FLOW STRUCTURE AND DYNAMICS IN LARGE TROPICAL RIVER CONFLUENCE: EXAMPLE OF THE IVAÍ AND PARANÁ RIVERS, SOUTHERN BRAZIL

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ABSTRACT – Morphology and dynamics of the confluence environment of the Paraná and Ivaí Rivers (South Brazil) are studied using echo-sounding and velocity profile surveys (ADCP) with suspended and bedload sampling. An area was surveyed in two periods of hydrological cycles: high water in the summer and low water in the winter. It can be considered an anomalous confluence where the tributary waters do not flow directly into the Paraná River, but rather a secondary channel of the same dimension as the Ivaí River. The results show an asymmetrical confluence in which the tributary channel is 30-50% deeper than the collector. The flow momentum ratio indicated that, after the confluence flow is dominated by the Paraná River over the Ivaí. Analysis on bedform dynamics and morphology and their control over flow roughness, turbulence and mixture are also discussed. The studied confluence is completely different from others in the same hydrographic basin and can be used as a model for rare non-impacted large river confluences.
Keywords: river confluence, flow dynamics, Ivaí River, Paraná River.

RESUMO – *J.C. Stevaux, A.A. Franco, M.L. de C. Etchebehere, R.H. Fujita - Estrutura e dinâmica do fluxo na confluência de grandes rios tropicais: O exemplo dos rios Ivaí e Paraná, PR*. A dinâmica e a morfologia da confluência dos rios Ivaí e Paraná são estudadas por meio de levantamento eco-batimétrico e por perfilagem de velocidade (ADCP) juntamente com amostragem da carga suspensa e de fundo transportada, em dois momentos do ciclo hidrológico (inverno e verão). Trata-se de uma confluência anômala onde as águas do tributário não desembocam diretamente no rio Paraná, mas num canal secundário de dimensões semelhantes às do rio Ivaí. Os resultados revelam uma confluência de assimétrica na qual o canal do tributário apresenta-se 30 a 50% mais profundo que o canal do coletor. A componente do fluxo pós-confluência (razão do momento do fluxo) indica o predomínio do fluxo do rio Paraná sobre o do Ivaí. São também feitas análises sobre o comportamento das formas de leito e de sua influência na rugosidade e turbulência do fluxo, como também no processo de mistura dos fluxos após a confluência. A metodologia mostrou-se válida e de fácil aplicação em outros sistemas fluviais de mesmas dimensões.
Palavras-chave: confluência, dinâmica de fluxo, morfologia, rio Ivaí, rio Paraná.

INTRODUCTION

River confluences are sites of fluvial systems with complex hydraulic interactions provided by the integration of two different flows. They constitute an environment of "competition and interaction" (Biron et al., 1993) with continuous alterations in flow velocity, discharge and structure, water physical-chemistry properties and channel morphology. Moreover, confluences are very important in fluvial ecology, presenting many characteristics and restrict environmental conditions (Turra et al., 1999), which can constitute areas of political conflicts at different scales: private areas (i.e. farms), municipal, national and international at the borders (Kessel & Hudson, 2007). Within a hydraulic perspective, confluences are susceptible to the occurrence of turbulence with convergent and divergent movements, forming upwelling, down welling flows and lateral vortex (Morizawa, 1968). These actions generate chaotic movements with the formation of secondary currents of different velocities and directions, including some which go against the river's main flow. These dynamics induce a major bed form sediment movement and consequently, a major variation and alteration in bedform (Christofoletti, 1981; Rhoads & Kenworthy, 1995; De Serres et al., 1999). The main controlling factors on flow mixture downstream confluence are: a) morphological factors – as confluence angle and asymmetrical channel bed, and b) hydraulic factors – as the flow moment ratio and contrast in flow density (De Serres et al., 1999; Best et al., 2007). The identification and understanding of flow mixture at a confluence is very important in studies on pollution, nutrients, dissolved oxygen dispersion, as other ecological variables. In these cases, the flow movement ratio ($M\tau$) of De Serres et al. (1999) is used in order to discriminate flow predominance in a confluence:

$$M\tau = \rho_T \,.\, U_T \,.\, Q_T / \rho_P \,.\, U_P \,.\, Q_P \qquad \text{(Eq. 1)}$$

where ρ_T and ρ_P = water density, U_T and U_P = flow velocity, Q_T and Q_P = discharge, the index ($_T$) and ($_P$) = tributary and principal rivers. In this equation, $M\tau < 1$ indicates the predominance of main river flow, and $M\tau > 1$ the predominance of tributary flow.

