

MORPHODYNAMICS IN THE CONFLUENCE OF LARGE REGULATED RIVERS: THE CASE OF PARANÁ AND PARANAPANEMA RIVERS

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Abstract: The confluence of the Paraná and Paranapanema Rivers is studied according to morphology and dynamics. It is probably the only example of this type of fluvial environment involving a large, tropical and intensive regulated river. Confluence channels were monitored along a hydrological cycle (high-low water level) in terms of morphology, flow velocity, magnitude, structure, and bedload dynamics. In this case, hydrology is controlled by the flow of the tributary, which develops a continuous and well-defined thalweg since the collector channel (a secondary channel of the Paraná River) that presents relatively large bedforms that reduce stream power by increasing roughness. Although significant differences in channel morphology were not observed along the hydrological year, bed material texture indicates that the channel bottom is suffering a slight armoring process. This is probably the reason for the large asymmetry of channel confluence where the depth of the tributary channel is larger than that of the main collector channel (the Paraná left branch). The Rosana Dam, closed in 1987 and located 26 km upstream from the confluence, is the cause of the changes in sediment transport and the generation of the channel pavement. With the closing of the Porto Primavera Dam (2000) in the Paraná River (27 km upstream from the confluence) a new morphodynamics is foreseen for this environment, and this paper can be seen a relevant pioneer reference for environmental monitoring and management.

Resumo: A morfologia da confluência de rios intensamente regulados de grande porte é estudada tendo como exemplo a confluência dos rios Paraná e Paranapanema. Para este trabalho foi realizado o levantamento batimétrico de detalhe em dois períodos do ciclo hidrológico (cheia e vazante), a velocidade e estrutura da corrente e o tipo da carga de fundo. A hidrodinâmica da confluência é controlada pelo rio tributário, que desenvolve um talvegue bem definido e contínuo. O canal coletor (canal secundário do rio Paraná), uma vez que possui grande carga de fundo constituída de formas de leito de relativa expressão topográfica, tem sua potência de canal reduzida (aumento da rugosidade). Por outro lado a ausência de carga do rio Paranapanema propicia a formação de um canal mais fundo que o do Paraná. Muito embora não se tenha observado alterações significativas na morfologia dos canais entre os períodos de vazante e cheia, o mesmo não ocorreu com a textura da carga de fundo: o canal do tributário está sofrendo processo de ajoamento (*armoring effect*) ligado ao fechamento da barragem de Rosana (1987). O trabalho é uma contribuição inovadora uma vez que estudos desta natureza foram apenas desenvolvidos em rios de pequeno porte, além de apresentar dados importantes para subsidiar estudos da dinâmica de fluxo, da ecologia fluvial e para avaliar as alterações introduzidas pelos reservatórios em áreas de confluência.

Keywords: river confluence, channel morphology, Paraná River, Paranapanema River.

Palavras chave: mapas batimétricos, confluência, rio Paraná, rio Paranapanema.

INTRODUCTION

Confluences are very complex fluvial environments where the combination of matter (water and sediment) and energy (flow strength) from two different channels takes place. The interaction of those elements produces a unique environment in fluvial system in which the functioning is fundamental for river management (Best, 1996; De Serres *et al.*, 1999). Some studies on river confluences show that channel bottom morphology has an important role in the flow structure and sedimentary dynamics (Best and Roy, 1991; Rhoads and Kenworthy, 1995; Gaudet and Roy, 1995; Biron *et al.*, 1996a,b; Axtmann *et al.*, 1997). Despite their environmental importance, most methods for confluence studies were tested in flumes or small water courses. Thus, the application of those methods is completely unviable for any large rivers such as the Paraná and its major tributaries.

