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FLUVIAL PROCESSES IN ATTACHMENT BARS IN THE UPPER PARANÁ RIVER, BRAZIL

PROCESSOS FLUVIAIS EM BARRAS DE SOLDAMENTO NO ALTO RIO PARANÁ, BRASIL

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Abstract:

Bars are semi-submerged fluvial forms associated with the availability of sediments and a temporal dynamic, whose dimensions are controlled by the flow and depth of the channel. Attachment bars are very common in large anabranching river systems and play an important role in island formation and ecology. The Upper Paraná River exhibits an anabranching pattern characterized by channels of different sizes, separated by islands and bars. The objective of this work is to present the processes involved in the formation and development of attachment bars in Santa Rosa Island, situated in Porto Rico, State of Parana, Southern Brazil. Acquisition campaigns were performed to obtain data on channel hydraulics (ADCP equipment), morphometry (Echo-sound profiles) and textural parameters (grain-size analyses) at high and medium water levels. Santa Rosa Island divides the flow into two channels of distinct hydraulic and sedimentary dynamics. Flow diversion produces a decrease in flow velocity and consequent sediment deposition near the upstream end of Santa Rosa Island. The formation and maintenance of attachment bars in Santa Rosa Island is related to flow competence reduction and the occurrence of divergent currents. Vegetation cover and flow regime control its permanence.

Resumo:

As barras são formas fluviais semi-submersas associadas à disponibilidade de sedimento e ao regime hidrológico cujas dimensões são controladas pelo fluxo e pela profundidade. As barras do tipo soldaduras são comuns em sistemas multicanais e desempenham um papel significativo na formação de ilhas e na ecologia local. O Alto rio Paraná – em seu trecho natural, não barrado – possui padrão multicanal caracterizado por canais secundários de diferentes tamanhos, que separam diversas ilhas e barras. Este estudo tem por objetivo apresentar os processos envolvidos na formação e desenvolvimento da barra de soldamento da ilha Santa Rosa, localizada em Porto Rico, Estado do Paraná, Sul do Brasil. Para tanto foram realizados levantamentos de parâmetros hidráulicos (perfis utilizando o equipamento ADCP), morfométricos (perfis batimétricos obtido por eco-sonda) e texturais (análise granulométrica). Verificou-se que a presença da ilha Santa Rosa divide o fluxo em dois setores de características hidráulicas e sedimentares distintas, esta separação do fluxo produz diminuição de sua velocidade, o que favorece a acumulação de sedimentos próximo à cabeceira da ilha. A formação e manutenção da barra de soldamento da ilha Santa Rosa está relacionada com a redução do fluxo, competência e ocorrência de correntes divergentes locais. A permanência desta forma é controlada pela cobertura vegetal e do regime de fluxo.

1. Introdution

In spite of a controversial and complex terminological discussion (SMITH, 1974; 1978; BRIDGE and TYE, 2000), fluvial sand bars, as used in this study, are in-channel deposits emerged at medium water level (BRIDGE, 2003). Bars are probably the most studied of the fluvial forms, and their wide classification is based on different parameters involving morphology (SMITH, 1978), genesis (ASHLEY, 1978; STEVAUX, 1994), grain size (KOSTER, 1978) and position in the channel (CHURCH and JONES, 1982).

Most of the bar studies were carried out in flumes (SMITH, 1974; LEOPOLD and WOLMAN, 1957; ASHMORE, 1982; ASHWORTH, 1996; LANZONI, 2000; LUI, 2009; CROSATO *et al.*, 2012), braided (JACKSON, 1975; BRIDGE, 1985; ASHMORE, 1993; RICHARDSON *et al.*, 1998; ASHWORTH *et al.*, 2011) or meandering rivers (LEVEY, 1978; KLEINHANS *et al.*, 2008; PARKER, *et al.*, 2011; SLOFF *et al.*, 2012). As for anastomosing rivers, there have recently been some studies on the mechanisms of bar formation and heterogeneity (LATRUBESSE and FRANZINELLI 2002, 2005; SARMA, 2005; LATRUBESSE, 2008; ROZO *et al.*, 2012, NICHOLAS *et al.*, 2012; NICHOLAS *et al.*, 2013; REESINK *et al.*, 2014).

The term 'anastomosing' was discussed by many authors (SCHUMM, 1985, KNIGHTON and NANSON, 1993, BRIDGE, 1993), and for a long time, this type of rivers has often been confused with braided rivers, which roughly have a comparable planform (MAKASKE, 2001). Nanson and Knighton (1996) enlarged the scope of the term anabranching, a former synonym of anastomosed, providing a genetic connotation concerning stream power and sediment size for multiple channel rivers. Latrubesse (2008) showed that many large rivers seem too complex in pattern to be simply categorized other than 'anabranching'. According to Lewin and Ashworth, (2014) many large rivers are simultaneously anabranching and plural systems (braided, meandering or straight), being the result of different process sets. Concerning the importance of bars on anabranching formation and maintenance, Dunne and Aalto (2013) stated that rivers with relatively high sediment: water discharge ratio, such as the Ganga, tend to form large amounts of mid-channel bars and, consequently, tend to be anabranching. As opposed to the case of braided rivers, studies on anabranching rivers have to be conducted in natural systems, since its complex relation between channels and stable vegetated islands, and its mixed suspended sediments and bedload involves time scale and flow conditions impossible to be reproduced in flumes.

The anabranching pattern is characterized by stable vegetated islands, which do not fit to flow seasonal variability. Furthermore, they present unconsolidated sediments that form river sand bars. However, anabranching rivers can also be characterized by bars as the Brahmaputra and the Orinoco, which had numerous sand bars that resulted in a local braiding pattern (LATRUBESSE, 2008).

The Upper Paraná River is defined as anastomosing by Stevaux and Souza (2004) and anabranching by Latrubesse (2008). The bars in this region were classified by Santos *et al.* (1992) and Souza Filho and Stevaux (2000) according to their morphology, evolution and position in central, lateral, tributary mouth, point bar and attachment bar. The latter can be considered a modification of the lateral bar, more commonly found in large anabranching river systems. The term attachment comprises the fact that it usually joins an island or channel bank. Junction can occur laterally (lateral attachment bar) and on the upstream face of an island (island-head attachment bar) (DRAGO *et al.*, 2013). The scars resulting from the attachment processes remain evident on the surface of the island.

The objective of this paper is to present the processes involved in the formation of attachment bars, as well as to discuss their development on an anabranching reach of the Upper Paraná River.

2. Field Setting

The Paraná River is the principal drainage of the La Plata River Basin and it drains 2.5 million km². The river runs for 3,965 km from the source of the Grande River (one of its formers) in the Mar Mountains, only 17 km of the Atlantic Ocean (S 21º), to the La Plata River Estuary in Argentina (S 34º), near Buenos Aires (ORFEO and STEVAUX, 2002). Its upper reach is almost totally man-controlled by a series of reservoirs on both trunk and main tributaries. The only "natural" condition is a 255 km reach between Itaipu and Porto Primavera Dams (Figure1).