There are numerous references about river confluences. However, the majority is related to small water courses or flumes. A good summary of these studies can be seen in Biron et al. (1993) and Rhoads & Kenworthy (1995) on the flow structure alteration and flumes and unequal channel of creeks and in De Serres (1999) on tri-dimensional flow structure in asymmetrical confluences. In Brazil, Turra et al. (1999) were the first to look into this subject by studying the morphological, sedimentological and limnological aspects of the confluence of the São Pedro Creek in the upper course of the Paraná River. The pioneers in large river confluences were Amsler & Drago (2001) on the analysis of bedload transport and deposition at the Paraguay and Paraná River confluence near Corrientes City, Argentina. Moreover, in this same confluence, Parsons et al. (2004a, b; 2005) analyzed bed morphology, flow structure and depositional dynamics using the Acoustic Doppler Current Profiler (ADCP) for the first time in confluence study.

This paper analyses the flow structure and dynamics, and channel bed morphology at the confluence of Ivaí and Paraná Rivers. This study becomes relevant since the Ivaí River is the only large "natural river" (not dammed, with sedimentary load in its original condition) in the upper sector of The Paraná Basin. In addition, the study confluence is situated downstream of the Porto Primavera Reservoir (closed in 1999) integrating the results with those developed by Martins & Stevaux (2004), Souza Filho & Stevaux (1997), Martins (2008), Stevaux et al. (2009) on the evolution of the impacts of this dam in the Paraná River.

THE STUDY AREA

The study area includes the confluence of the Ivaí and Paraná Rivers at the border of the Paraná State with that of Mato Grosso do Sul (S 23° 13' 12" and W 53° 45'48"), at Pontal do Tigre, Icaraíma, PR (Figure 1). The landscape presents a gentle hilly topography around 230 m (a.s.l.) formed over Cretaceous sandstone of the Caiuá Formation. At the confluence area, the Ivaí River runs over an alluvial plain of 15 km in width, and a surface of 3.5 m above the median river water level constructed by both river systems: Paraná and Ivaí (Biazin, 2005; Barros, 2006; Santos et al., 2008). Alluvial plain is formed by more than 10 m clay, organic clay and fine sand sediments deposited by river activity since the end of Pleistocene. Santos et al. (2008) dated the base of these deposits in ^{14}C 14,307±68 BP. Ox-bow lakes, swamps, small tributary, and continuous string of natural levees (2m in height) are common features in the floodplain (Figure 2). (IPARDES, 2004; Silva et al., 2004; Santos et al., 2008). The floodplain sector constructed by the Paraná River is relatively small compared to those of the Ivaí. Basically it presents a wavy surface formed by a succession of channeled forms, generated by lateral bar evolution (Stevaux, 1994). The Ivaí River's floodplain is probably in an abandonment phase, once it is not inundated by the ordinary floods ($Q_{1.3}$). The occurrence of vertical sand bars corroborates this hypothesis (Santos et al., 2008). The Ivaí River in spite of its relatively high sinuosity (s = 1.5) cannot be considered meandering, once its channel is superimposed to the high resistant sandstone bedrock of the Caiuá Formation. The climate, at the confluence area, is humid (from September to February) with a well defined dry season (from March to August) with and an annual precipitation of 1400 mm (Andrade & Nery, 2003; Meurer, 2008).

Because the Upper Paraná River has a large number of dams, its hydrological regime is strongly controlled and shows an annual hydrograph with the peaks of flood and low water very flattened compared to the less dammed rivers of the basin (Figure 3, upper). The Porto Primavera Dam operation (Figure 1) produces in the channel a daily discharge regime where the water level can range up to 0.8 m (Stevaux et al., 2009). The Ivaí River (Figure 3, lower) does not have any dams in its hydrographic net and presents a completely natural regime, with flood peaks higher than ten times the mean water level (Meurer, 2008). The rainy and wet periods can happen in any time of the year and change each year, presenting no seasonality (Destefani, 2005; Girardi Jr., 2008).