In this sense, the understanding of the morphology (form and dimension) and dynamics of a large river channel in confluence environments is extremely necessary. In the last ten years, a group of Argentine and British researchers has been working in the confluence of the Paraguay and Paraná Rivers, near Corrientes, Argentina (Fig. 1) (e.g. Parsons *et al.*, 2004; Orfeo *et al.*, 2006). Although these studies focused on large rivers, this confluence has a very peculiar characteristic concerning suspended load introduced by the tributary. The Paraguay River receives water from the Bermejo River about 70 km upstream from its confluence with the Paraná, with a suspended load concentration of 3,500 to 5,000 mg l⁻¹. At the mouth, the Paraguay introduces a suspended load of 580 mg l⁻¹ in the Paraná (Orfeo *et al.*, 2006). In the Paranapanema mouth, the water regime is completely controlled by hydroelectric regulation. The Paraná River, upstream from the confluence,

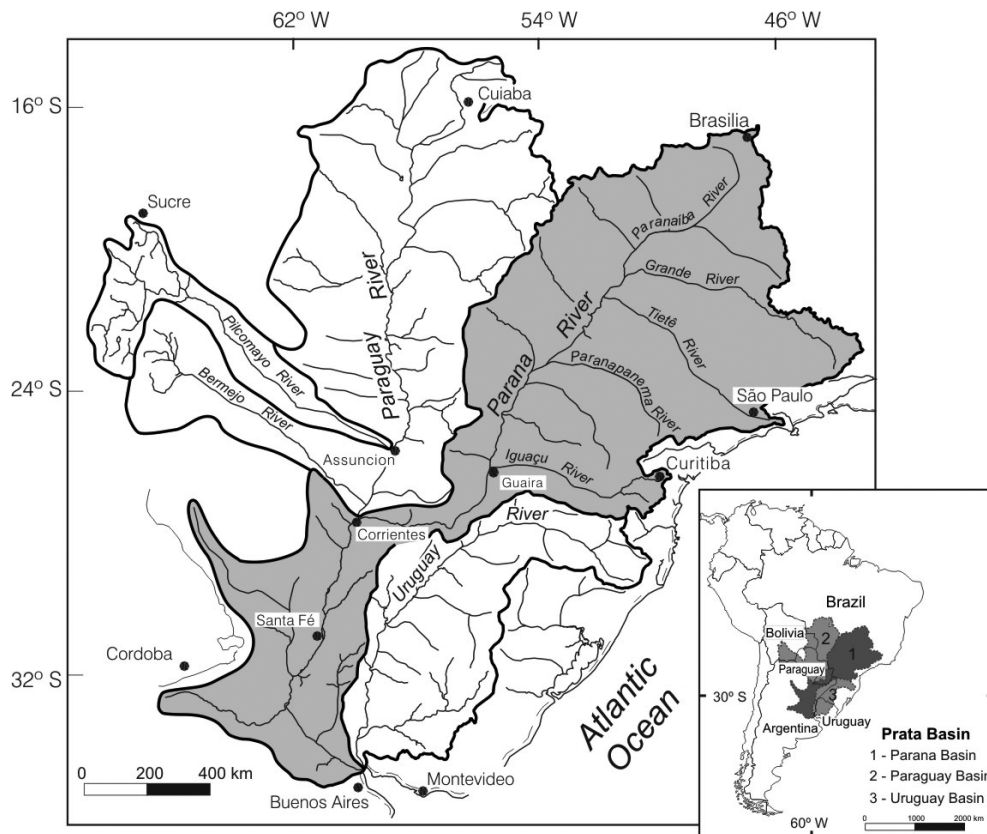


Figure 1. Paraná River Basins and main tributaries.