The studied bars are formed along the Santa Rosa Island (SRI) (22°46'15"S, 53°17'48"W), near the town of Porto Rico, PR, Brazil (Figure1). This reach is directly influenced by the upstream dams of Porto Primavera, located at a distance of 48 km, and Rosana, located on the Paranapanema River, 53 km (STEVAUX *et al.*, 2009).

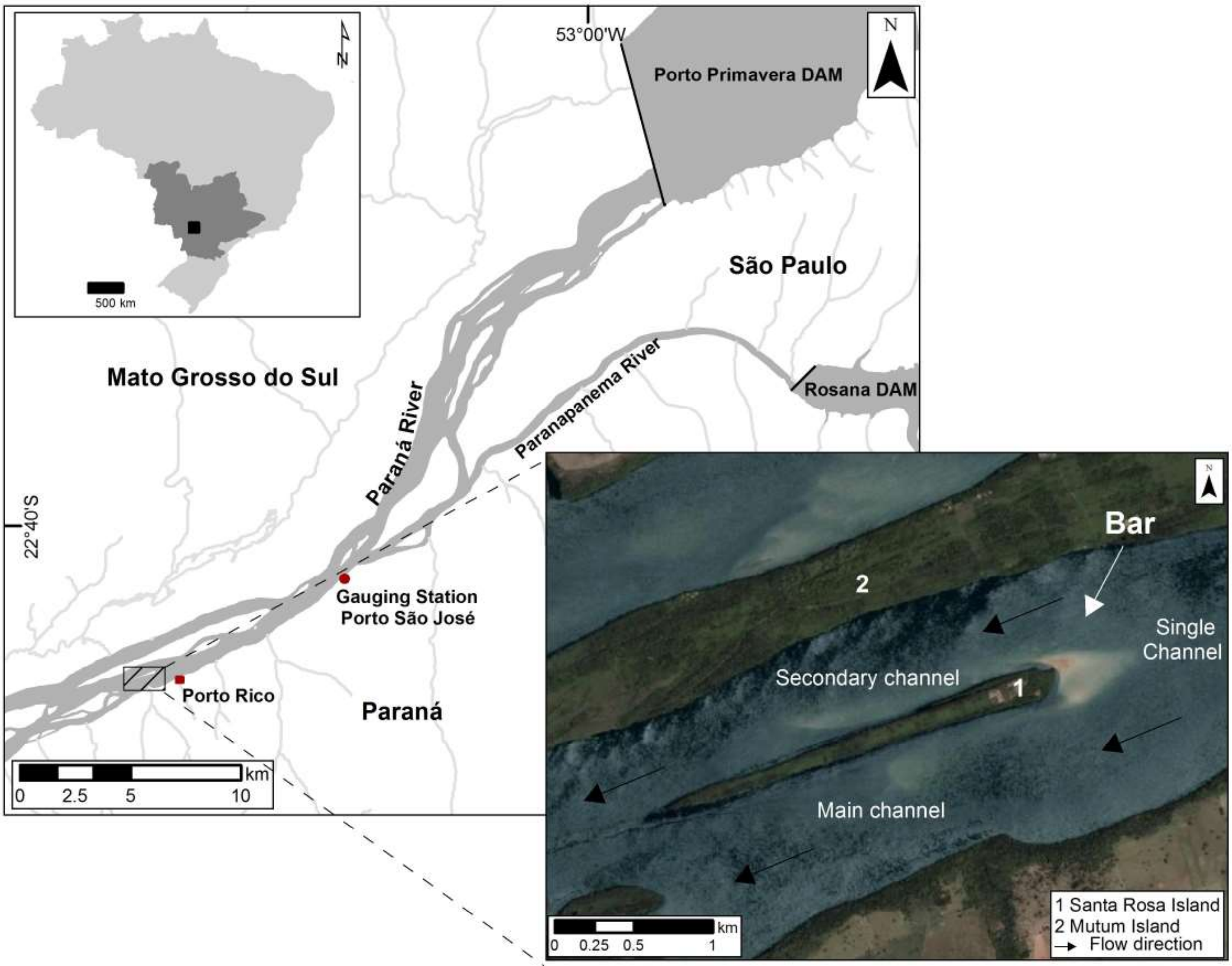

Figure 1 - A. Upper Paraná Basin in Brazilian territory; B. Study reach: observe anabranching pattern with elongate island archipelagos separated by a upstream nodal section (Porto São José is the nearest gauge station); C. Santa Rosa Island with frontal and island-head attachment bars(Google EarthTM, sensor SPOT, 2009).

In this reach, the river channel has 3,200 m in width and is separated into three anabranching channels by the Mutum Island and SRI The SRI is a relatively small island (2,500-m long and 150-m wide), which divides the left channel of the Paraná River into two channels of 600 and 900 m in width. In this reach, the thalweg is asymmetrically shifted to the left and ranges from 10 to 15m in depth. The secondary anabranching channel on the right of the SRI is 600 m wide with average depth of 4-5 m. The water slope in the reach is 0.00007 with local variation of 0.00002 to 0.00004 (LELI, 2015).

The Porto São José Fluvial Station (Figure1), in operation since 1964 – located in the upstream sector of the study reach – gauged a medium discharge of 8,912 $m^3 s^{-1}$, with a minimum and a maximum recorded annual average discharge of 7,089 $m^3 s^{-1}$ 10,853 $m^3 s^{-1}$, respectively, and extremes of 2,551 $m^3 s^{-1}$ in 1969 (probably associated to La Niña event) and 34,912 $m^3 s^{-1}$ in 1982-83 ENSO. In this reach, the periods of high and low water levels are well defined. The largest discharges occur between the months of December and March (summer), followed by a period of low water levels between the months of April and November (STEVAUX *et al.*, 2009).

Along the study reach, the Paraná River's bed channel is essentially sandy, formed by mega-ripples and dunes. In large floods, it is possible to develop a large bedform called "sand wave", composed of the accretion of ordinary bedforms. Sand waves generally emerge at medium water levels and form mid-channel bars (STEVAUX, 1994).

Although it is non-damned, this reach suffers the impacts produced by the dam upstream such as discharge control with (1) reduction of flood tension (difference between minimum and maximum water level); (2) significant decrease in suspended sediment concentration (from 35 to 0.3 mg L^{-1}); (3) formation of armor layers (increase in bed channel grain-size); and (4) reduction in bedform size and steepness (STEVAUX *et al.*, 2009). According to Martins (2008), bedload discharge measured by bedform migration is 1,152,325 ton. y^{-1}. However, this value tends to drop over time because of the bedload flow interruption by the Porto Primavera Dam.

