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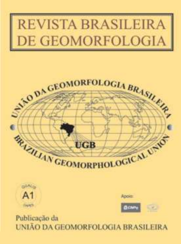

RIVER FUNCTIONING ANALYSIS FROM SUSPENDED SEDIMENT AND WATER DISCHARGE STUDY: THE CASE OF THE IVAÍ RIVER, SOUTHERN BRAZIL

ANÁLISE DO FUNCIONAMENTO FLUVIAL A PARTIR DO ESTUDO DA DESCARGA DE ÁGUA E SEDIMENTO SUSPENSO: O CASO DO RIO IVAÍ, SUL DO BRASIL

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Abstract:

This paper presents the spatial distribution of liquid and solid (suspended load) discharge in the Ivaí River Basin, and its implication in the functioning of this river system. The Ivaí is a typical medium-size river of the basaltic plateau, on the left side of the Paraná River Basin in southern Brazil. The data relating to water discharge and concentration of suspended sediment come from 19 gauging stations controlled by the former Superintendence of Water Resources and Environmental Sanitation Development – SUDERHSA, today Water Institute of Paraná. The river drains an area of 36,587 km^2, and its average discharge during the study period (1974–2008) was 702.9 m^3 s^{-1}. The specific discharge (Qsp = Qm:Ab) varied uniformly between 0.01 and 0.02 m^3 s^{-1} km^{-2}, however, an anomalous result of 0.11 m^3 s^{-1} km^{-2} was identified. Most of the water that enters the

Ivaí River comes from the smaller sub-basins (< 500 km^2), and the specific discharge from the tributaries decreases from upstream to downstream, from 0.028 to 0.015 m^3 s^{-1} km^{-2}. Correlations are high between the annual production of suspended sediment *versus* average discharge (R^2 = 0.97) for all river gauging stations, and the contribution of suspended load versus basin area (R^2 = 0.95). This suggests that the elongate morphology of the basin is main variable controlling of water and sediment distribution. The water and suspended sediment discharge of the Ivaí River is similar to those dry-wet, temperate climate river in the world. A good correlation was also obtained when the river was compared with others plateau river in the world. The results make a great contribution to the management and planning projects for many basaltic-plateau rivers along the eastern side of the upper Paraná Basin, Brazil.

Resumo:

Este estudo apresenta a distribuição espacial de descarga líquida e sólida (carga suspensa) na Bacia do rio Ivaí, e suas implicações no funcionamento deste sistema fluvial. O Ivaí é um rio de porte médio, típico de platô basáltico no lado oriental da Bacia do Rio Paraná no sul do Brasil. Os dados referentes à descarga de água e concentração de sedimentos em suspensão são provenientes de 19 estações fluviométricas, no período em que foram controladas pela antiga Superintendência de Desenvolvimento de Recursos Hídricos e Saneamento Ambiental – SUDERHSA, hoje Instituto das Águas do Paraná. O rio Ivaí drena uma área de 36,587 km^2, e sua vazão média durante o período (1974-2008) foi 702,9 m^3 s^{-1}. A descarga específica (Qsp = Qm:Ab) variou uniformemente entre 0,01 e 0,02 m^3 s^{-1} km^{-2}, no entanto, um resultado anômalo de 0,11 m^3 s^{-1} km^2 foi identificado. A maior parte da água que entra no rio Ivaí vem das pequenas sub-bacias (< 500 km^2), e a descarga específica das bacias afluentes diminui de montante para jusante, 0,028 e 0,015 m^3 s^{-1} km^{-2}. As correlações são altas, tanto na produção anual de sedimentos em suspensão *versus* descarga média (R^2 = 0,97), e a contribuição da carga suspensa por trecho *versus* área da bacia (R^2 = 0,95). Isto sugere que a morfologia alongada da bacia é a principal variável de controle para os sedimentos e água. O volume de descarga líquida e carga suspensa do Ivaí é compatível com outros rios do mundo localizados em regiões de clima seco e temperado-húmido. Uma boa correlação foi também obtida quando o rio foi comparado com outros rios de platô do mundo. Os resultados deste estudo contribuem para os projetos de gestão e planejamento para muitos rios de platô basáltico do lado oriental da alta Bacia do Rio Paraná, Brasil.

1. Introduction

The understanding of the hydrological regime of water and sediment of a hydrographic basin is the base for environmental questions concerning floodplain-channel coupling in terms of connectivity processes (NEIFF & POI DE NEIFF, 2003; STEVAUX *et al.,* 2013), as well as the regional economic, social and cultural structure (DOWNS & GREGORY, 2004).

Medium-sized river systems running over basaltic plateau are very common in the Southern Brazil, and they constitute all the tributaries on the left-hand side of the Upper Paraná River Basin (Figura 1). The aggressive Brazilian hydroelectric policy resulted in the rapid construction of hundreds of large dams spread over the Upper Paraná River Basin (Figura 1), more specifically in its tributaries in the basaltic plateau. Among several impacts in the fluvial system, dam construction reduced the suspended load in the Paraná River from 90 mg L$^{-1\text{ to }0.5\text{ mg.L-1}}$ (STEVAUX *et al.,* 2009), with irreversible consequences to the river's ecology (AGOSTINHO *et al.,* 2004; STEVAUX *et al.,* 2013). The majority of these medium-sized tributaries (Qm 500-1000 m^3 s^{-1}) were not studied in terms of hydro-sedimentological and ecological functioning before the completion of the dams construction. The construction of many other dams are in the planning stages for the Ivaí, Piquirí, Iguaçu and Pelotas-Uruguay Rivers (the last one belonging to the Uruguay River Basin) over the next few years. From this perspective, a more accurate study concerning water and suspended sediment regime and dynamics is needed in order to cope with the resulting changes in the Upper Paraná left-hand tributaries in Brazil. However, all these rivers already have one or more dams which would harm the quantification and modeling of hydrosedimentary dynamics. The Ivaí River is an exception. Even with a relatively high hydroelectric potential of 900 MW (COPEL, 1984), and a longitudinal profile with narrow rocky valleys and rapids in its upper and middle courses, its drainage basin remains practically in its natural condition, with only a few small dams in some tributaries.

Generally, studies relating to water and discharge of suspended sediment, at least in tropical mega-rivers in Brazil, such as the Amazon (Qm 209,000 $m^3 s^{-1}$), Madeira (Qm 32,000 $m^3 s^{-1}$), Negro (28,400 $m^3 s^{-1}$) and Japura (Qm 18,600 $m^3 s^{-1}$) (LATRUBESSE, 2009), are supported by data collected from a small number of gauging stations which are normally processed without much understanding of their spatial dynamics (FILIZOLA, 1999). However, since these rivers have such large channels, normally wider than 1 km, the use of remote sensing tools compensates for the lack of sufficient gauging station data (MONTANHER *et al.,* 2014, 2017; PARKER & LATRUBESSE, 2014). However, these methods are not applicable in medium-sized rivers where the pixel resolution is normally larger than the channel width (ESPINOZZA *et al.,* 2012). Considering the above, this paper deals with important issues such as: (a) the spatial distribution of suspended load in a typical basaltic plateau river on left-hand side of the Paraná River Basin; (b) the methods used in the study of suspended load in medium-sized rivers flowing over rocks; and (c) the importance of the Ivaí River as the main contributor of suspended load to the upper Paraná River.

2. Background information

The Ivaí River runs 798 km, crossing the Brazilian sedimentary-basaltic plateau that covers most of the Southern Brazil. With an annual average discharge of 702.9 $m^3 s^{-1}$ (1974–2008), it drains an area of 36,587 km^2. The relief amplitude is 930 m with the headwater at the Boa Esperança Mountains (1,160 m a.s.l.) in the Third Paraná Highland and the mouth in the Paraná River at 230 m a.s.l. Although the Ivaí River does not have any dams, about 75% of its basin is occupied by agriculture and pasture lands, especially in the low and middle sectors. Because of the steep relief, the upper sector is sparsely occupied by cattle pasture. Some authors have divided the Ivaí River Basin according to on land use and geomorphology, and in relief-lithology relation (MEURER, 2008, 2010; MEURER *et al.,* 2011). In this paper, we have used the triple division: upper, middle and lower basins (Table 1, and see Figura 2).