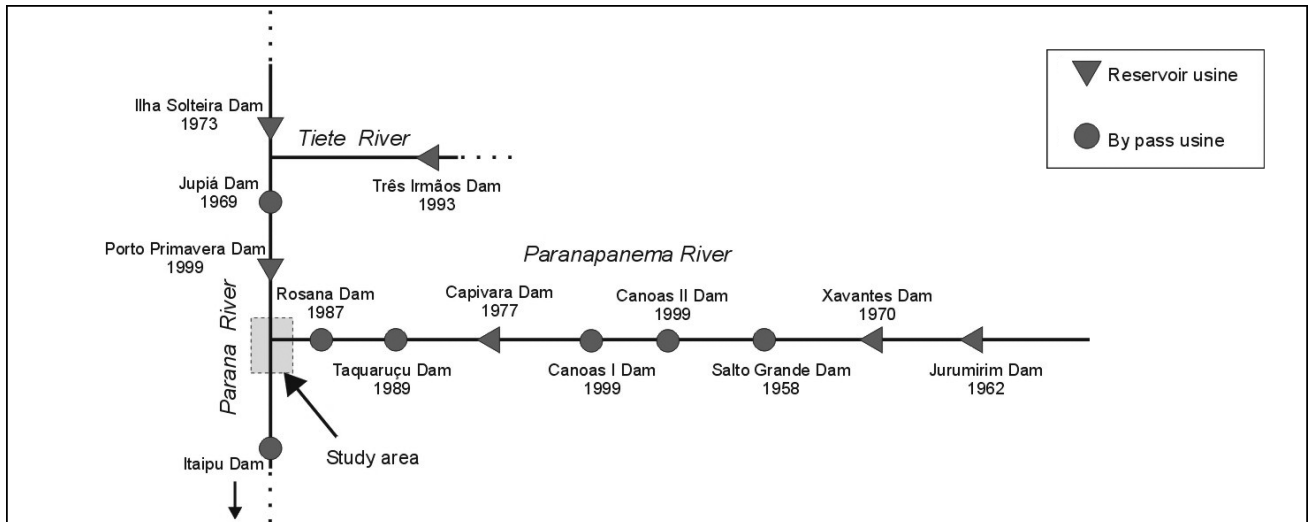


Figure 2. Upper Paraná River basin drainage root and main dams. (Closing date).

($Q_{\text{mean}} = 6,739 \text{ m}^3 \text{ s}^{-1}$, 1998-2003) is controlled by a series of dams being the most important and the nearest the Porto Primavera Hydroelectric Dam (Fig. 2). Suspended load of the Paraná river downstream the dam was reduced from 30 mg l^{-1} to 0.5 mg l^{-1} since dam closure (Stevaux *et al.*, 2009). The same happened in the Paranapanema River ($Q_{\text{mean.}} = 1,483 \text{ mg l}^{-1}$, 1987-2004). The large number of dams constructed along the Paranapanema River reduced considerably the suspended load to almost zero at the mouth reach. After the confluence, the Paraná River has an annual average discharge of $8,828 \text{ mg l}^{-1}$ (1964-2003).

With a total of $285,603 \text{ GW h}^{-1}$ (Martins, 2008), Brazil is the third electric energy producer country in the world and has an audacious plan for the construction of other new large hydroelectric dams in the Amazon Basin rivers. In this context, the present study is of capital importance and pertinent since it could be considerate as a model for the understanding of confluence environments in other large regulated rivers.

The Paraná River is formed by the confluence of the Grande and Paranaíba Rivers (Fig. 1) and runs for 3,965 km from its source (Grande River headwater) up to its mouth in the La Plata Estuary, near Buenos Aires, Argentina (Orfeo and Stevaux, 2002). The Paranapanema River, one of the most important tributaries of the upper Paraná River, has the source at the Panapiacaba Range (900 m a.s.l.) southeast of the state of São Paulo, 100 km from the Atlantic Coast. After running for 930 km, the Paranapanema reaches the Paraná River in the Pontal do Paranapanema Region

(230 m a.s.l.). The Rosana Hydroelectric Dam is located only 26 km from the river mouth (Fig. 2). The Paraná River reach downstream from the Paranapanema confluence has been studied in the last decade focusing on suspended load (Crispim, 2001), fluvial regime (Souza Filho *et al.*, 2004), bedload (Martins, 2004; Stevaux *et al.*, 2004, 2009), bank and island erosion (Destefani, 2005; Borges, 2004) and social-economic impact (Violante, 2006; Galvão, 2008).