The bars of this study ware chosen due to their spatial position and previous studies by Santos *et al.* (1992). These authors described such bars as deposits, which rapidly change their morphology over time.

3. Methods

3.1 Data collection

Two field observations at high (Jan. 2007) and medium (Feb. 2009) water levels were carried out for discharge determination, bottom profiles, flow velocity and directions, and bedload sampling. The first field observation – the Porto São José Fluvial Station – gauged 632 cm (over fluvial station zero) and a discharge of 17,730 m^3s^{-1} (Bankful discharge). In the second field observation, water leveled at 351 cm and daily discharge of 9,240 $m^3 s^{-1}$ (Figure2).

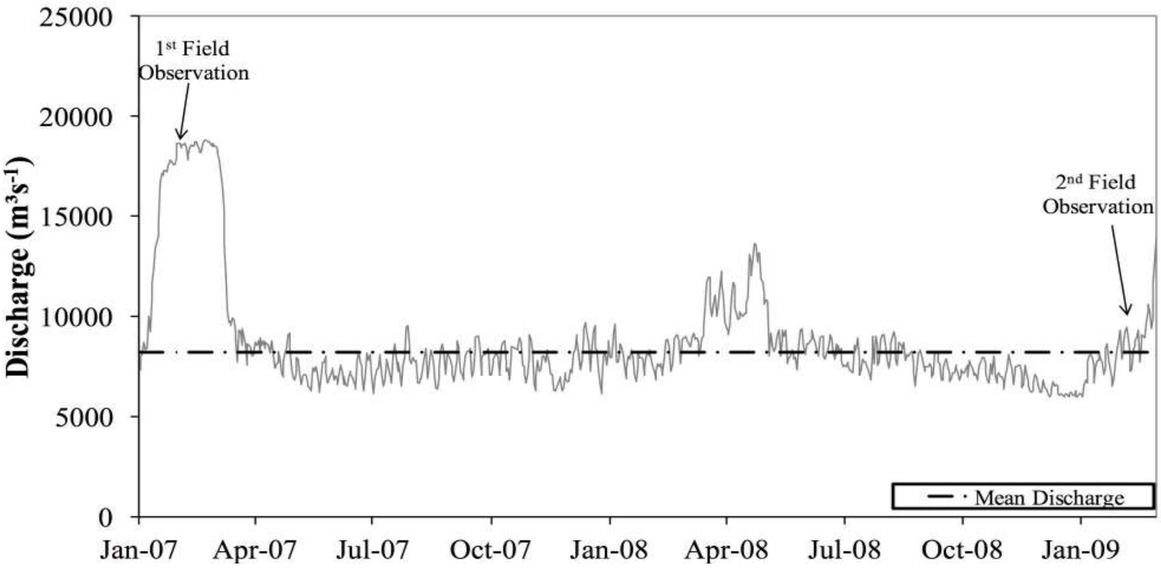

Figure 2 - Daily discharges at Porto São José gauging station (Jan/2007-Feb/2009).

Flow measurement was obtained using the ADCP (Acoustic Doppler Current Profiler of the RD Instruments®, Rio Grande, 600 KHz and software Winriver software (Acquire mode). Longitudinal (15) and transversal (19) profiles were performed at high (2007) and medium (2009) water level by ADCP device along the Santa Rosa Island (Figure3). The data collected by the ADCP were processed by Winriver (Playback mode).

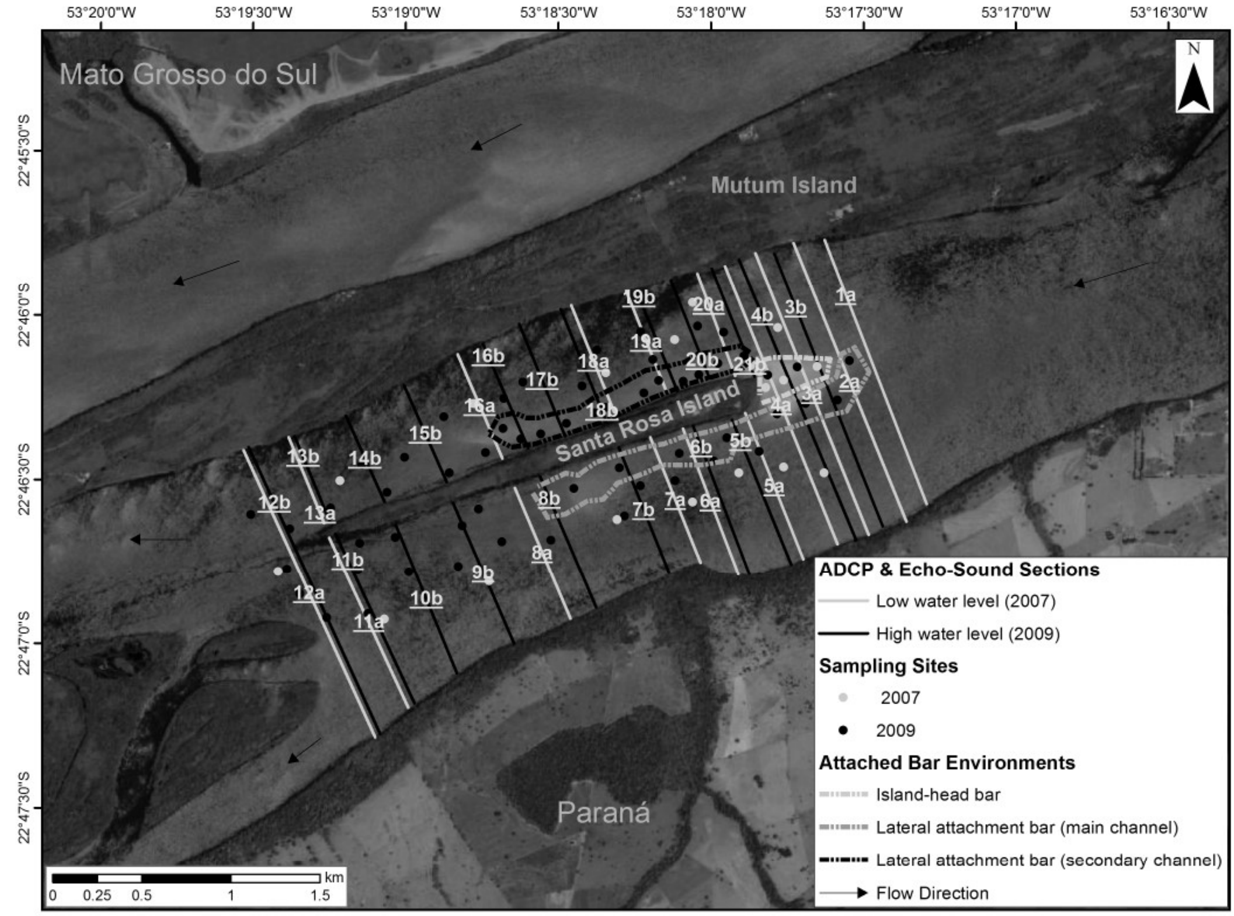

Figure 3 - Cross-section profiles (ADCP and Echosound) and samples sites (Google Earth®, 2009).