Geological-tectonic control for left-hand side tributaries of the Paraná River: The Paraná Sedimentary Basin is spread across 2,000,000 km^2 of southern Brazil. It is a Paleozoic-Mesozoic geotectonic unit that contains the largest basaltic plateau in the world which was generated during the breakdown of the Gondwana Continent in the Mesozoic Age (Figura 1). The basalt has a maximum of 2000 m thick, spread over 1,200,000 km^2 in Brazil, Uruguay, Argentina and Paraguay (PONTELLI & PAISANI, 2015). The geological basin has an elliptical form with the Paraná River running NE-SW along its longer axis. The basalt exposition is asymmetric, developing predominantly in the eastern side of the basin (Figura 1). The rising of the Serra do Mar Mountains (900–1000 m) on the Atlantic border during the Mio-Pliocene Age (BRAUN, 1971) generated an extensive westward monoclinal surface that, together with NW-SE structural lineaments (FERREIRA, 1982), created the formation of long tributary rivers (> 800 km long) such as the Grande (1360 km), Tietê (1150 km), Paranapanema (929 km), Ivaí (798 km), Piquirí (660 km), Iguaçu (1320 km) and Pelotas-Uruguay (2270 km) rivers (the last being the tributary of the La Plata River). On the other hand, the Maracajú Mountains (900 m) rising 250 km west of the Paraná River, separates the Paraguay River Basin from the Paraná Basin, which originated during the Mio-Pliocene Age (Stevaux, 1994), and also generated a right-hand side drainage network of small rivers (Amambaí, Ivinhema, Sucuri and Iguatemi rivers 200–300 km long) that run over Cenozoic sandstone that covers the basaltic rocks (Figura 1).

3. Data Provenance and Methods

In this study, we used the historical series of discharge, concentration of suspended sediment, and rainfall data from the former SUDERHSA network of gauging stations. Gauging stations have different historical series intervals for water discharge. The earliest and lengthiest record in the Ivaí River is that of the Paraíso do Norte station which has been in operation since 1953 (20,228 days), while among the tributaries, the station of Patos River, the most upstream station, continuously operates since 1930 (28,520 days). The same performance cannot be obtained for suspended sediment, which data were predominantly recorded in the Ivaí River stations, being the Novo Porto Taquara station that consisted of the most extensive series of 157 measurements, (Figura 2, Table 2).

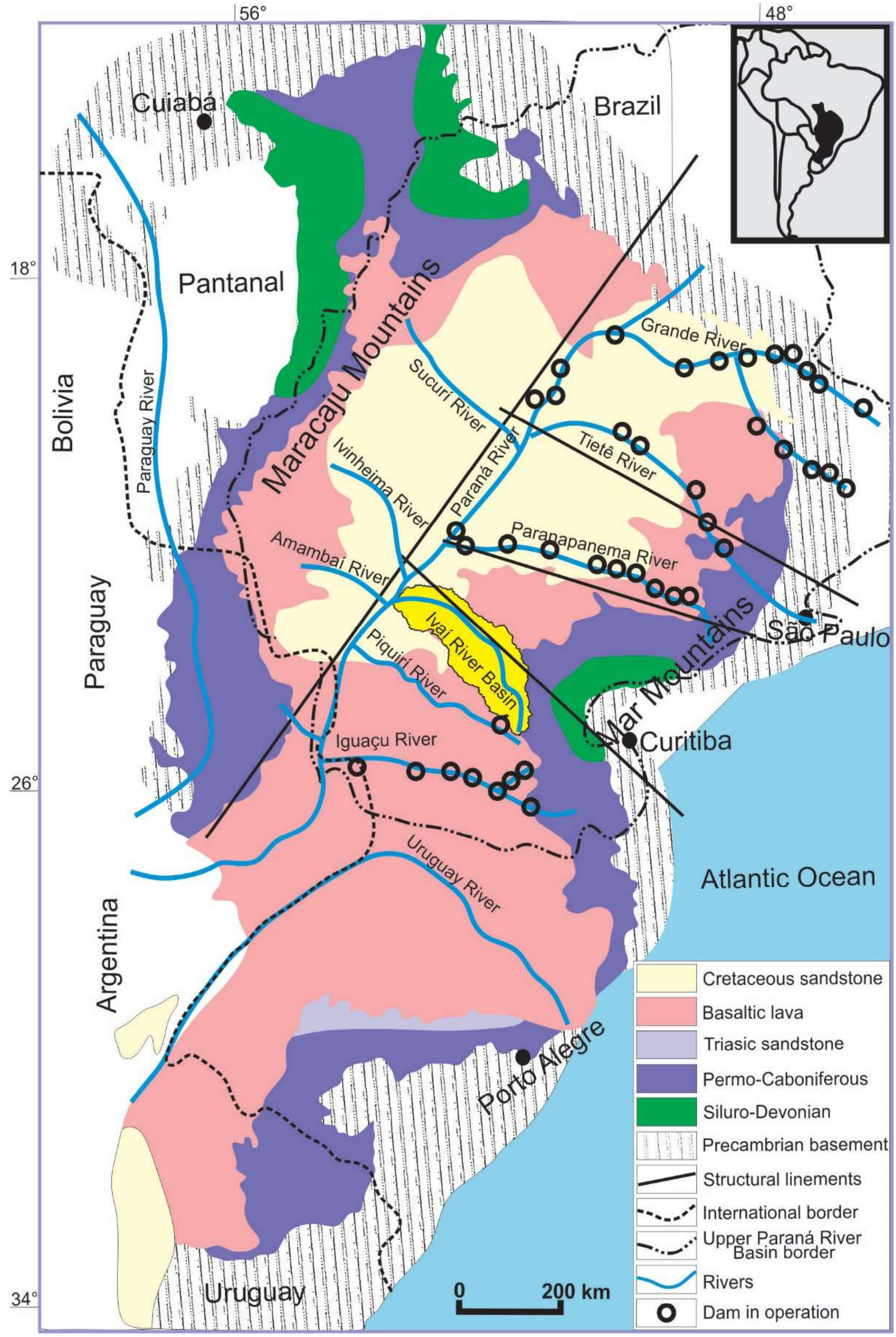

Figure 1 - Paraná Sedimentary Basin and main dams in the Upper Paraná River. Mod. (Stevaux & Latrubesse, 2010).

Table 1: Synthesis of physical characteristics of the Ivaí River Basin (Leli *et al.,* 2011; Destefani, 2005; Andrade, 2003; Meurer, 2008; Bhering & Santos, 2008).

Sector basin	Lithology and soil	Relief	Vegetation	Climate
Upper: Length: 370 km Area: 12,926 km^2 Description: From headwater to Alonso River mouth.	Shale, fine to very fine sandstone and limestone of the Passa Dois Group (Permian) with diabase sills and dikes. Eutrophic Regolithic Neosol, Cambisol with 0.5–1.3 m in thickness, yellowish red dystrophic Argisol and secondarily Red Dystrophic Latosol, Red Dystroferric and Eutroferric Latosol.	From 1,200 to 500 m. Very sculpted relief with falls and rapids in the main and tributary rivers.	Mixed Ombrophilous with Araucaria Forest Land use: natural landscape.	Subtropical Annual rainfall: 2,000 mm.
Middle: Length: 230 km Area: 15,281 km^2 Description: From Alonso River to the Porto Paraíso do Norte gauging station.	Basaltic traps and sandstone of São Bento Group. Red Eutroferric Nitosol, Lithilic Neosol, Red Dystrofferric and Eutroferric Latosol, Red Dystrophic and Eutrophic Argisol.	From 500 to 300 m. Tabular relief with *mesetas*, and *demi-orange* mountains and hills. River flow with rapids and minor falls.	Seasonal semideciduous Forest. Land use: 30–40% agriculture and reforestation.	Subtropical Annual rainfall 1,700 mm.
Lower: Length: 200 km Area: 8,380 km^2 Description: From Porto Paraíso to its mouth in the Paraná River.	Bauru Group sandstone, alluvium-colluvium covering Red Dystrophic Latosol, secondarily Yellowish red Dystrophic Argisol and Fulvic Neosol.	From 300 to 230 m. Gentle hills, tranquil flow with very scarce rapids in main channel and tributaries.	Seasonal semideciduous Forest. Land use: 60–70% agriculture and pasture.	Tropical Annual rainfall 1,400 mm.