This paper presents an analysis of the channel morphology in the confluence of the Paranapanema and Paraná Rivers and its comparison with the confluence of the Paraguay-Paraná Rivers in Argentina. This analysis intends to be a contribution to the understanding of large river confluences and provide a reference for the management of intensively controlled rivers.

METHODS

We surveyed a detailed topographic map at the confluence reach, and characterized bedload through bed channel sampling. These surveys were performed in two moments of hydrological cycle (low water level in July 2005 and high water level in January 2006) in order to identify the possible changes in the channel morphology and to evaluate the rate of channel transformation through time.

Data Collection: The confluence bathymetrical survey was performed with an echo sound-GPS FURUNO/GP 1650 of 200 kHz and the data was stored in a PC and processed with Fugawi 3 software. The channel was surveyed by a boat in a zigzag tract, crossing the

channel from side to side, with a lateral distance of 50 m for each cross-section (Fig. 2). Some longitudinal profiles were also performed. Bed material was collected with a Van Veen sampler in three sectors: in the Paraná channels, upstream and downstream from the confluence, and in the Paranapanema River downstream Rosana Dam (Fig. 2).

Computing and Laboratory: Echo sounding data was exported in *txt* format to the SURFER 8.0 software in three columns: position (latitude and longitude) and depth. A series of zero meter depth was introduced in order to supply elements for the interpolation. This data was obtained from Landsat 7 ETM+ satellite imagery. Lines and polygons were digitalized and exported using the AUTODESK MAP 2004 software in *dxf* format. Bathymetrical digital models and maps were generated in a SURFER 8.0 environment by linear interpolation and triangulation method. Bedload material was processed and sieved at the Guarulhos University Sedimentological Laboratory.

RESULTS

Channel Morphology

Upstream the confluence of the Paraná and Paranapanema channels. At the confluence reach, the Paraná River shows an anabranching low-sinuosity pattern (Stevaux, 1994; Latrubesse, 2008), with channels separated by vegetated islands. The confluence with the Paranapanema River is not directly located in the Paraná's main channel but rather in a secondary one formed by the Óleo Crú Island and the left bank of the Paraná River (Fig. 3). This characteristic is also found at the confluence of the Ivaí River, 100 km downstream from the study area (Franco, 2007). The Paraná channel is straight, averaging 1,000 m in width, with a measured discharge during field work of 1,546 and 2,063 m³ s⁻¹ (Fig. 4a-b). The depth of the channel varies from 1 to 2 m, and the occurrence of bedforms (ripples, mega ripples and dunes) generates a vague and discontinuous 3 m depth thalweg (at low water level). Bedforms at times can emerge and form ephemeral sand bars dividing the water flow. Stevaux (1994) observed that these bars can rest in the system for a long time (for months or even up to years), since they are covered by grass vegetation. Bed sediment is mainly formed by medium sand (D₅₀) ranging from