Bathymetrical surveys were conducted using Furuno echo sound (GP 1650-F model) with GPS acquired and stored by the Fugawi 3 software and processed by the ARCGIS 10.1 software for the generation of bathymetric maps through the geostatistical procedure of kriging.

Grain-size analyses were processed in 76 samples (n =17 medium water, n = 59 high water), collected during the two water-level moments for attachment lateral and head-island bars, main and secondary channels (Figure3). The large difference between the sample collection for the first and second field work is due to the emersion of many sectors of bedforms during low water. The samples were analyzed by the sieving method to assess the particle size distribution, afterward it was calculated mean particle diameter (D50) and the coarse fraction of 10% (D90).

3.2 Hydraulic parameters and equations

Some basic hydraulic parameters such as stream power, specific stream power, critical shear stress and the Shields parameter can reveal the characteristics and changes in the flow and, consequently, the fluvial processes involved in bar formation:

a) *Specific stream power* (ω) is the stream power (Ω) by channel width unity and it "determines the capacity of a given flow to transport sediment" (Knighton, 1999). It is expressed by the following equations:

$$\Omega = \rho g Q S \text{ (in W.m}^{-1}\text{)} \quad \text{(eq. 1)}$$

$$\omega = \frac{\Omega}{w} \text{ (in W.m}^{-2}\text{)} \quad \text{(eq. 2)}$$

where ρ (kg m^{-3}) is the constant water density, g (ms^{-2}) is the gravitational, Q ($m^3.s^{-1}$) is the water discharge, S is the slope and w (m) is the cross-section width.

b) *Critical shear stress* (τ_{cr}) characterizes the interaction between the flow-channel bed and the beginning of the movement of a certain particle size (D). It is defined by Richards (1982) as

$$\tau_{cr} = 0.06(\rho_s - \rho)gD_{50}\ (N.m^{-2}) \quad \text{(eq. 3)}$$

where ρ_s and ρ (kg m^{-3}) are the sediment and water specific mass, and D_{50} (mm) is the grain-size median.

c) The *Shields parameter* (Shields, 1936) relates a dimensionless critical shear stress (θ_s) with the particle Reynolds number (R_*) weight immersed in water and is expressed by

$$\theta_s = \frac{\tau_{cr}}{(\rho_s - \rho)gD_{50}} \quad \text{(eq. 4)}$$

$$R_* = \frac{uD_{50}}{\nu} \quad \text{(eq. 5)}$$

where u (m s^{-1}) is the fall velocity ν (or friction) and ν (m^2 s^{-1}) is the kinetically water viscosity.

4. Results

4.1 Flow distribution, direction and channel energy

The area between the channel and the island is a complex of morphologies and flows that generates seven sub-environments: (1) main (left) and (2) secondary (right) channels defined by flow separation by SRI (Figure 1 and Table 1); (3) main and (4) secondary channel attachment bar; (5) head-island bar, formed in the upstream face of the island; (6) island-bar channel to the left and (7) the right side of the island (Figure 3).

SRI divides the flow into two – main (left) and secondary (right) – channels, with distinctive hydraulic characteristics (Figures. 4, 5). The main channel leads the largest portion of flow and has a high flow velocity, especially in the thalweg. On the other hand, the secondary channel has lower values for the parameters mentioned above. Flow division generates two low-velocity and divergent "shadow" zones (secondary currents) on each side of the island (Figure 5).

In studies of the anabranching river systems, is usual the calculation of stream power (eq. 1) and specific stream power (eq. 2), considering the entire section

Table 1: Hydraulic data in single and two channel sections.

	Single channel*		***Two anabrancing channels***			
			Main channel (Left)		***Secondary channel (Righ)***	
	High level	***Med. Level***	***High level***	***Med. level***	***High water***	***Med. Level***
Q ($m^3.s^{-1}$)	*12,678,62*	*7,001,58*	*8,187,43*	*4,896,71*	*4,028,68*	*2,125,82*
V (ms^{-1})	*1.01*	*0.84*	*1.03*	*0.86*	*0.95*	*0.77*
$d_{max,med}$ (m)	*8,1/7,7*	*5/4,8*	*9,3/8,7*	*8,2/6,8*	*7,5/6,6*	*5,5/4,6*
Rh (m)	*7,657*	*4,861*	*8,532*	*6,694*	*6,353*	*4,535*
Flow direction	*N181,15º*	*N180,13°*	*N122.31°*	*N133,56°*	*N258.19°*	*N267,44°*
Diversion angle	-	-	*56°*	*47°*	*78°*	*87°*
Ω ($W.m^{-2}$)	*6.32 to 4.89*	*2.75 to 2.82*	*7.43 to 5.7*	*4.4 to 3.11*	*5.44 to 4.2*	*2.77 to 2.14*

(*) It is important to state that the term single channel used in this table corresponds to large left channel of the Paraná River separated by the Mutum Island (See figure 3 for localization).

(margin to margin). In this study, these parameters were calculated for each branch (single, main and secondary channel). Therefore, it is possible to better understand the transport and morphology of each channel. Specific stream power in this study reach varied according to the space and time (Table 1). The highest values were found in the main channel both at high and medium water levels.