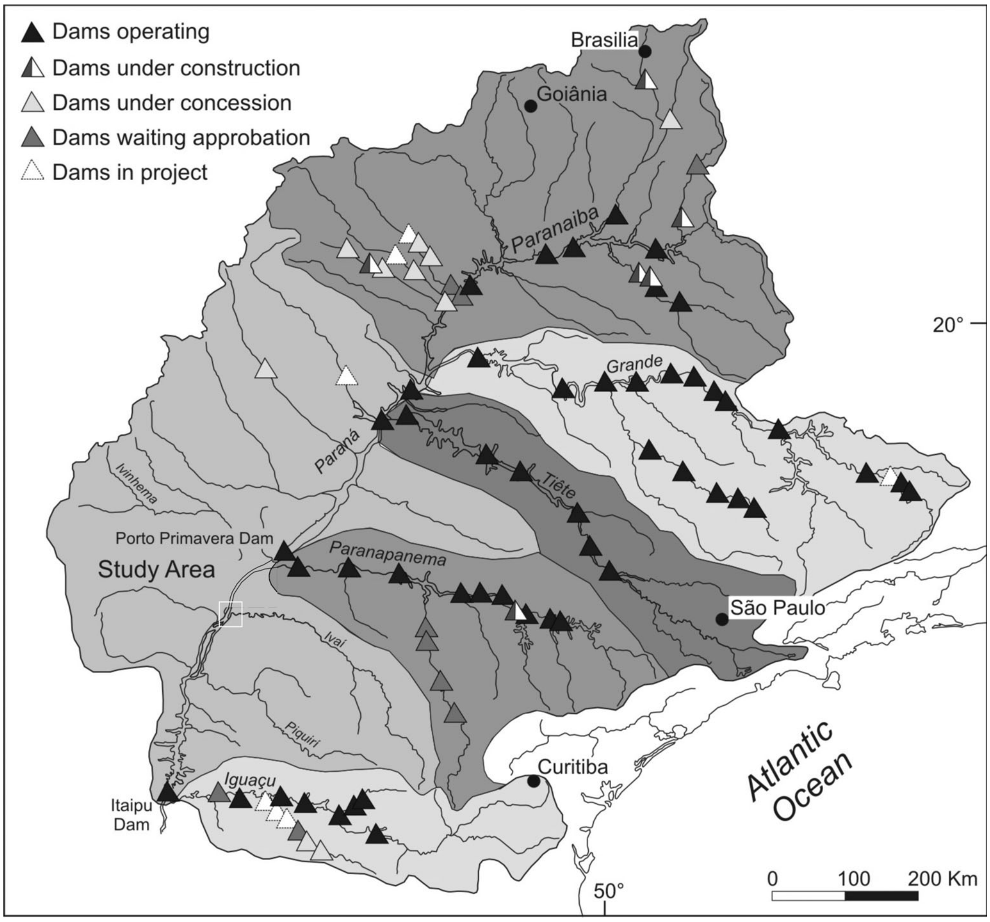

FIGURE 1. The Upper Paraná and Ivaí Basins. Large hydroelectrical power plants and dams distribution.