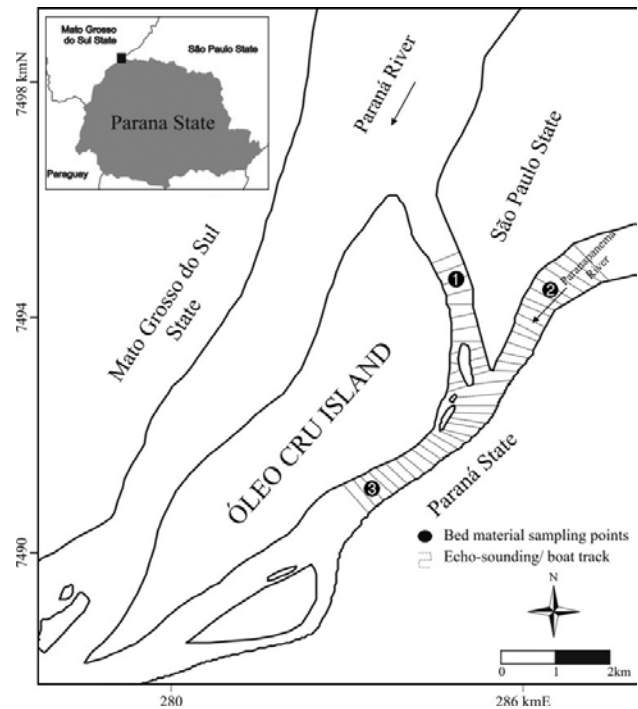


Figure 3. Paranapanema-Paraná rivers confluence area. The waters of the Paranapanema enter in a secondary channel of the Paraná, between the Óleo Crú Island and the left bank of the river. The map also shows the boat track for bathymetrical survey and bed material sampling points.

coarse to fine sand, with local occurrence of gravels (D₅₀ means grain diameter corresponding to 50% at grain-size frequency curve).

Paranapanema River channel upstream confluence.

The tributary channel has approximately the same width than that of the collector branch of the Paraná River, but a very different morphology. The Paranapanema shows a continuous, meandering and well defined 4 m deep thalweg (at low water level). Few studies on large rivers confluences present a different situation where the collector channel is normally deeper than the tributary (Biron *et al.*, 1996a, b).

Confluence site. The confluence of the Paranapanema and the Paraná forms an angle of 45° (Fig. 4), which is not so frequent in river confluences of this magnitude (Bristow and Best, 1993). At a low water stage, a central bar divides the collector channel flow. However, the occurrence of a lateral bar at the left bank right after the confluence produces a narrow reach. During the high water stage, both central and lateral bars are submersed. Another important characteristic of this