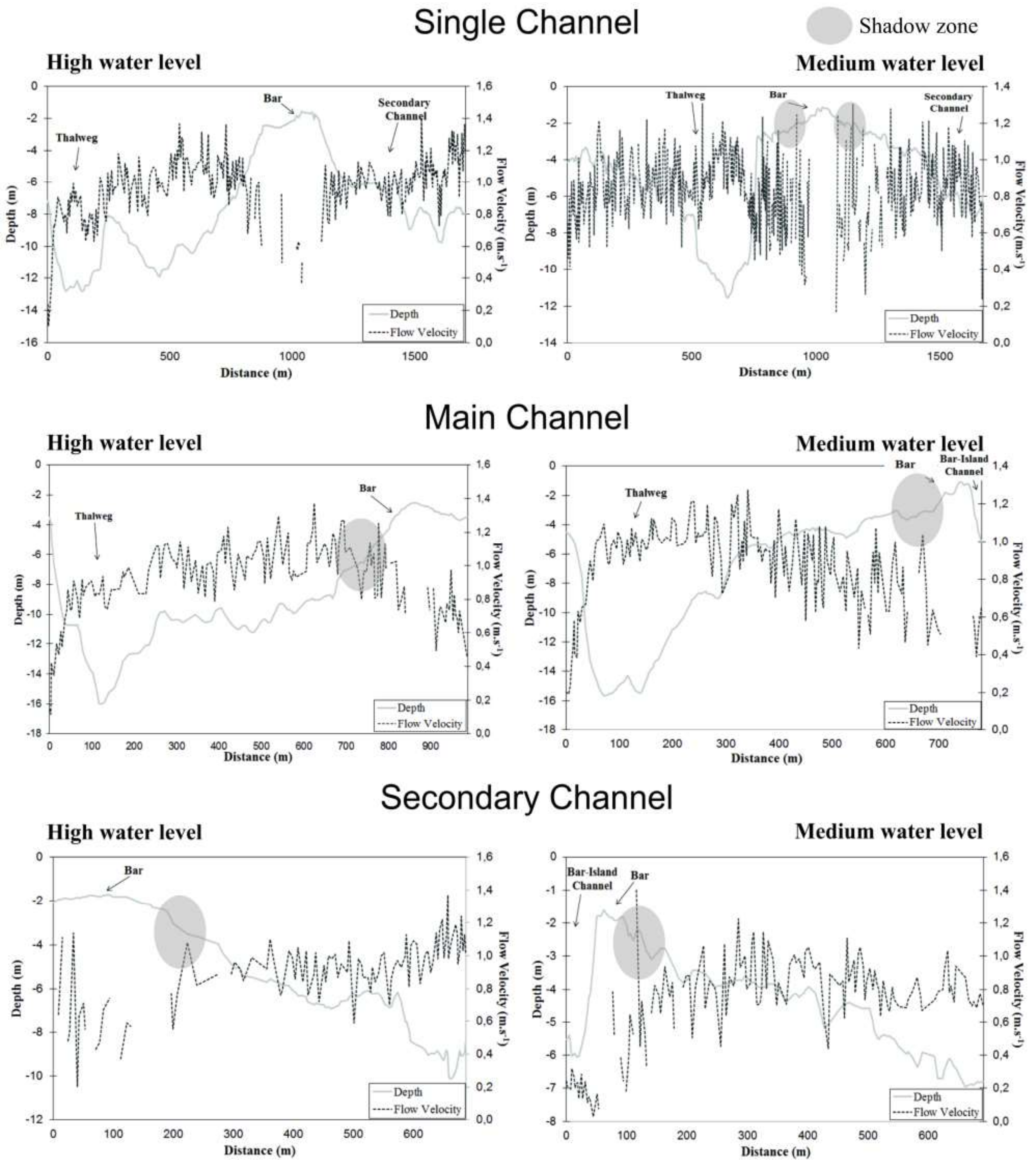

Figure 4 - Cross-sections with flow velocity for high water level (2007) and for medium water level (2009).

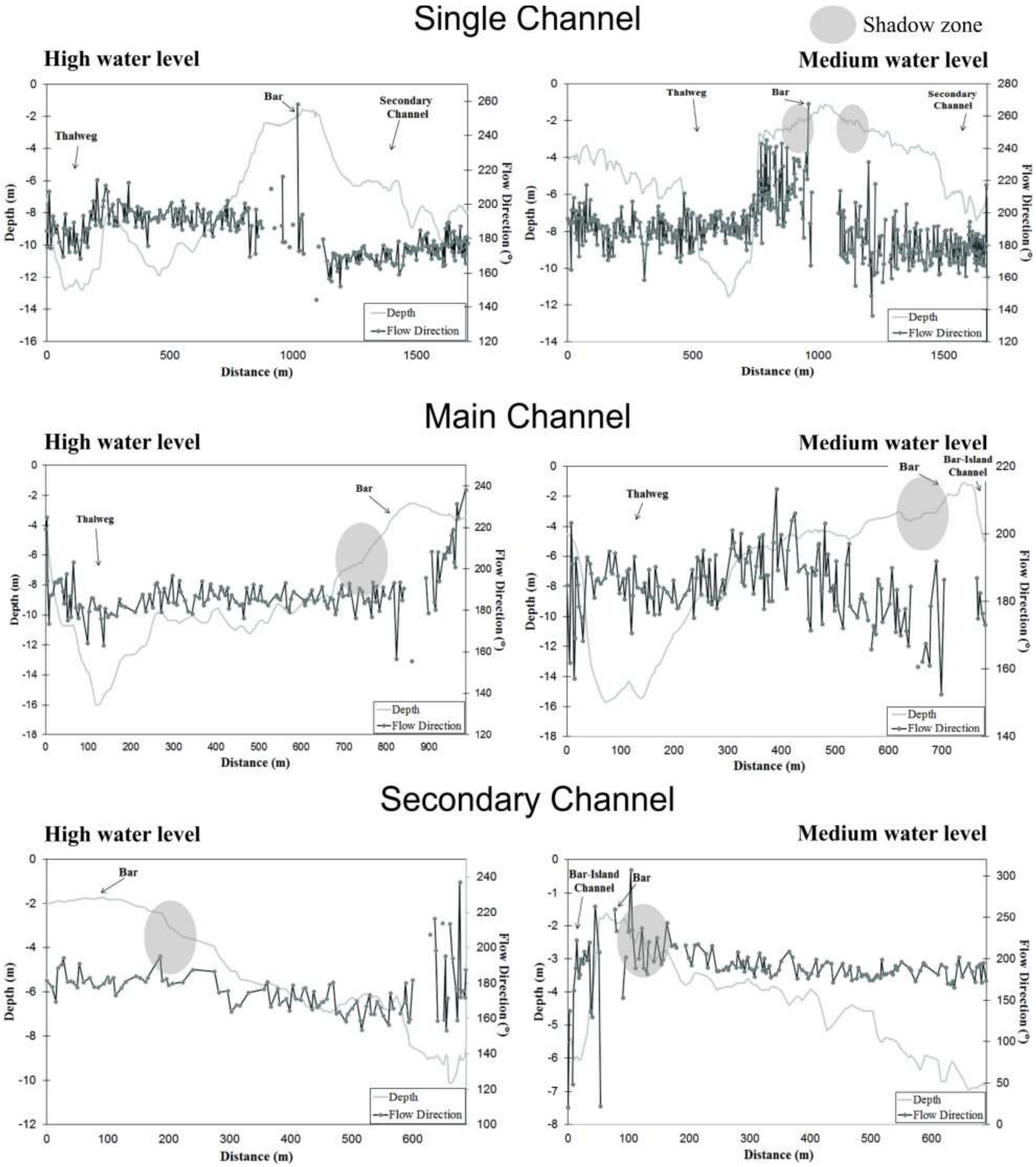

Figure 5 - Cross-sections with flow direction for high water level (2007) and for medium water level (2009).

4.2 Bar morphology

On the bathymetrical surveys conducted during the high water periods, the attachment bars (lateral and head-island) completely submerged, making it difficult to recognize their morphology, considering that in floods, there is a larger reworking of river forms. (Figure 6). In the medium level period, the bars emerged and spread across a large channel area, keeping a more stable morphology (Figure 7).