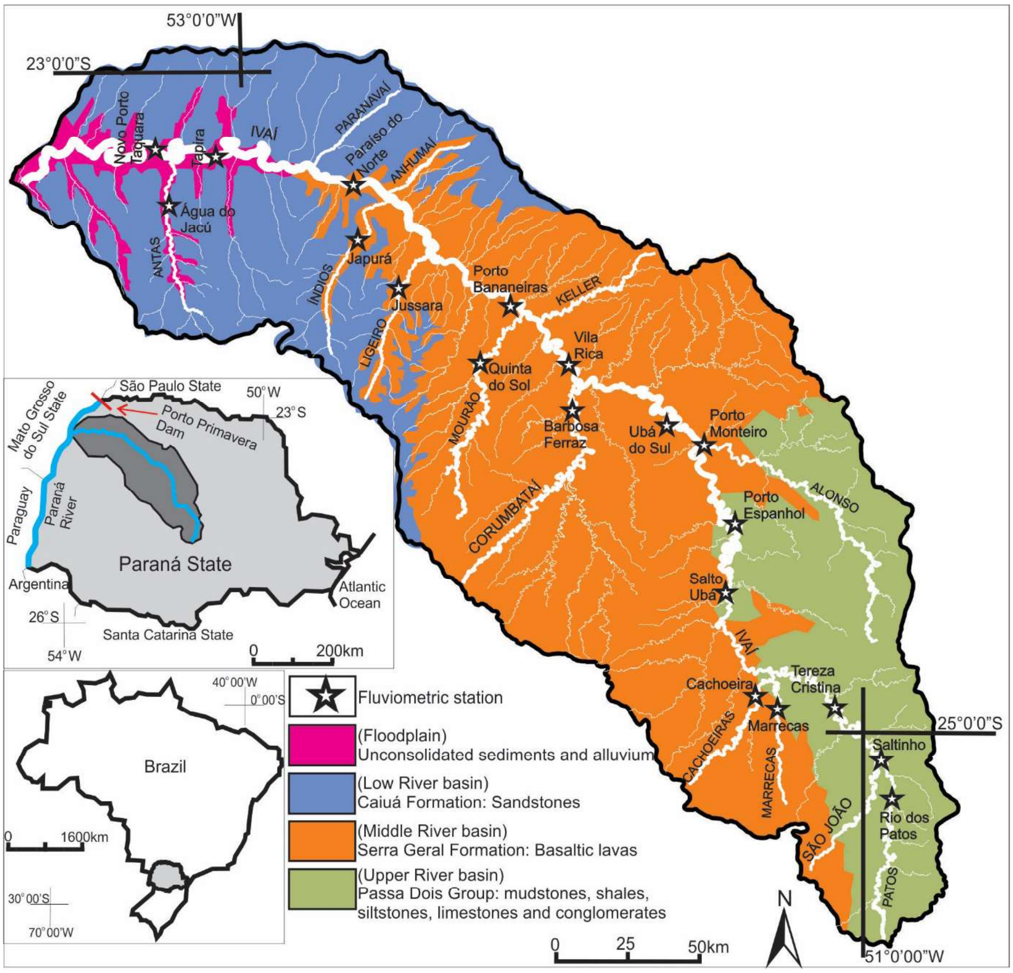

Figure 2 - Hydrographic map of the Ivaí River Basin: its basin divisions and gauging stations.

The parameters used for presenting this analysis includes historical series mean discharge (Qm), daily discharge (Q), specific mean discharge (Qsp), mean discharge between stations (Qm*), mean suspended load concentration (Cssm), annual suspended load discharge (Qss), annual suspend load discharge between stations (Qss*), suspended sediment concentration between stations (Css*), specific suspended load discharge (Qsssp), whose definition and equation are presented in Table 3. In order to solve problems in gauging station distribution, a kind of regionalization was attempted (Table 4). The discharge of reaches or between tributaries (Qm*) with no fluvial stations was obtained by grouping sub-basins as a unique tributary basin. In these cases, discharge was estimated by subtracting the discharge of upstream (Qm[us]) from downstream stations (Qm[ds]) according to the following equation:

$$Qm^* = Qm[ds] - Qm[us]$$

The concentration of suspended sediment between stations (Css*) was estimated using the annual suspended load between stations (Qss*) divided by annual water production of the reach (Qm*k) collected at 19 stations for water discharge and 13 stations for suspended sediment, as showed in the next equation:

$$Css^* = Qss^*/(Qm^*k)$$

k is conversion factor (see table 3).

Table 2: Historical series for water and suspended sediment discharge and rainfall in gauging stations of the Ivaí River Basin (Source: SUDHERSA).

Stations(*)	River	Days for Qm	Historical series	Days for Css	Historical Series	Days for rainfall	Historical series
Rio dos Patos	Patos	28,502	05/20/1930 06/30/2008	30	02/10/1982 06/05/2008	7,066	03/01/1937 06/08/2008
Saltinho	São João	670	01/10/1955 2/09/1956	-	-	2,660	10/22/1975 06/08/2008
Tereza Cristina	**Ivaí**	**18,890**	**08/07/1956** **04/30/2008**	**84**	**02/1/1982** **04/30/2008**	**6,463**	**08/01/1956** **04/13/2008**
Marrecas	Marrecas	1,095	09/02/2004 12/09/2007	-	-	-	-
Cachoeira	Cachoeira	2,555	11/10/2000 11/09/2007	-	-	-	-
Salto Ubá	**Ivaí**	**4,015**	**05/11/1949** **05/08/1960**	-	-	**103**	**01/01/1956** **12/31/1956**
Porto Espanhol	**Ivaí**	**15,695**	**08/13/1965** **05/10/2008**	-	-	**4,214**	**08/10/1965** **06/08/2008**
Porto Monteiro	Alonso	12,410	01/29/1974 07/08/2008	-	-	2,767	01/01/1974 06/08/2008
Uba do Sul	**Ivaí**	**15,150**	**04/16/1967** **06/05/2008**	**95**	**0116/1982** **06/05/2008**	**3,874**	**04/01/1967** **06/08/2008**
Barbosa Ferraz	Corumbataí	12,385	08/19/1974 07/16/2008	79	01/18/1982 11/21/2007	3,118	08/01/1974 06/08/2008
Vila Rica	**Ivaí**	**8,360**	**08/14/1985** **06/05/2008**	**76**	**11/06/1990** **06/05/2008**	**1,963**	**09/14/1985** **11/10/2007**
Quinta do Sol	Mourão	12,392	08/08/1974 06/05/2008	132	04/18/1977 06/05/2008	2,775	08/01/1974 06/05/2008
Porto Bananeiras	**Ivaí**	**12,510**	**02/19/1974** **06/05/2008**	**59**	**09/16/1980** **06/07/2008**	**3,394**	**02/19/1974** **06/05/2008**
Jussara	Ligeiro	56	01/24/1982 06/06/2008	56	01/24/1982 06/06/2008	1,633	01/22/1975 12/31/1997
Japurá	Índios	11,06	01/01/1977 06/05/2008	83	01/25/1982 06/06/2008	2,851	12/16/1975 06/05/2008
Paraíso do Norte	**Ivaí**	**20,226**	**05/23/1953** **07/29/2008**	**95**	**04/16/1977** **06/04/2008**	**664**	**05/23/1953** **06/05/2008**
Tapira	**Ivaí**	**5,110**	**10/24/1976** **07/31/1990**	**50**	-	**2,970**	**12/16/1975** **06/05/2008**
Água do Jacu	Antas	1,625	06/04/1977 03/01/1991	47	08/12/1979 08/30/1989	2,045	01/06/1978 05/16/2001
Novo Porto Taquara	**Ivaí**	**12,210**	**01/07/1974** **06/05/2008**	**157**	**09/14/1974** **06/05/2008**	**2,589**	**07/01/1974** **06/05/2008**

(*) Bold letters represent stations in the Ivaí River.

The three main stations that gauge the major sectors (and their respective gauging period) of the Ivaí Basin the Ubá do Sul in the upper, (1982-2008), Paraíso do Norte in the middle (1977-2008), and Novo Porto Taquara in the lower (1974-2008) (Figura 2).

Table 3: Definition of hydrosedimentological variables.

Variable	*Definition*	*Unit*
Historical series mean discharge (Qm)		$m^3\ s^{-1}$
Specific discharge (Qsp)	$Qsp = Qm/Ab$	$m^3\ s^{-1}\ km^{-2}$
Mean suspended load concentration (Cssm)		$mg\ L^{-1}$
Annual suspended load discharge (Qss)	$Qss = Csm.Qm.k.10^{-6}$	$t\ year^{-1}$
Annual suspended load discharge between stations (Qss)*	$Qss^* = Qss[ds] – Qss[us]$	$t\ year^{-1}$
Mean water discharge between stations (Qm)*	$Qm^* = Qm[ds] – Qm[us]$	$m^3\ s^{-1}$
Suspended sediment concentration between stations (Css)*	$Css^* = Qss^*/(Qm^*k)$	$mg\ L^{-1}$
Specific suspended load discharge (Qsssp)	$Qsssp = Qss/Ab$	$t\ year^{-1}\ km^{-2}$

Q = daily discharge, Ab = basin area, Css = daily suspended load concentration, n = number of days of historical series, [ds] and [us] = down and upstream, k = unit conversion factor = 31,536 (60 seg × 60 min × 24 h × 365 days).

4. Results

In spite of the small number of gauging stations and their irregular distribution over the drainage basin (Figura 2), the relatively long historical series for water and suspended load discharge (Table 2), and the uniformity in the basin's elongated morphology (compaction coefficient = 2.46; form factor = 0.06), with regular joining of tributaries, contributed towards a good correlation between the hydrosedimentologic parameters and the spatial distribution of load suspension dynamics in the basin.