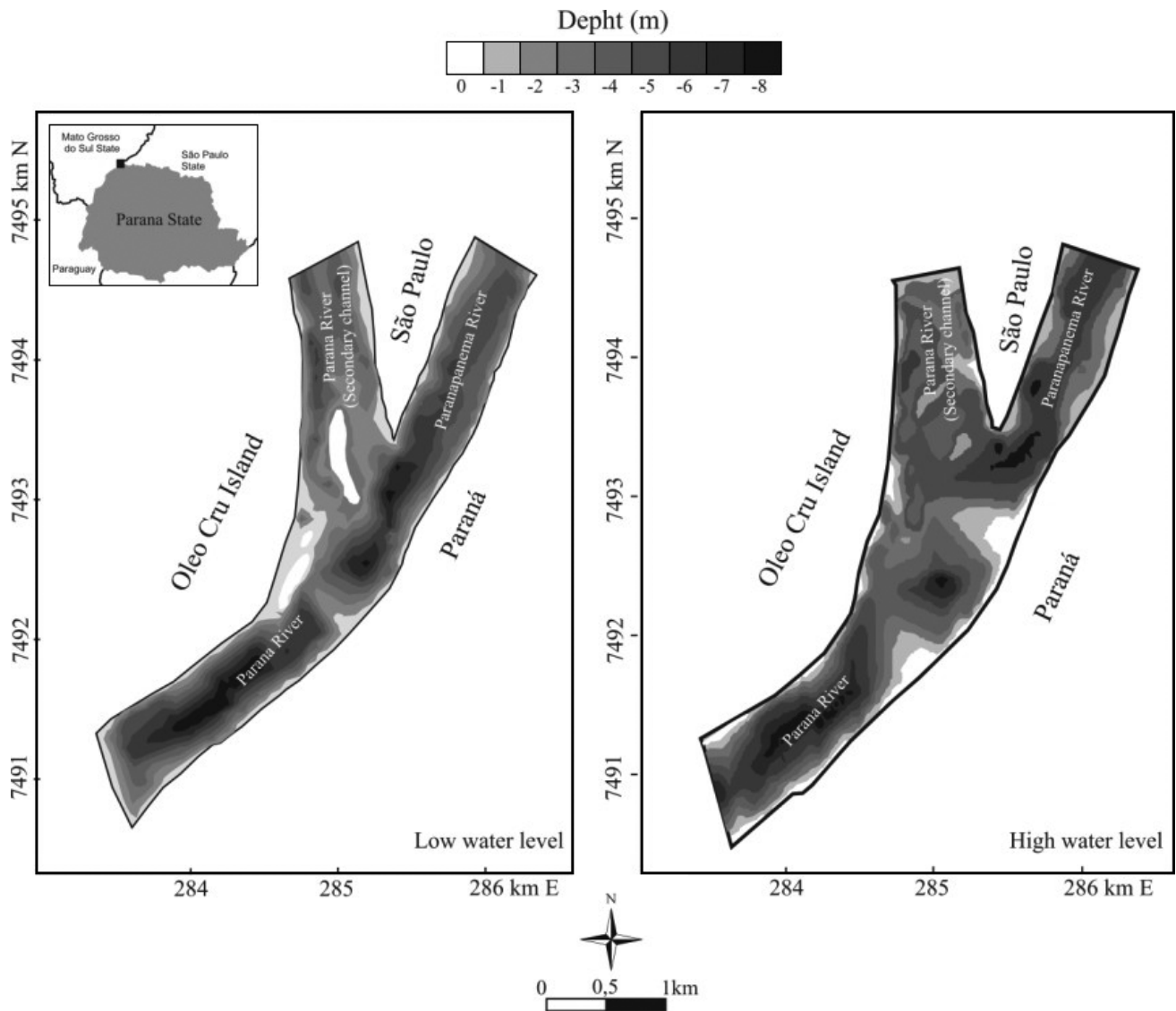


Figure 4. Paraná-Paranapanema River confluence bathymetrical maps at low (left) and high (right) water level. Note the depth asymmetry between the tributary and main river.

confluence is the occurrence of a 6 to 7 m deep scour pool aligned with the thalweg.

Paraná channel downstream confluence. After receiving the Paranapanema River and during the study period, the Paraná secondary channel had 2,900 and 3,584 m³ s⁻¹ in discharge. The Paraná forms a straight channel that runs 7.3 km along the left bank of the Óleo Crú Island up to the junction with the Paraná main channel. The channel width increases slightly after the confluence (1,100 to 1,250 m) and presents a central thalweg 7 m deep. At that place, the thalweg sinuosity increases slightly because of the occurrence of minor lateral bars. The bedload is composed of coarse sand (D_{50}) ranging

from very coarse to medium sand (Fig. 5). After the confluence, the channel maintains the same direction and the same hydrological characteristics of the Paranapanema.

Changes in time

Morphological changes. No significant changes on the confluence morphology between low and high water level periods were observed (Fig. 4). It is important to point out that the flood during the study period was weak and probably cannot be considered as a flood of morphological significance. Arenas-Ibarra (2008) suggests that an effective flood (or morphological flood) for the Paraná River in the study area should