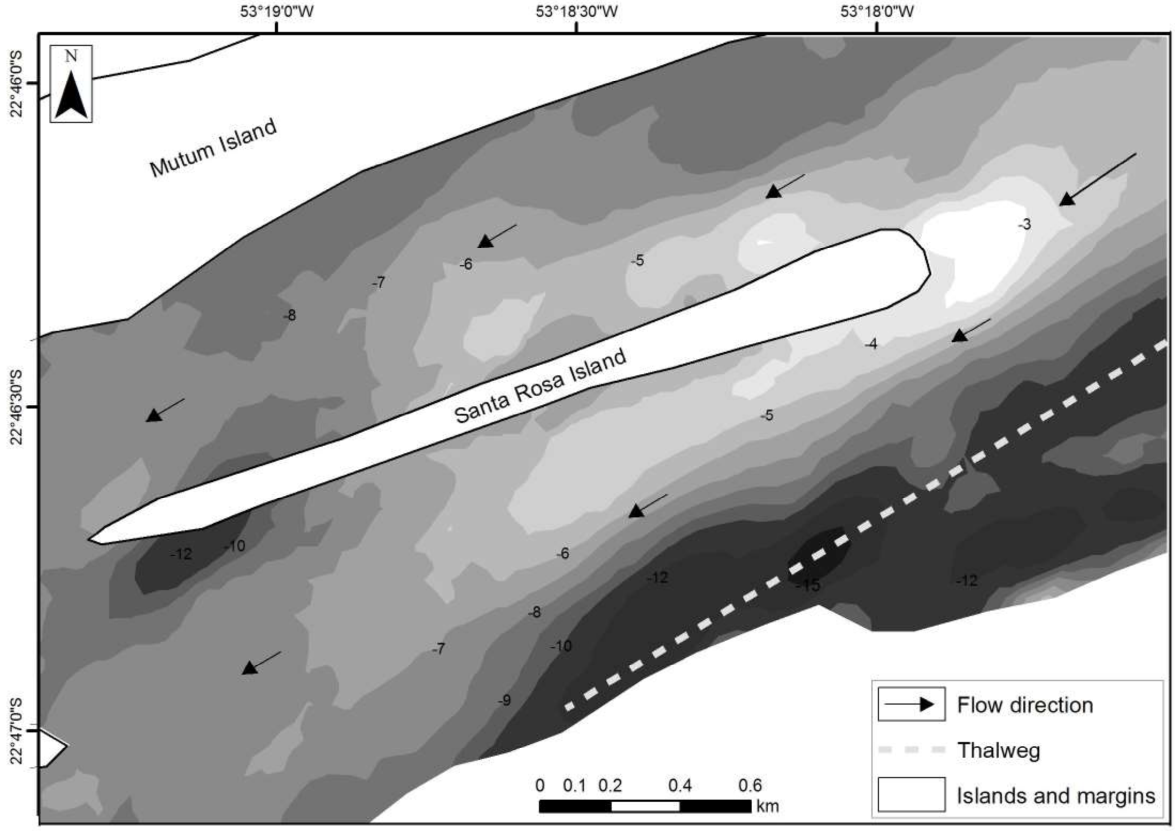

Figure 6 - Bathymetrical map at high water level, depth expressed in m. Q = 17,730 m³.s⁻¹, surface water level 632 cm (over fluvial station zero).

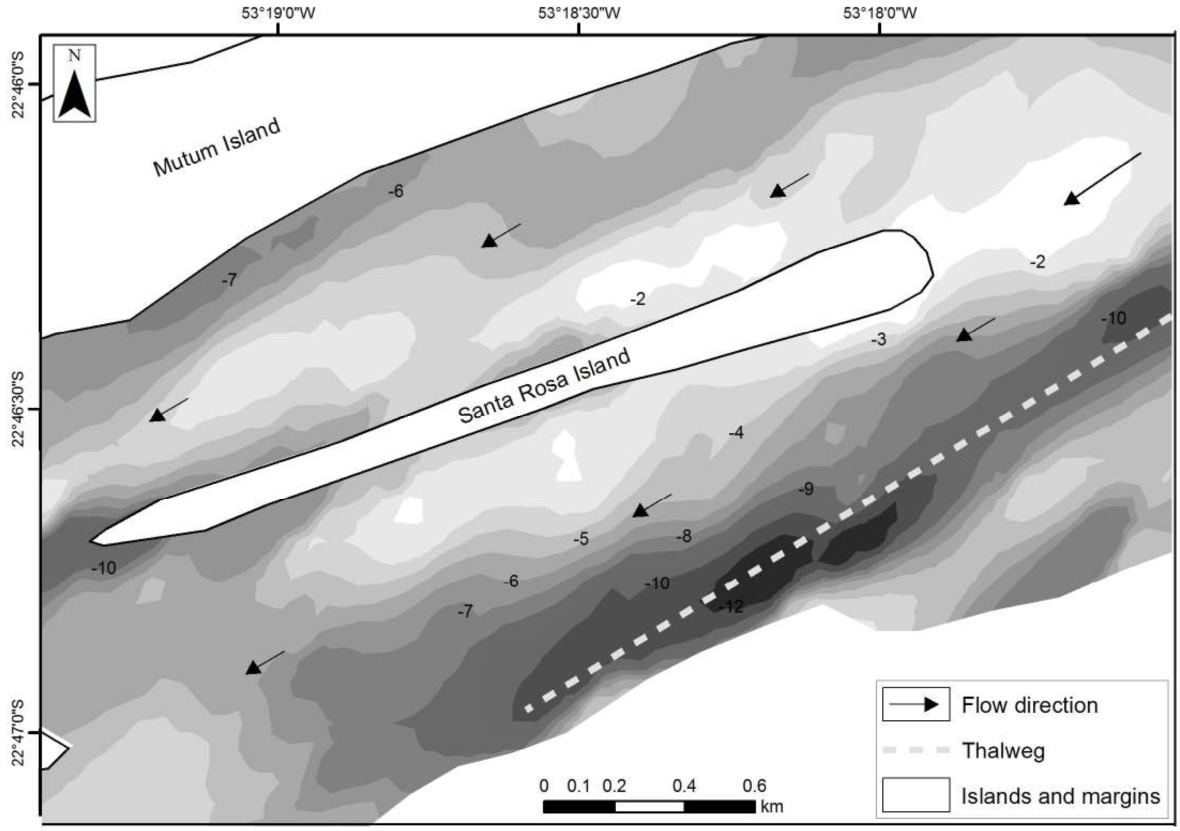

Figure 7 - Bathymetrical map at medium water level, depth expressed in m Q = 8,788 m³.s⁻¹, surface water level 334 cm (over fluvial station zero)

The secondary channel bars developed downstream and laterally. Its morphological stability was such that allowed the development of a sparse grass vegetation cover. The main channel bar was not as developed as the secondary one and remained submerse in its majority, even in the medium period. Active erosive features could be found in many parts in both periods. The sharp outer border of this bar is parallel to the thalweg of channel, with the depth downing abruptly from 2 to 10m. With bar formation, an island-bar channel was formed, generating a lentic to semi-lotic environment separated from the channel flow. The island-bar channel was also more developed in the secondary than in the main channel. Although the head-island bar was also submersed during the flood, its morphology did not suffer major changes. In this type of bar, vertical accretion is more effective than in the attachment bar. In medium water, the head bar practically connected with the island and presented sparse patches of grass vegetation.