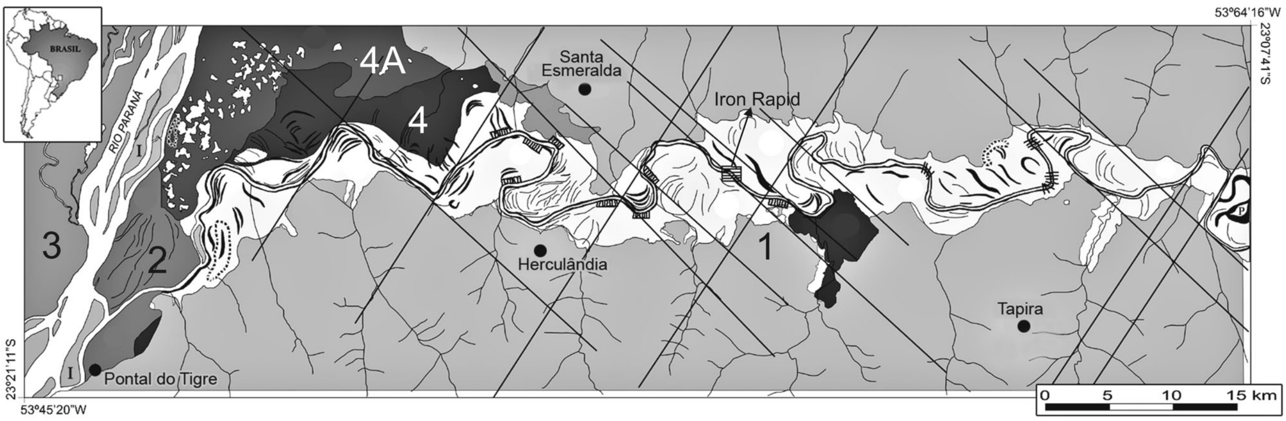

FIGURE 2. Geomorphological map of the lower Ivaí River floodplain. The relatively high sinuosity of river channel is not meandering but superimposed over the resistant sandstone bedrock. 1) Ivaí River floodplain; 2) Paraná-Ivaí mixed floodplain; 3) Paraná River floodplain; 4, 4A) Terraces. (Mod. Santos et al., 2008).

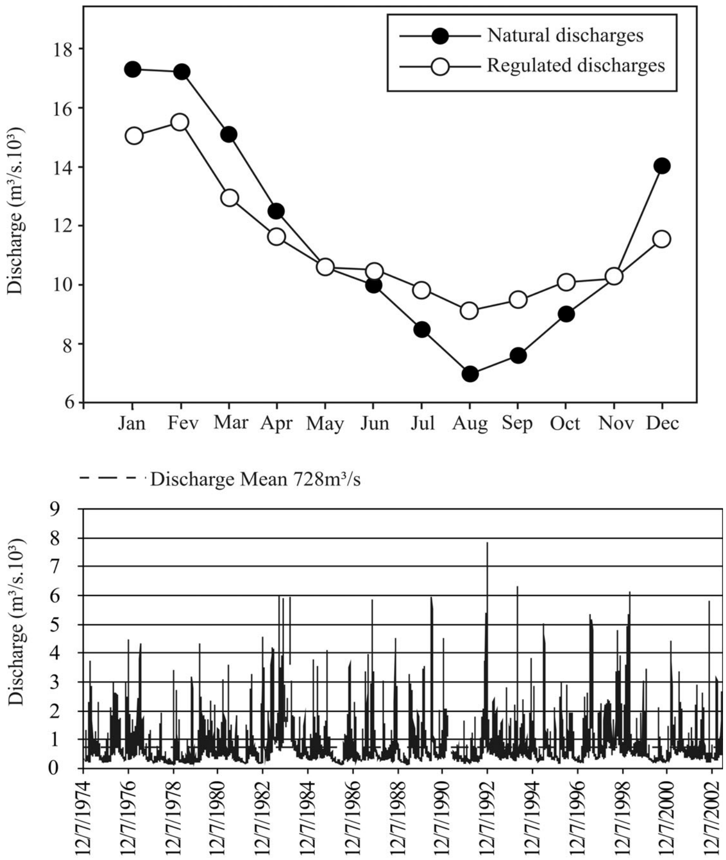

FIGURE 3. Upper – Paraná River annual hydrograph: flow regulation flattened the high-low water peaks if compared with natural discharge. Lower: Ivaí River annual hydrograph: Flood peaks reaches more than 10 times mean water level.

METHODS

This study was based on two kinds of surveys: a) Channel echo bathymetrical map and cross-sections, and b) Flow structure data collected by acoustic Doppler current profiler – ADCP, according current methodology described by many authors (*e.g.* Parsons et al., 2005, Best et al., 2007, Paes, 2007). Bedload material was collected by the van Veen sampler and analyzed in the Sedimentology Lab. of the University Guarulhos.

Field work was performed in July 2005 (winter) and February 2006 (summer) in order to have the extreme flow situation – low and high water, respectively. In these surveys, echo-sound FURUNA/GP 1650 with GPS and the Acoustic Doppler Current Profiler (ADCP) RD Instrument™ RIO Grande of 600 kHz were used. Data was obtained by transversal and longitudinal sections over a one-km reach upstream and downstream of the confluence of both rivers (Figure 4). Boat velocity, track and position were monitored in real time by geo-referenced satellite imagery, by maintaining boat velocity at 1m/s according to the suggestions made by Szupiany et al. (2007).

Digital data from echo-sounding and ADCP were processed by FUGAWA, WINRIVER 3 and SURFER softwares.