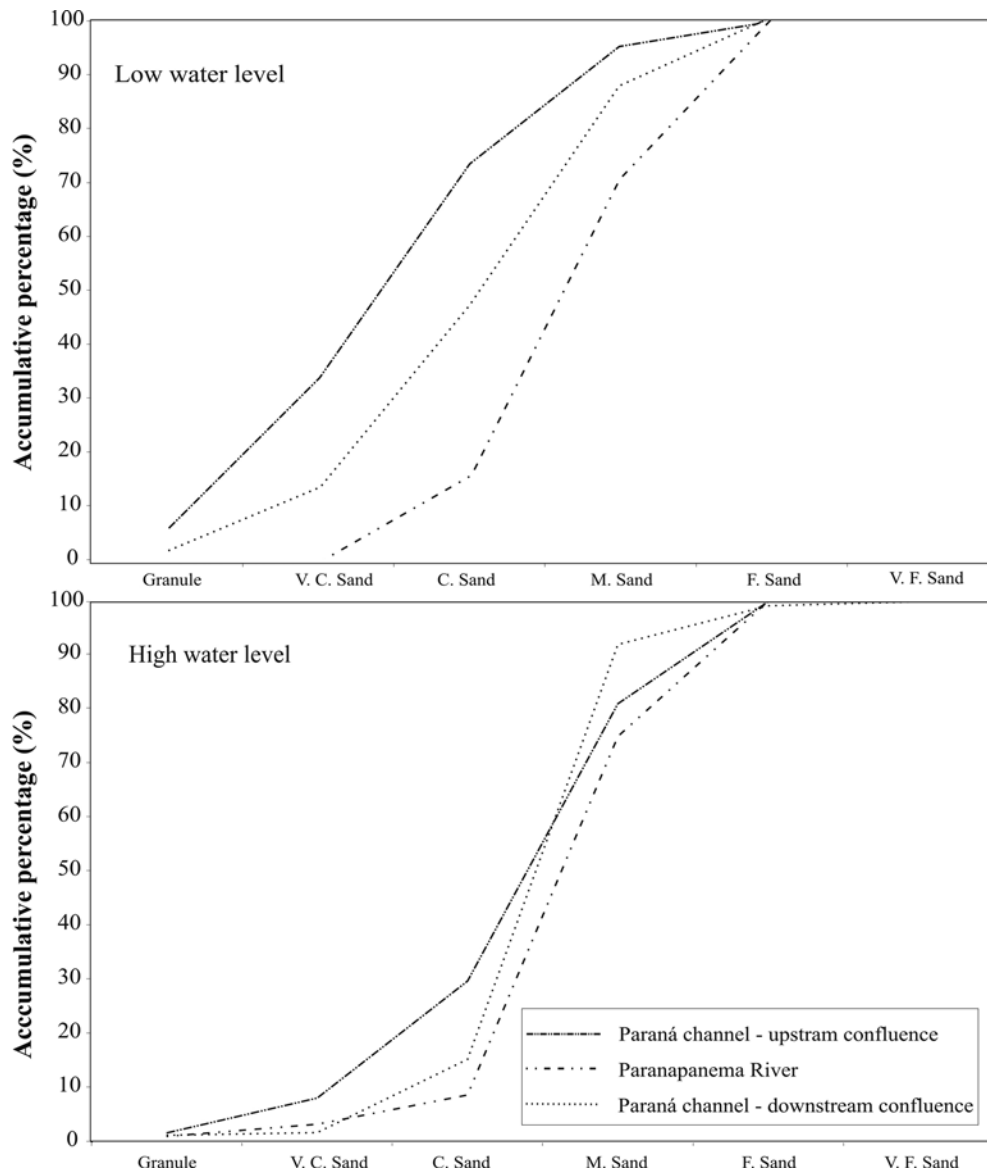


Figure 5. Accumulative frequency curves of bedload grain size for high and low water level stages.

reach $20,000 \text{ m}^3 \text{ s}^{-1}$. Floods during the study period reached a maximum discharge of $12,000 \text{ m}^3 \text{ s}^{-1}$. The submersion of the near confluence islands and bars increases the roughness, consequently reducing the shear stress. Flow dispersion induced the formation of a thalweg flatter than that recorded during the low water stage. The hydraulic environment during the high water flows intensifies sedimentation and bedform formation. Changes are less expressive in the downstream reach of the confluence channel except for the thalweg that became meandering by lateral bar development in the left side of the channel (Fig. 4).

Changes in bedload texture. A discrete reduction in

bedload grain size in the Paranapanema and in the secondary channel of the Paraná River downstream confluence was observed when comparing high and low water stages. The more expressive reduction occurred in the Paranapanema River where D_{50} changed from coarse to medium sand and the granules reduced from 10% to practically be absent. The downstream confluence channel also presented a more discrete change in sand, from coarse to medium. Sorting increased in both cases (Fig. 5).