4.3 Bar composition and sediment entrainment

Particle diameter changed according to water level. Comparing the frequency curve for both water levels (Figure 8) for samples of all sub-environments, it is possible to see that, during the flood, the bedload presented a high sorting degree for D_{50} with a small variation from 1.8 to 1.0 mm (Φ -0.9 to 1). The condition of flow homogenization, that normally occurs during the flood, might be responsible for the very similar texture of all sub-environments. During the flood, all environments are almost under the same flow energy, in a situation quite similar to the one that occurs in braided channels.

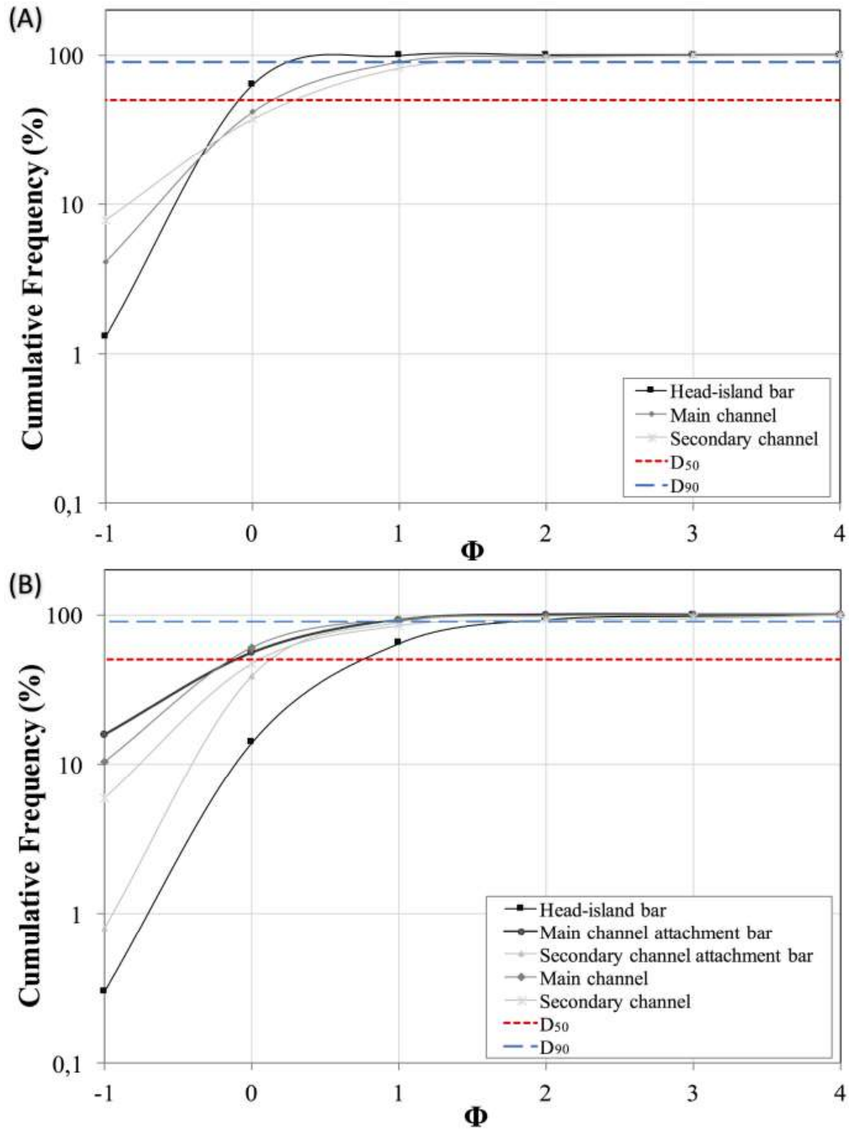

Figure 8 - Accumulated frequency curve of bed sediment for (A) high and (B) medium water level.

In medium water, the sub-environments are relatively disconnected and present different flow velocities. Under this condition, sediment texture presents a lower sorting degree with D_{50} ranging from 1.8 to 1 mm. Still in medium water, some samples from island-bar channel deposits presented finer (silt and clay) texture, because at some moments the isolation of this environment from the river channel is almost complete with lotic to semi-lentic flow conditions.

Samples generated four groups when plotted in a grain-size diagram for all sub-environment samples and the two water levels (Figure 9). This diagram assumes that sediments arriving at the stream have different sizes and they suffer different transport processes according to local flow conditions. The forces acting on the particles can keep them in suspension or on the river bottom (rolling and traction). This is due to the size, weight and shape of the particle, as well as the function of flow type (whether it is laminar or turbulent), flow velocity, bed obstacles and various other interrelated functions, such as slope bed and channel shape, among others. Passega (1957, 1963) proposed a diagram (Figure 9) to establish the relationship between the particle size characteristics of sediments and deposition processes. In this diagram, the abscissa corresponds to the average grain diameter of a sample (D_{50}), and the ordinates corresponds to the first percentile of the sample or the grain diameter that is only surpassed by 1% of the sample (D_{90}). The latter value indicates the competence of carriers.

