River. According to the data by Drago and Amsler (1988) during the 1970–1974 period, the concentration of the Bermejo River was 6500 mg l^{-1}. Recent data show a noticeable increase of the water and solid discharges; in the latter case from 3660 (1970s) to 6750 kg s^{-1} (1990s). This means an increment of 35% in the wash load discharge transported annually by the Middle Paraná River.

On the basis of the previous results, it is possible to conclude that the climate change has been strongly affecting the hydrosedimentological regime of the Upper Paraná and Paraguay network. However, as a consequence of the different magnitude of the anthropogenic impacts in the two sub-basins during the last 30 years, their response is not the same. Thus, it is observed that the natural hydrosedimentological asymmetrical behaviour of the Paraná River basin not only persists but also more notable now.

It is generally concluded that the monitoring programmes of this hydrosystem must not only be continued but also extended in order to get increasing knowledge on the future variations of its solid and water discharges towards a better comprehension of possible changes in its ecological integrity.

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