Over a 34-year historical series (1974–2008), the Ivaí River has a mean discharge of 702.9 $m^3.s^{-1}$, corresponding to a 64% permanence, measured at its lowest gauging station (Novo Porto Taquara), and a mean flood discharge of 4,019 $m^3\ s^{-1}$ with a permanence of 1% (Figura 3).

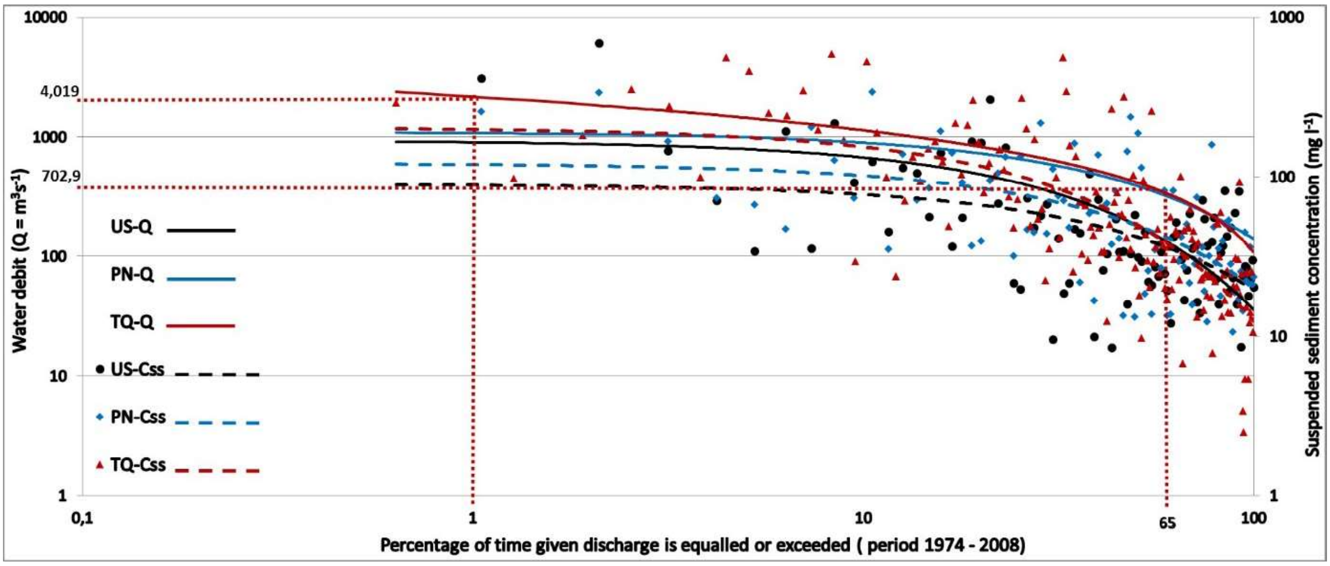

Figure 3 - Percentage of time to a given water discharge (Q) and suspended sediment concentration (Css) at Ubá do Sul (US), Paraíso do Norte (PN) and Novo Porto Taquara (TQ) gauging stations. Red dotted line shows the percentage of time of mean (65 %) and mean flood discharges (1 %) at TQ.

According to Paiva (2008), base flow cannot maintain river flow near mean discharge, so, the Ivaí River hydrological regime is controlled by surface runoff. The largest discharge recorded in the historical series is 5,800 m^3 s^{-1} in 1992 with a recurrence of 23 years (DESTEFANI, 2005). The river hydrograph is characterized by significant discharge variability with abrupt changes in magnitude (Figura 4). Flood peaks do not follow a seasonal pattern, occurring in any month of the year, and may change from one year to another because of the action of cold front rains and orographic precipitation (ANDRADE, 2003). Data of water and suspended sediments for the Ivaí and tributaries are synthetized on table 4.

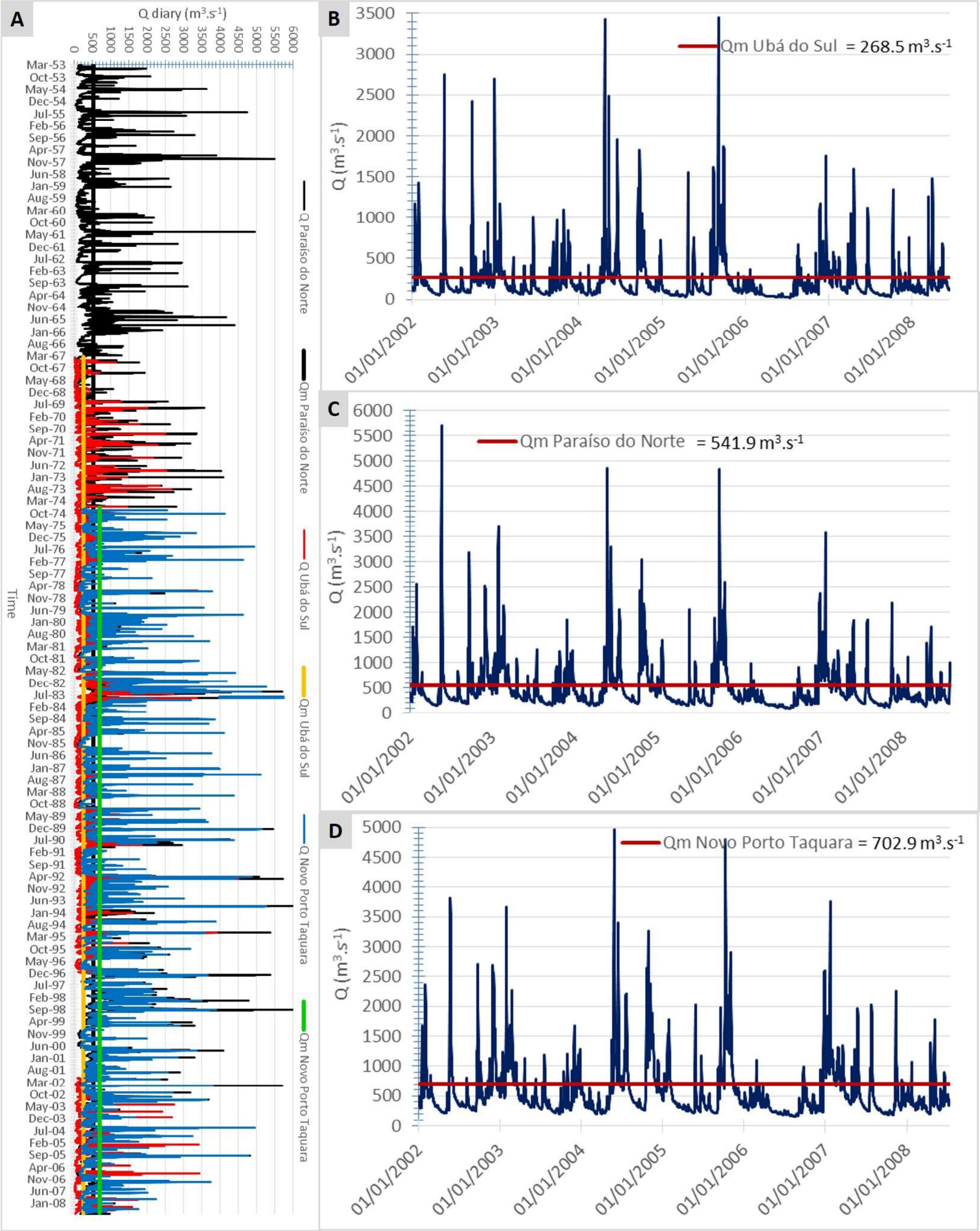

Figure 4 - Hydrograph of the Ivaí River at the principal gauging stations. A: Total historical series hydrograph, Paraíso do Norte (1953), Ubá do Sul (1967), Novo Porto Taquara (1974). B, C, D: detailed hydrograph for these gauging stations

Table 4: Synthesis of results for water and suspended sediment in the Ivaí River, tributaries, gauging Stations, and reaches between gauging stations.