CONCLUSION

The Óleo Crú Island is the most remarkable characteristic of the studied confluence environment,

Channel	Percentage	Low water	High water	Changes
Paraná channel upstream confluence	D ₅₀	Medium sand	Medium sand	+/-
	D ₂₅	Coarse sand	Coarse sand	+/-
	D ₁₀	Coarse sand	Coarse sand	+/-
Paraná channel downstream confluence	D ₅₀	Coarse sand	Coarse sand	+/-
	D ₂₅	Coarse sand	Coarse sand	-
	D ₁₀	Very coarse sand	Coarse sand	-
Paranapanema	D ₅₀	Very coarse sand	Coarse sand	-
	D ₂₅	Very coarse sand	Coarse sand	-
	D ₁₀	Granules	Very coarse sand	-

Table 1. Changes in bedload material at the confluence channels during low a high water levels.

generating a secondary channel in the Paraná River with approximately the same size as the tributary Paranapanema River. This type of confluence is different from any other in the Paraná, such as the Piquiri, Iguazú and Paraguay Rivers that do not present confluence islands (Parsons *et al.*, 2004; Orfeo *et al.*, 2006). An exception can be seen in the confluence of the Ivai and Paraná River as described by Franco (2007). The reason for confluence island formation was attributed by the confluence angle by De Serres *et al.* (1999). The resultant flow forms a 45° angle convergence that is favorable for the generation of a depositional site in the channel that in some cases can originate bars or, as in this case, islands (Best and Roy, 1991; De Serres, 1999). However, these authors presented studies in small creeks and flumes and this is the first time that bar/island confluence is studied in large rivers. The Paranapanema's thalweg alignment and its continuity downstream the confluence on the Paraná branch is a feature that supports this hypothesis. The confluence angle also induces the formation of helical flows, responsible for the formation of lateral bars and consequent increase in thalweg sinuosity.

The Paranapanema channel is deeper than the Paraná channel (Fig. 4). The same situation was also observed by Franco (2007) at the mouth of the River in the Paraná channel. The authors ascribe this situation to tectonic imposition by faults, where the tributary moved down in relation to that of the Paraná. Although this question is not well studied, we believe that only flow dynamics and sediment supply can produce this depth anomaly. The Paranapanema River has less bedload than the

Paraná, and not enough sediment to cover its own channel. On the other hand, the Paraná above the confluence has a high sedimentation rate in its secondary channel and the bedforms formed there increase roughness and consequently reduce flow velocity and shear stress. This situation is favorable for the flow of the Paranapanema River that dominates the confluence site. The low quantity of bedload sediment transported by the Paranapanema cannot be deposited in the mouth, but is easily transferred to the Paraná. These two facts contribute to generate an asymmetric depth confluence as commented before by Rhoads and Kenworthy (1995).

After closure of the Rosana Dam (Fig. 2) the Paranapanema bedload reduced to practically zero (Paes, 2007). As a consequence, strong armouring can be observed in the reach downstream of dam. There, fine and medium sand removed are not supplied to channel and the coarser texture (coarse sand to granules) stays as lag deposits. A recent paper states that the same process are suffering some reaches of the Paraná River as a consequence of Porto Primavera Dam (Fig. 2), 15 km upstream this confluence (Stevaux *et al.*, 2004, 2009). Santos (2008) observed that the changes in the Paraná River bedload in some reaches (including the confluence area) were so intensive that are interfering in the dynamics of sand extraction (mining). The armouring effect in the Paranapanema is much more intensive than in the Paraná River, due to the longer time span of dam closure: Rosana (Paranapanema River) in 1987 and Porto Primavera (Paraná River) in 1999. Stevaux *et al.* (2009) observed this effect in the Paraná River's main channel and called attention to the benthic

community impact once the bedload texture is the most important factor on zoobenthic community density and diversity, especially for interstitial organism as Hapaticoida (*Ptamocharis*) e Oligoqueta (*Narapa bonettoi*) (Stevaux and Takeda, 2002).

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