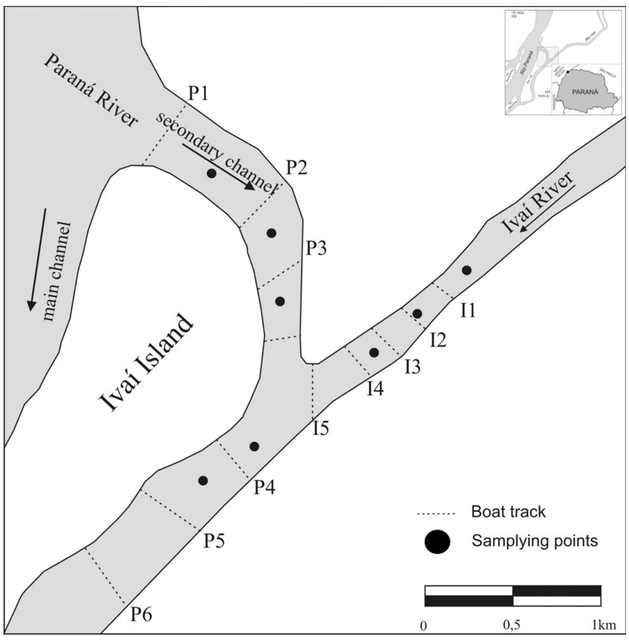

FIGURE 4. Localization of echo-sounding and ADCP profiles (interrupted lines) and bedload sampling points.

RESULTS AND DISCUSSION

CONFLUENCE MORPHOLOGY AND SEDIMENTOLOGY

The Ivaí River's water does not flow directly into the Paraná River main channel but rather in a secondary one formed by the Ivaí Island and its left bank (Figure 2, 4). This type of mouth, with island formation and flow diversion also occurs in the Paranapanema River at about 120 km upstream (Paes, 2007). It is probable that this kind of mouth is related to sedimentary load and confluence angle. This situation is not observed in the confluence of the Piquiri River (90 km downstream) or in the Paraguay River, near Corrientes, Argentina (Orfeo et al., 2007). The studied confluence channels forms an angle of 45° and presents strong lithological as well as a structural control (Santos et al., 2008). A summary of confluence data is presented in Table 1.

The thalweg and the channel of the Ivaí River are straight upstream confluence. In this reach, river runs, for the most part, over alluvial deposits with few points as bedrock channel. The channel has width/depth ratio of 50 to 80 and thalweg depth ranges from 5 to 7 m. Bed load is composed of fine to medium, well sorted, quartzose deposits in the form of ripples of 0.2-0.3 m height and 7.0-14.0 m long and with low mobility (Biazin, 2005). Suspended load ranged 21.0 to 6.8 mg/L (Kürten, 2006); but values around 100 mg/L were found in Porto Paraíso, 100 km upstream from its mouth (ITAIPU BINACIONAL, 1990). During the field work, slight alterations in the Ivaí channel were observed, concerning to channel morphology: thalweg sinuosity was slightly reduced from 1.3 to 1.1 from low to high water level and migrated discretely to its right bank, producing an asymmetrical channel section (Figure 5).

The Paraná River channel is relatively shallow with width:depth ratio of 200 to 250. It is slight meandering in its last 1000 m upstream confluence and changes to a straight channel after receiving the Ivaí waters. Channel depth is inferior to that of tributary depth and varies from 3 to 4 m. Thalweg is not continuous but forms isolated and irregular pools. Bed material is formed by fine to medium sand with local concentration of gravel. At upstream confluence bedforms dunes of 0,3 to 1,5 m in height are formed (Figure 6).

Downstream reach is straight and constitutes a continuity of the Ivaí River (Figure 5). This channel has a continuous and well-defined thalweg, with sinuosity of 1.4 and do not changes along the hydrological regime (low and high water level). Thalweg sinuosity induces the formation of lateral bars with about 500 m in length.

The asymmetry between the tributary and collector channels depth is not common for large river systems (Biron et al., 1993). In this case the Ivaí channel is 50% deeper than the Paraná. The same asymmetry was found by Paes (2007) in the Paranapanema River confluence 90 km upstream (Figure 1) and by Parson et al. (2004 a, b) in the confluence of the Paraguay and Paraná Rivers near Corrientes, Argentina. The reason for this asymmetry is not well understood, however, Franco (2007) suggested, in the case of the Ivaí River confluence, neotectonics control as being responsible for the channel asymmetry. On the other hand, Orfeo et al. (2007) attribute only to flow and sedimentary load dynamics the occurrence of asymmetrical confluence in the Paraguay-Paraná case.