Reach	Subasin reach	Qm ms^{-1}	Ac Qm $m^3\ s^{-1}$	A km^2	AcA km^2	Qmsp $m^3\ s^{-1}\ km^{-2}$	Css mg L^{-1}	Qss ty^{-1} (ton y^{-1})	Qsssp $ty^{-1}\ km^{-2}$
Upper	*Patos (PA)*	22.4		1,086		0.022	49.86	35,221.4	32.43
	São João (SJ)	14		560		0.025			
	*PA/SJ-TC	*39*		*1,926*		*0.02*	*63*	*77,020.9*	*40*
	Tereza Cristina (TC)		**75.4**		**3,572**	**0.02**	**57.56**	**136,867**	**38.8**
	Marrecas + Cachoeira	19.2		698		0.027			
	*TC-SU	*28.4*		*3,733*		*0.008*	*60*	*366,322.2*	*40.13*
	Salto Ubá (SU)		**123**		**8,003**	**0.015**			
	*SU-PE	*68*		*597*		*0.113*			
	Porto Espanhol (PE)		**191**		**8,600**	**0.022**			
	*PE-US			*1,481*					
	Foz do Rio Alonso	51		2,620		0.019			
	Ubá do Sul (US)		**269**		**12,701**	**0.018**	**63.49**	**538,597.4**	**42.4**
Middle	*US-VR	*79.*		*3,305*		*0.024*	*51.6*	*130,131.8*	*39.37*
	Bacia Corumbataí	74.6		3,294		0.023	41.44	97,491	29.6
	Vila Rica (VR)		**423.3**		**19,300**	**0.023**	**49.92**	**666,391.5**	**34.52**
	*VR-PB	*38.8*		*2,273*		*0.017*	*58.53*	*71,617.1*	*31.51*
	Rio Mourão	32.6		1,534		0.021	44.55	45,800.7	29.85
	Porto Bananeira (PB)		**494.7**		**23,107**	**0.021**	**81.12**	**1,265,541.7**	**54.8**
	*PB-PN	*23.9*		*3,786*		*0.006*	*66.6*	*39,695.6*	*10.48*
	Bacia do Índio	14,6		807		0.018	38.64	17,790.8	22.04
	Bacia do Ligeiro	14,8		727		0.02	75.39	35,187	48.4
	Paraíso do Norte (PN)		**543**		**28,427**	**0.019**	**71.27**	**1,220,430**	**42.93**
Lower	*PN-TP	*68.3*		*3,528*		*0.019*	*54.21*	*116,763.4*	*33.1*
	Tapira (TP)		**611.3**		**31,955**	**0.019**	**37.15**	**1,373,940**	**43**
	*TP-TQ	*75.2*		*1497*		*0.05*	*65.7*	*155808*	*104.08*
	Bacia Rio Das Antas	14.,5		980		0.015	69	31551.8	32.2
	Novo Porto Taquara (TQ)		**701**		**34,432**	**0.02**	**90.68**	**2,004,638.8**	**58.22**
	*TQ-FI	*32.4*		*2155*		*0.015*	*90.68*	*92,653.7*	*43*
	Foz do Ivaí (FI)		**733.4**		**36,587**	**0.02**	**90.68**	**2,097,292.6**	**57.32**

Bold letters represent stations in the Ivaí River; (*) reaches between gauging stations, AcQm and AcA = accumulate mean discharge and accumulate basin area.

4.1. Spatial distribution of discharges

The increase in discharge of water is progressively constant along the river (Figura 5 A), generating a high correlation ($R^2 = 0.99$) among drainage area and discharge (Figura 5 B). This is directly related with the basin's elongation and tributary drainage distribution. Sub-basins are similar in shape and size, are subjected to the same climate, and therefore, provide similar discharges to the trunk river.

The main tributaries of the Ivaí River are the Alonso River (Qm = 51.0 $m^3\ s^{-1}$) on the right-hand side, and the Corumbataí and Mourão (sum total Qm = 107.2

m^3 s^{-1}) on the left-hand side (Figura 5 A, C). However, the majority of the water that enters the main channel comes from smaller tributaries (basin area <500 km^2) that contribute 387.3 m^3 s^{-1}, that is, 53 % of the Ivaí River's average discharge (Figura 5 C). The contribution of these tributary basins is quite varied along the Ivaí (Figura 5 B). The highest contributions observed came from the drainages between the Ubá do Sul and Vila Rica gauging stations (Qm 79.0 m^3 s^{-1}) in the high and middle reach limits, and between the Paraíso do Norte and Tapira gauging stations (Qm 68.3 m^3 s^{-1}) in the lower reach (Figura 5 C).

If the correlation of Qm *versus* basin area is high, the flood discharge shows an anomaly when plotted with area in the last two stations (Figura 6A). Destefani (2005) analyzed the 1992 flood and showed that above 4,000 m^3 s^{-1}, the river lost water to the floodplain downstream of the Paraíso do Norte Gauge Station (Figura 6B). It can also be observed that when this threshold flood discharge (4,000 m^3 s^{-1}) is reached, Novo Porto Taquara station presents discharge lower than the four upstream gauge stations. In this flood, an estimated volume of 200 × 10^7 m^3 of water was diverted to the floodplain in 5 days.

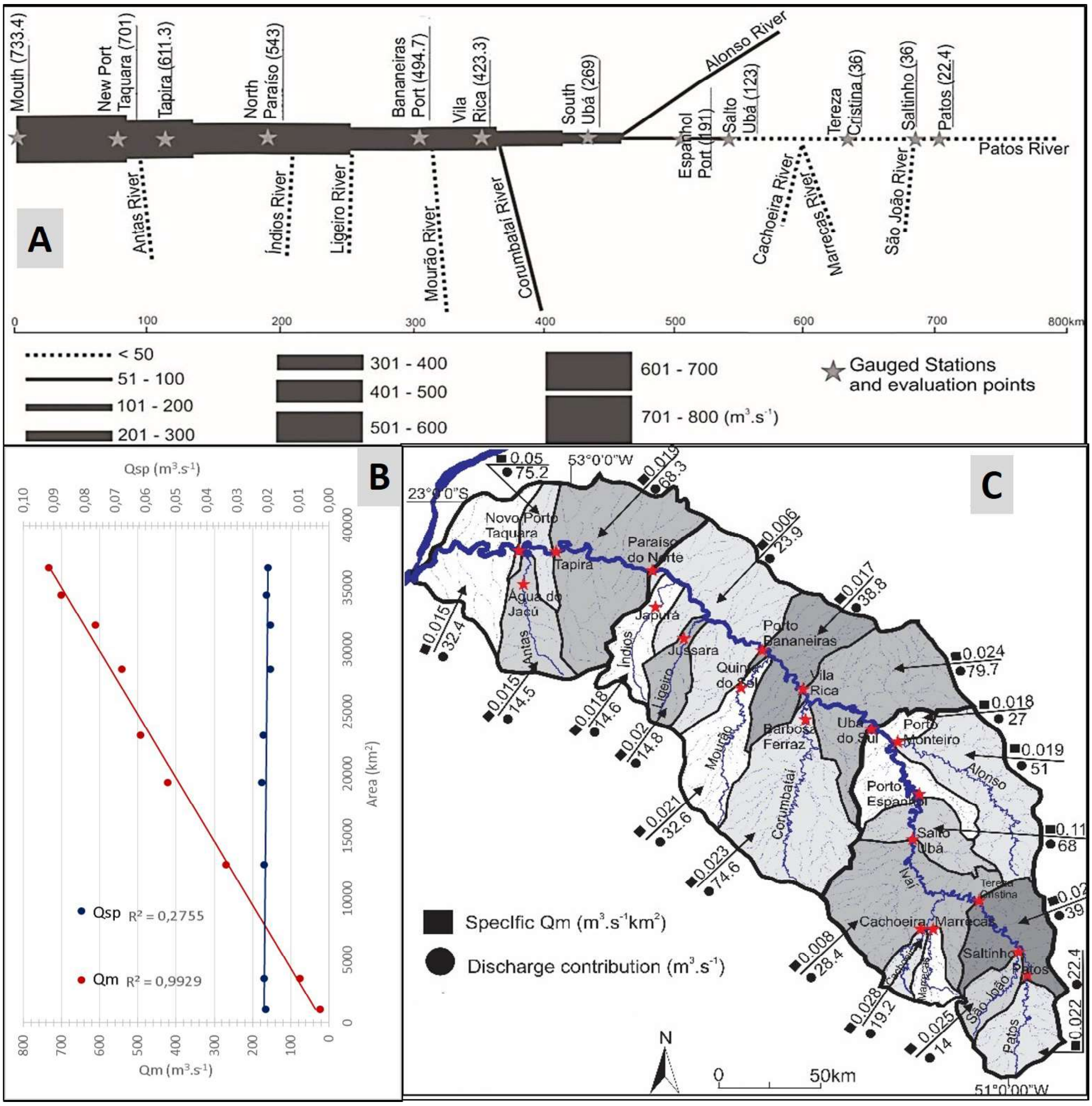

Figure 5 - A. Drainage tree for discharge in the Ivaí River Basin, the main water contribution. B. The mean discharge and basin area present strong correlation, and the specific discharge is relatively constant along the basin. C. Ivaí River Basin with main tributary basins and small basin groups, (Source: Table 4).

The specific discharge is relatively constant along the basin (Figura 5 B). The largest tributary basins that feed the Ivaí present specific discharges between 0.019 and 0.023 $m^3 s^{-1} km^{-2}$ as the Corumbataí and Alonso Rivers. The largest specific discharges (Marrecas-Cachoeira = 0.028 $m^3 s^{-1} km^{-2}$ and São João = 0.02 $m^3 s^{-1} km^{-2}$) are in the upper reach, where the orographic precipitation is more significant. In general, the specific discharge varies from 0.019 to 0.20 $m^3 s^{-1} km^{-2}$ for basins in the upper reach, and from 0.015 to 0.020 $m^3 s^{-1} km^{-2}$ for basins in the lower reach.

Unlike the values for contribution of discharge, the specific discharge for the smallest basins, when taken together, present lower values than the main tributaries. These values, in general, do not exceed 0.020 $m^3 s^{-1} km^{-2}$. However, some anomalies are found. Between Salto Ubá and Porto Espanhol gauging stations, a reach of only 30 km contributes 65 $m^3 s^{-1}$ to the Ivaí medium discharge, which corresponds to a specific discharge of 0.11 $m^3 s^{-1} km^{-2}$, 10 times larger than the other tributary basins (Figura 5 C). Paiva (2008) suggests that some sub-basins have strongly influenced groundwater contribution in discharge owing to local distribution and the concentration of basalt fractures.

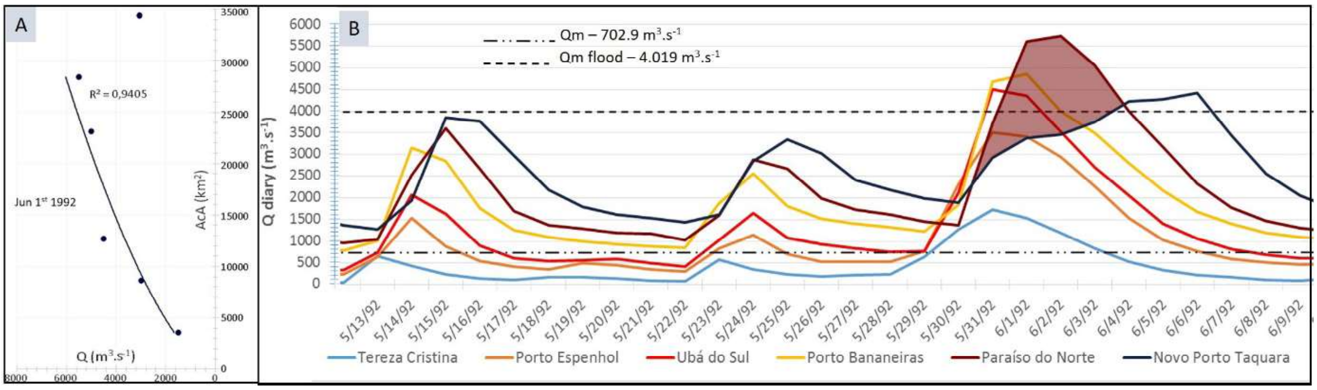

Figure 6 - A. Mean flood discharge versus basin area. Note that the last two stations (corresponding to two largest basin areas) present lower discharge values than the upstream station. B. Hydrograph of the Ivaí River gauging stations. Three flood peaks are observed between May 21 and June 10, 1992. There is a normal increase in water discharge in the downstream direction in the first and second peaks. In the third peak, the volume in the Paraíso do Norte is greater than in the downstream station of Novo Porto Taquara, thus showing water lost to the floodplain downstream of Paraíso do Norte. The shaded area in the hydrograph curves corresponds to the volume of water diverted to the floodplain (~200 × 107 m3). (Mod. DESTEFANI, 2005).

4.2 Formation of the suspended load

The correlation of suspended load concentration and discharge is very dispersive to the Ivaí River. However, small variations can be observed during the year. Agriculture seasonality is the major controlling factor for concentration of suspended sediment. The combination between soil preparation, planting and high rainfall from September to March, produce a more dispersive correlation between water discharge and concentration of suspended load than in the April to August period, when soil is covered (Figura 7 A). Leli *et al.,* (2011) pointed out that agricultural seasonality associated with basin morphology and valley slope, are responsible for the clockwork hysteresis diagram of concentration versus discharge (Figura 7 B). A more suitable agricultural management in the basin, implemented by the state government, reduced laminar erosion caused by the rain, thus reflecting the rate of reduction of sediment production for the river (Figura 7 C).

In spite of low correlation between concentration of suspended sediment and water discharge (Figura 7A), the annual transport of suspended sediment calculated for all stations during the historical series presented high correlation ($R^2 = 0.97$) in respect of both water discharge and basin area (Figura 8). The basin asymmetry related to the trunk river, slightly shifted to the right-hand side, generates larger basins on the left-hand side. This fact controls the spatial distribution for suspended load. The largest contribution of suspended load comes from the main tributaries on the left side of the medium reach: Corumbataí, Mourão, and the Ligeiro Rivers that add up to 17.8 × 10^4 ton $year^{-1}$, and the Antas River (Q_{ss} = 31.5 × 10^3 ton $year^{-1}$) of the lower reach. The Patos, one of the

Ivaí-forming rivers, also presents a high contribution of 35.2 × 10^3 ton year^{1} (Figura 9 A, B). The Alonso River, the main right-hand tributary of the Ivaí does not have a gauging station for suspended sediment. The huge production of 366.3 × 10^3 ton year^{-1} (Figura 9 B), estimated for an area of 9,121 km^2, is not related only to the Alonso River, but to a group of tributary basins including the Marrecas and Cachoeira Rivers, that also do not have a suspended sediment gauging station. The annual production of suspended sediment of 96.5 × 10^3 ton year^{-1} estimated for the Alonso River is inferred from the average suspended concentration for the reach of 60 mg L^{-1}.

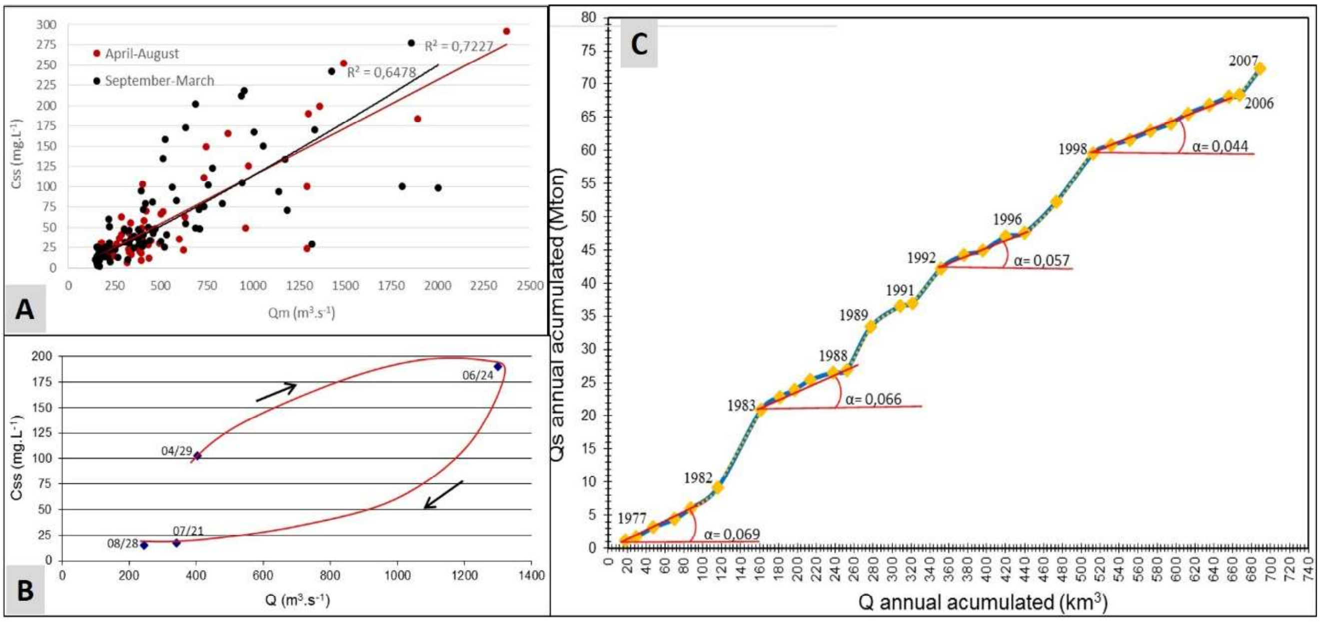

Figure 7 - Correlation between concentration of suspended sediment versus water discharge in the dry April–August, and rainy September–March (A) periods. Clockwork hysteresis diagram (B) for concentration of suspended sediment and water discharge average during the 1977 flood. (C) Reduction in the sediment production rate (α) since the end of the 1970s, by a more accurate agricultural land use (Mod. Leli et al., 2011).