TABLE 1. Resume of the Ivaí-Paraná River confluence characteristic.

Reach	Paraná upstream		Ivai		Paraná downstrem	
Water level	HW	LW	HW	LW	HW	LW
Discharge (m^3/s)	731	674	316	257	1047	931
Mean flow velocity (m/s)	0.63	0.99	0.35	0.29	0,75	1,02
Width:depth	250-120	250-146	50	60	142	213
Thalweg morphology	Irregular	Irregular with pools	Straight to meander	Straight	Irregular	Meander
Thalweg depth (m)	3 - 4	2 - 3	7	5	3 - 4	3
Bedform type	dune	dune	Vertical bar	Vertical bar	Lateral bar	Lateral bar
Bedform texture	Fine to medium	Fine to medium	Fine sand to mud	No sediment	Fine to medium	Fine to medium
*Water density (kg/m^3)	1000	1000	1000	1000	---------	---------

HW, LW low and high water level; (*) used for flow moment ratio (Mϒ) calculation (see text).

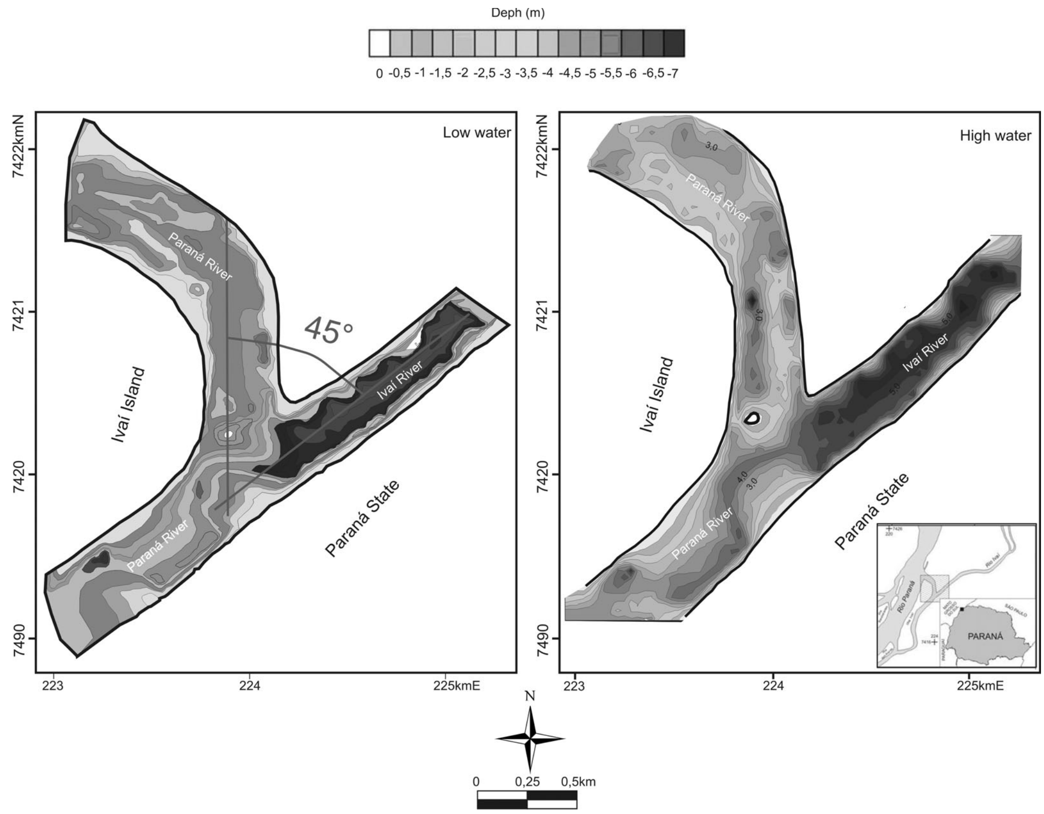

FIGURE 5. Bathymetric map of Ivaí and Paraná Rivers confluences in two moments of the hydrological cycle.