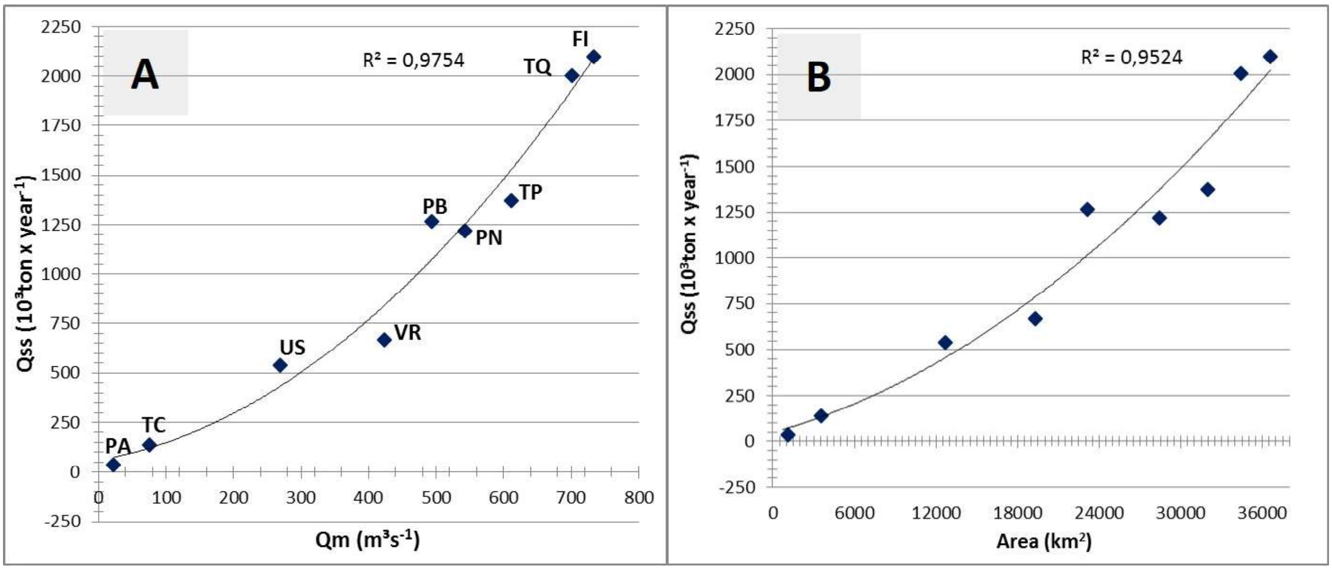

Figure 8 - Correlation ($p < 0.005$) between annual discharge of suspended sediment (Qss) vs. mean water discharge (Qm) in A and basin area in B in the gauging stations of the Ivaí River: PA – Rio dos Patos, TC – Tereza Cristina, US – Ubá do Sul, VR – Vila Rica, PB – Porto Bananeira, PN – Paraíso do Norte, TP – Tapira, TQ – Novo Porto Taquara, FI – Ivai River mouth (Data source: Table 4).

The input of the suspended load along the Ivaí River's longitudinal profile takes place gradually, thus implying a homogeneous intake of suspended sediment into the channel (Figura 9 A). The specific suspended load discharge for tributary basins is not homogenous, but increases slightly downstream (Figura 9 B, C) even with the specific water discharge staying constant (see Figura 5 D). The intensive land use of the lower Ivaí River Basin, predominantly with agriculture and pasture, increases sedimentary yield, enhanced by the highly erosive sandy soil derived from the Caiuá Formation. In addition, in its lower basin, the Ivaí has a 20 km wide floodplain (Figura 2) with intensive farming occupations, especially for rice, soybean, and pasture, which enhance transport of sediment to the channel. On the other hand, the almost 200 x 10^7 m^3 of water loss observed during the 1992 great flood between Paraíso and Novo Porto Taquara gauging stations (Figura 6), also transferred about 500,000 tons of sediment to the floodplain.

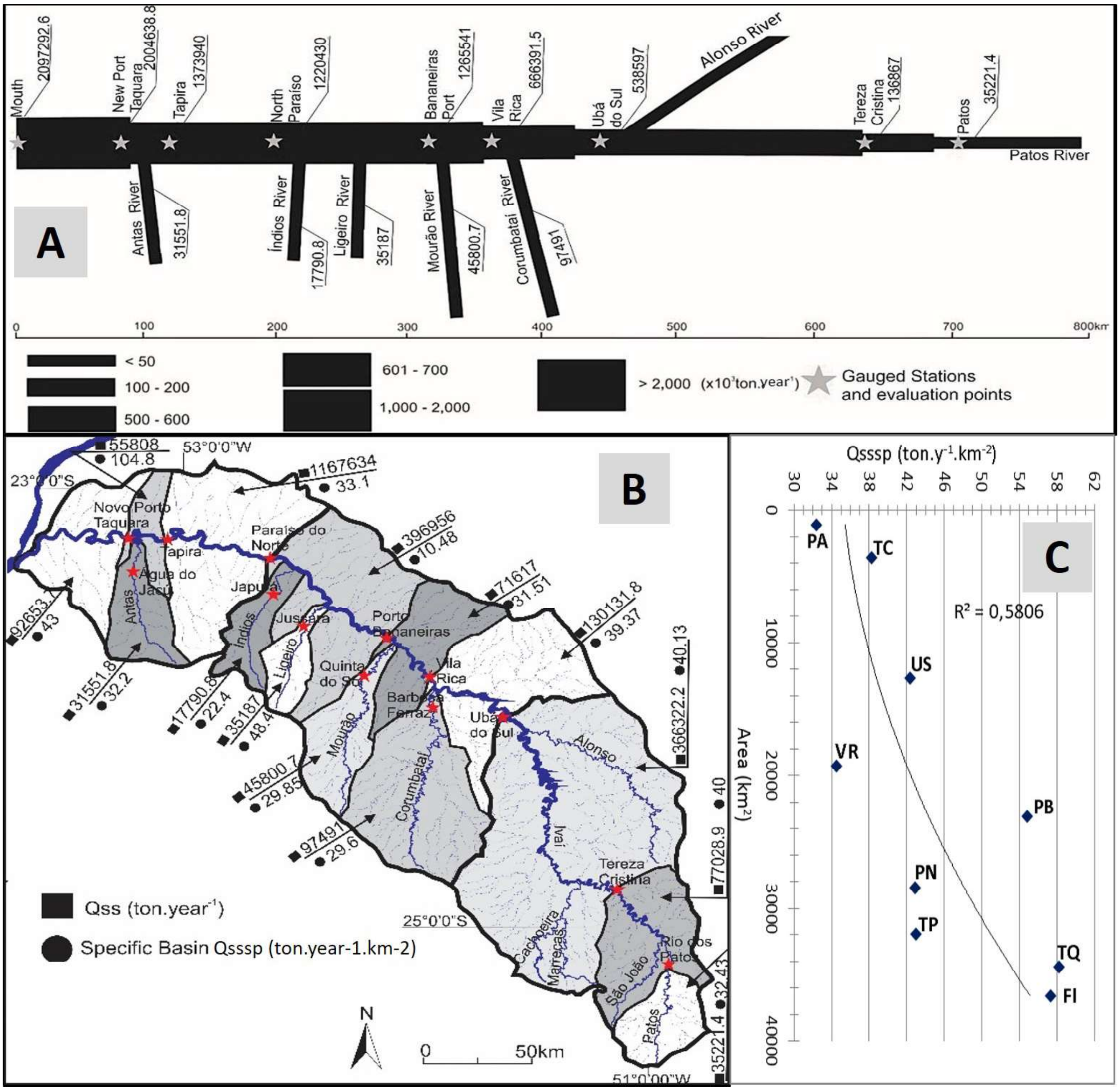

Figure 9 - A. The Ivaí River Basin drainage tree for the annual suspended sediment discharge. B. Annual suspended load and specific discharge for tributary basins and group of basins. C. Correlation between specific suspended sediment discharge versus basin area. The correlation is weak; however, the downstream increase of values to the last gauging stations is evident.

5. Discussion

As mentioned earlier, the Ivaí is one of the unique medium tributaries of the Paraná Basin, and is in a natural condition concerning its flow regime, and therefore, should be considered as a model for this type of river for future projects on river restoration and management. In Brazil, where studies concerning impact mitigation, management and restoration were normally made after dam construction, the present study of this river can be considered as a laboratory for fluvial investigation, and efforts should be made with the aim to preserve this system from hydroelectric power stations.