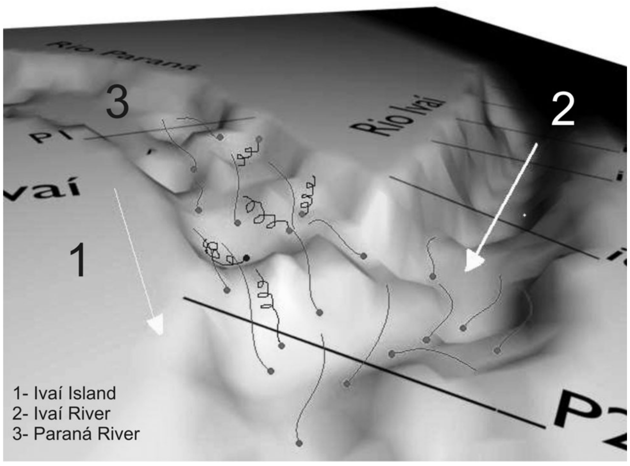

FIGURE 6. 3-D Diagram of the Ivaí and Paraná River confluence constructed from detailed echo-bathymetric survey. Note sand bar morphology in the Paraná River channel upstream confluence. Arrows indicate horizontal and vertical vortex flow.

As a conclusion, it is important to remark that although relatively stable, the Paraná River channel (up and downstream confluence) presented more morphological alterations than the Ivaí during the hydrological regime. This fact is related to the nature of the channel composition, sandy in the case of the Paraná and clayey-rocky for the tributary, Ivaí River. Other factors linked to flow and dynamics will be commented bellow.

HYDRODYNAMICS CHARACTERISTICS OF THE CONFLUENCE

During the study period the Ivaí channel showed a quite homogeneous flow in its cross-section with a mean flow velocity varying from 0.2 to 0.4 m/s for a discharge of 260 m³/s (Figure 7 - Ivaí River). On the other hand, the flow distribution in the channel cross-section of the Paraná upstream the confluence was very heterogeneous with punctual variations in flow velocity introduced by bedform roughness. Mean flow velocity was 0.6 m/s with values higher than 1.2 m/s. The occurrence of large bedforms induced the formation of upwelling flows that, at the surface, generates the characteristic of circular forms (Figure 7 - Paraná River). Parsons et al. (2004b) found the same dynamics at the mouth of the Paraguay River. This dynamic also puts sand in suspension, increasing bedform steepness.

After the confluence, a reduction in upwelling flow is observed, and consequently deposition of suspended fine sand (this fact reduces bedform height and channel roughness) (Knighton, 1998). This pattern, added to the increase in discharge, generates helical flow responsible for the construction of a straight asymmetrical channel

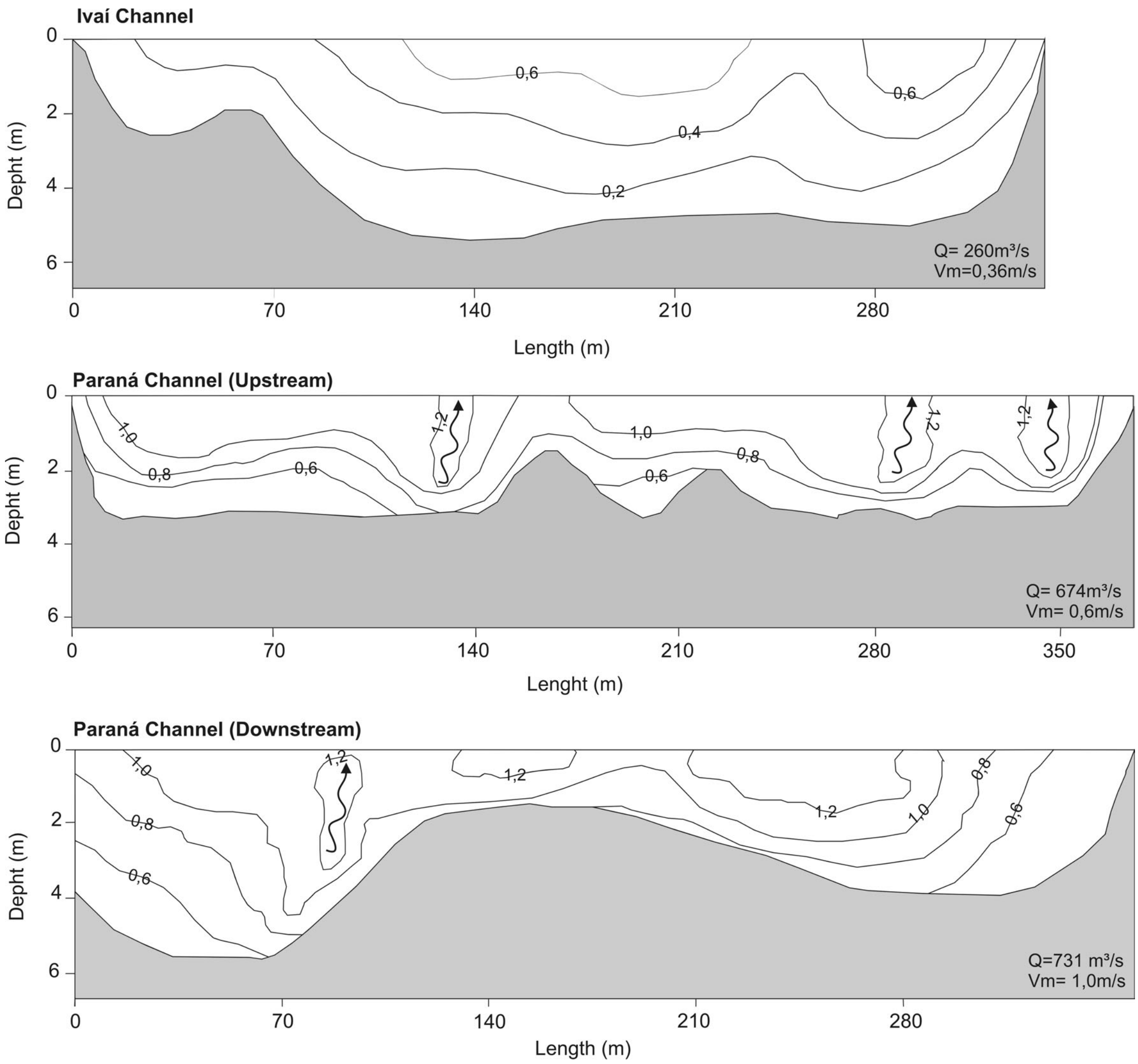

FIGURE 7. Flow velocity distribution in channel cross sections at confluence area obtained by ADCP. A. Ivaí River and B. Paraná River – vertical and sinuous arrows mark upwelling flows (See Figure 4 for localization).

with deposition of lateral bar which is very stable during hydrological regime. The flow moment ratio was calculated for high and low water level stage (Table 1) and in both cases, the obtained values were less than 1.0 (M_ζ = 0,19 and 0,14) indicating the predominance of the Paraná River flow at the confluence.

An important process occurring in river confluences with direct control over ecology is the flow mixture (Lowe-McConnel, 1987). Using satellite imagery it is possible to identify that flow mixture at the Ivaí confluence is not so effective and a strong difference in suspended load concentration is maintained at a considerable distance from the river mouth. The same situation was analyzed by Orfeo et al. (2007) in the mouth of the Paraguay River. In this case, although flows involved have expressive density difference (obtained indirectly by suspend sediment concentration) and favorable flow moment ratio, factors that would help flow mixture, the occurrence of anabrancing in the Paraná channel, separates the flows and maintains flow miscibility up to 200 km downstream (Orfeo et al., 2007).

CONCLUSION

The Paraná and Ivaí Rivers confluence is not a typical one according to literature examples. In spite of the large difference between the receptor river (Q = 7000 m^3/s) and tributary (Q = 260 m^3/s), Ivaí water does not flow directly into the Paraná, but in a secondary channel of the same size of the tributary formed by an island situated in front of the mouth. It is the same case for the Paranapanema River, 90 km upstream from this area. This fact is probably linked to flow moment ratio and sedimentary load.

Other atypical characteristic of this confluence is the strong depth difference between tributaries (4-6 m) and collector (3-4 m). The origin for this asymmetry is not well understood for large rivers and can be linked to both neotectonics and sedimentary flow dynamics.

The occurrence of secondary flows (upwelling and lateral flow) is not sufficient to produce an effective flow mixture. The entrance of the Ivaí flow reduces the size and quantity of bed form, consequently reducing channel roughness and flow turbulence, permitting the formation of helical flow. This last hydrodynamic condition induces the formation of very stable large lateral bars during the river's hydrological cycle.

The methods used in this research were adequate to the study of confluences and shall help future studies.

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