Latrubesse *et al.,* (2005) classified the tropical rivers in the world based on a geological-geomorphologic setting and climate zone. Under these criteria, the Ivaí is classified as *platform/plateau river draining dominantly platform areas, bedrock channels, with incised valleys and rapids under wet-dry climate*. In spite of the referred paper using only large rivers (Qm > 4000 $m^3 s^{-1}$), the Ivaí presents the same characteristics as those of large rivers, when compared under these criteria. Concerning maximum (Q_{max}), minimum (Q_{min}) and medium (Q_{mean}) water discharge, the Ivaí can be clubbed along with the rivers in dry-wet and temperate climates (Figura 10 A).

With most of the basin located south of the Tropic of Capricorn, the Ivaí River is under the influence of two types of climate. While its lower basin presents a wet-dry tropical climate with a dry winter and a rainy summer, the central and upper basins are under the influence of a temperate climate, with rainfall of 1800 mm, with strong orographic influence (Caramori, 1989; IAP, 1994; Brasil, 1985). This fact justifies grouping of the Ivaí with temperate and wet-dry climate rivers (Figura 10 A). The same high correlation can be seen when plotting the Ivaí River in terms of annual suspended load discharge versus basin area for plateau-cratonic rivers (Figura 10 B). In this correlation, the Ivaí lines up with the Araguaia, Paraná, Sanaga (Cameroon), Zambesi (SW Africa), Tocantins, and Xingu Rivers (Latrubesse *et al.,* 2005).

Leli *et al.,* (2011) concluded that sediment yield to the Ivaí River had decreased in the last two decades, due to more suitable land use management in terms of agriculture and pasture. However, when the values of sediment yield of the Ivaí River are compared with those from the Araguaia River, the large Brazilian river most impacted by agricultural and pasture (Latrubesse and Stevaux, 1999; Latrubesse *et al.,* 2009), it is possible to assume that the situation in the river under study is very delicate in terms of human impact (Table 1, 5). Unlike the Araguaia River, the Ivaí is a suspended-load-dominant river, and the possible impacts will not be in the channel morphology like the Araguaia, but, in changes to the water quality and river ecology. Evidences of impact of agriculture and pasture on sediment yield of the Ivaí could be related with the anomalous values in the concentration of suspended sediment obtained in some gauging stations. Concentrations between 300 and 600 mg L^{-1} were observed in Novo Porto Taquara gauging station 11 times in the historical series. Such occurrences, though not very frequent, may be signaling impacts due to wrong procedures in the basin, especially in the floodplain of its lower basin.

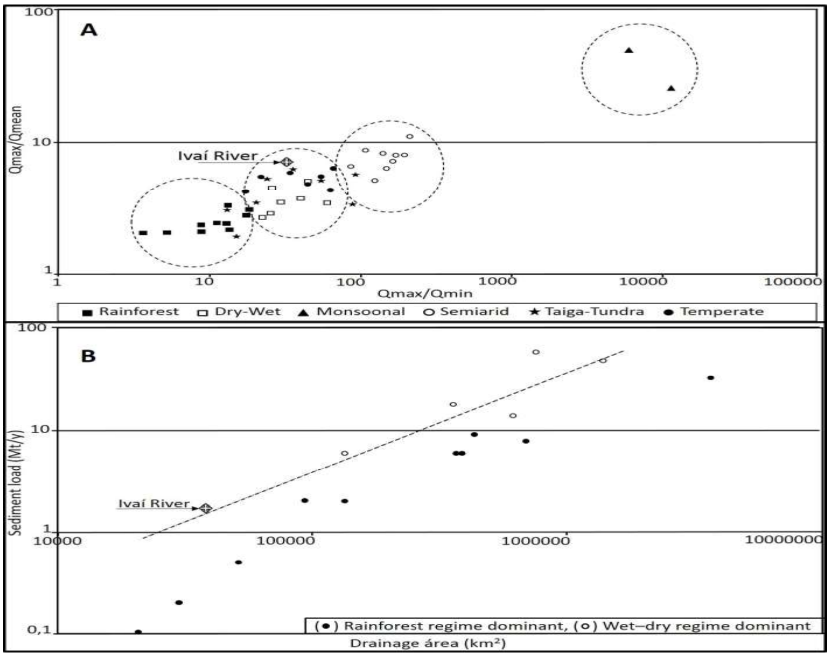

Figure 10 - The Ivaí River plotted with large tropical rivers in the world in terms of (A) Discharge variability, and (B) Plateau-cratonic rivers. The Ivaí River clusters and lines with wet-dray climate rivers (Mod. Latrubesse et al., 2005).

Table 5: Comparison between the Araguaia and Ivaí Rivers.

River	*Qmean* ($m^3 s^{-1}$)	*Barea* (km^2)	*Qss (Mt)*	*Source*
Araguaia	*1100*	*375,000*	*4.0*	*Latrubesse et al., 2009*
Ivaí	*702.9*	*36,587*	*2.0*	*Leli et al., 2011*

(Mt) = Million tons by year

Conclusion

The Ivaí River has a historical (34 years) mean discharge of 702.9 $m^3 s^{-1}$, with high variability generating a hydrograph with non-seasonal peaks of maximum discharge. The elongated morphology of the river basin induces a gradual and well-defined process of discharge contribution along the longitudinal profile at rates varying from 0.01 to 0.02 $m^3.km^{-2}$ with a maximum value of 0.11 $m^3 km^{-2}$, this probably by base flow contribution. The largest amount of water that enters the main channel comes from smaller tributaries (basin area < 500 km^2), with a total contribution of 387.3 $m^3 s^{-1}$, 53% of the Ivaí mean discharge, while the main tributaries (Alonso, Corumbataí, Mourão, Antas, Índios and Ligeiro) add only 201.5 $m^3 s^{-1}$. In general, a reduction in the specific water discharge is observed downstream, from 0.028 to 0.015 $m^3 year^{-1} km^{-2}$, with the largest values coming from the Marrecas-Cachoeira (0.028 $m^3 s^{-1} km^{-2}$) and São João (0.025 $m^3 s^{-1} km^{-2}$) in the upper basin. On the other hand, the basin's largest tributaries present the lowest specific discharge: the Corumbataí River with 0.023 $m^3.s^{-1}.km^{-2}$ and the Alonso River with 0.019 $m^3 s^{-1} km^{-2}$.

Suspended load discharge has a dispersive correlation with water discharge ($R^2 = 0.72$) to dry season with work-clock hysteresis in its hydrograph, and ($R^2 = 0.65$) to wet season. However, the correlation between the annual discharge of suspended sediment and the average water discharge is very high ($R^2 = 0.97$). It occurs because, even with a heterogeneous constitution in terms of relief and soil, the elongated basin morphology arises as the main variable on yield distribution of suspended sediment along the basin. The correlation between contribution of suspended sediment and basin area is also high ($R^2 = 0.95$) showing a regular contribution of suspended sediment along the basin. The observed anomalies for Tapira and Paraíso do Norte gauging stations are promoted by loss of water to the flood plain during the flood (over the threshold of 4,000 $m^3 s^{-1}$). The tributary basins with the largest suspended sediment production are the Corumbataí (Qss = 97.5 × 10^3 ton $year^{-1}$) and Alonso Rivers (Qss = 96.5 × 10^3 ton $year^{-1}$), followed by the Mourão, Patos, Ligeiro, and Antas Rivers totaling Qss = 147.6 × 10^3 ton $year^{-1}$. The left margin tributaries present larger values sediment yield to the Ivaí River (Figure 9). This may be due to the fact that the left margin is a high tectonic block (SOUZA JR. *et al.*, 2013),and supposed to have a higher degree of erosion Specific discharge of suspended load increases with basin area in behavior opposite to other river systems. This occurs by anthropic (more intensive agricultural and pasture land) and geological-pedological (high erosivity of sandy soils) causes specific for lower basin.

The study on dynamics of water and suspended sediment, as presented in this paper, can be a useful tool on river basin management and planning. Through this study, it is possible to localize key points with problems concerning anthropogenic impacts, or even areas with high sensibility or fragility that can be preserved for occupational protection.

The present study emphasized not only the importance of suspended load functioning and distribution on the proper river flood plain, as well on the Parana River channel. In the first case, the channel filled with large amounts of sediment provide the plain, as in the case 1992 in which the channel has transferred a total of 200 x 10^7 m^3 of water, and 500,000 tons of suspended sediment to the plain. And in the case of the Paraná River, the Ivaí contributes 2,097,292.6 ton y^{-1} of suspended sediment. It is a volume of great importance to the Paraná, whose natural suspended load is greatly reduced by retention in the large dams in its upper basin.

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