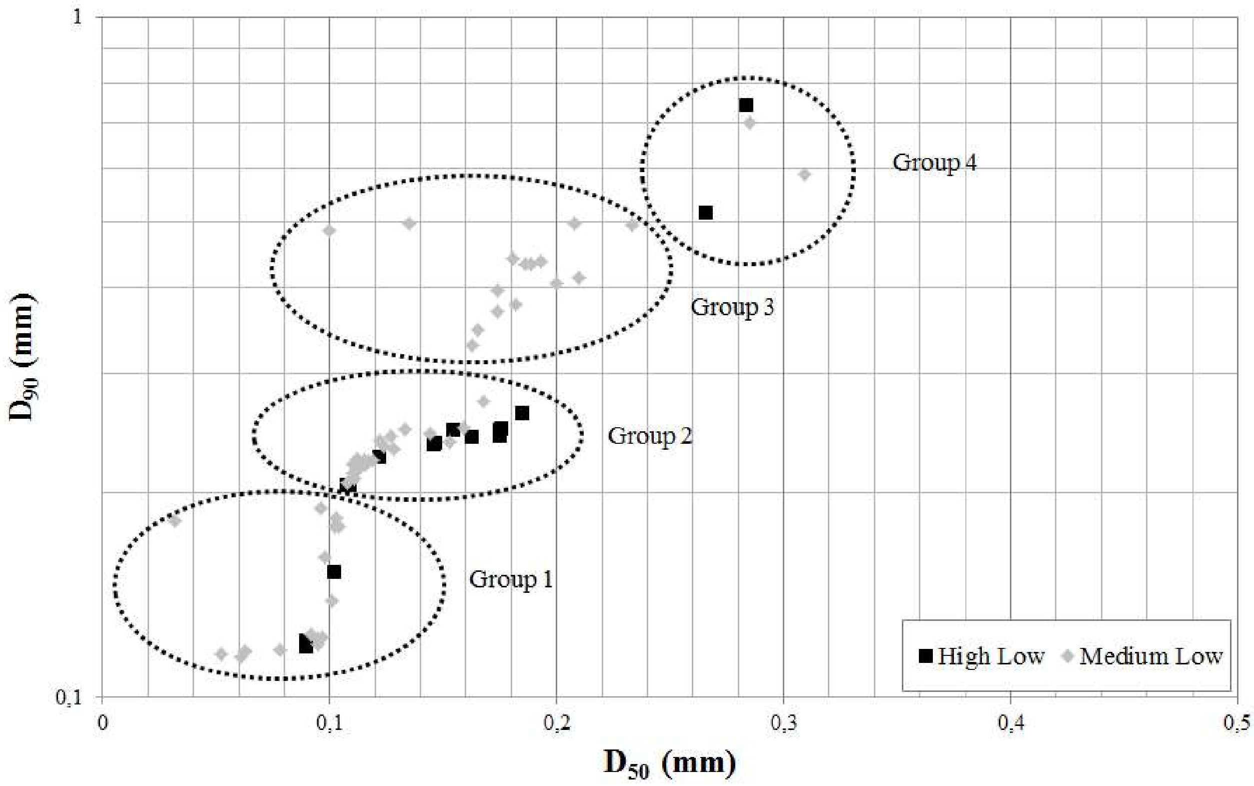

Figure 9 - Grain size relation for sample of all sub-environments.

Finer sediments were found in places of greater depth and flow velocity (thalweg) in both water level periods. Coarse and medium grains were distributed regularly to all environments. In medium water level periods, coarse and medium sand was found in shallow environments (Table 2).

The relation between critical shear stress – Ɵs – (Eq. 4) and particle Reynolds number – R_* – (Eq. 5) is presented in the Shields diagram (Shields, 1936) (Figure 10). These parameters were obtained in different sub-environments both at high and medium water levels. According to the diagram, the values obtained are in an intermediary zone, in which particles are covered by a sub-laminar layer with an initial movement at Ɵs > 0.6 at both water levels. Critical shear stress and particle Reynolds number are higher in the main channel, with no great variations in both periods analyzed.

Table 2: Textural groups identificated from the grain-size diagram (See figure 9)

Group	Sub-environment (water level)	D_{50}	D_{90}
1	Main channel (h, m/l); secondary channel (M)	Very fine sand	Fine sand
2	Bar, main & secondary channels (H, M), secondary-channel bar (H, M)	Fine sand	Fine sand
3	Main-, secondary-channel bars, secondary channel	Fine sand	Medium sand
4	Single channel (h), main-secondary-channel bars (m/l)	Medium sand	Coarse sand

H, M = high and medium water level

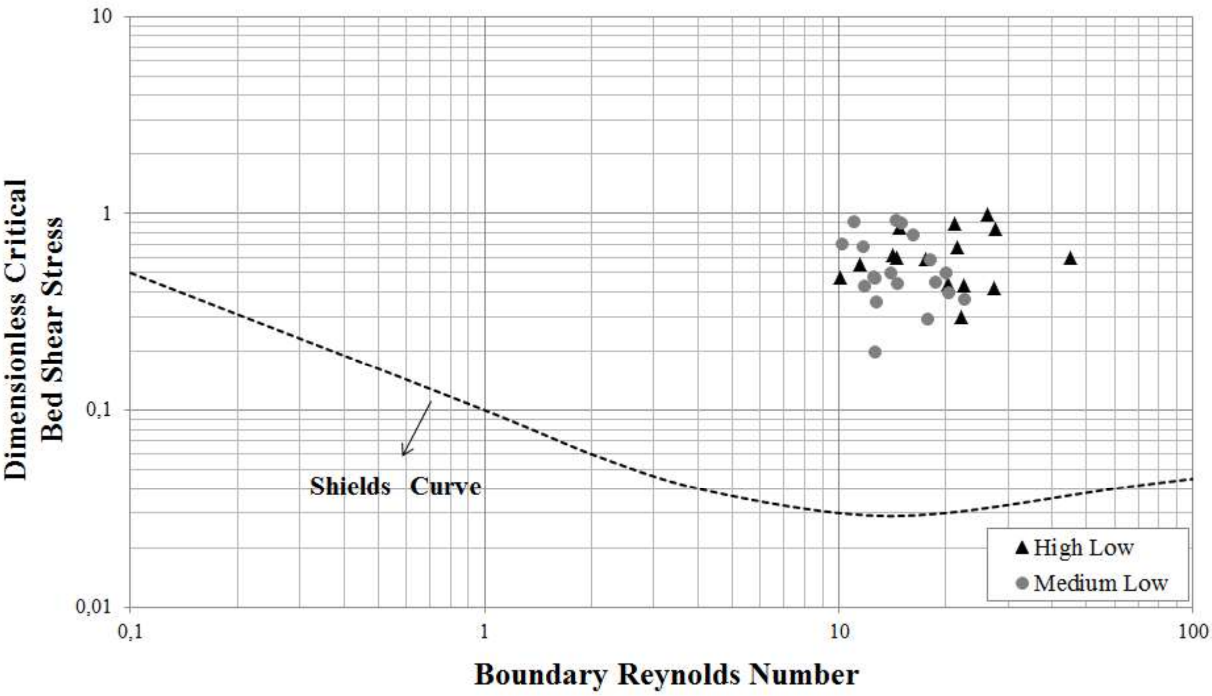

Figure 10 - Relation between critical shear stress and particle Reynolds.

5. Discussion

Earlier studies (LATRUBESSE and FRANZINELLI, 2002, 2005; SARMA, 2005, LATRUBESSE, 2008; ROZO *et al.*, 2012; NICHOLAS *et al.*, 2013; REESINK *et al.*, 2014) indicate that fluvial bars in anabranching rivers are deposited in sites with: (i) divergent secondary flows (ii) flow competence reduction (specific stream power and flow shear stress) and (iii) sand availability. These conditions were present in the study site. The flow separation caused by SRI induces the formation of a low-energy zone, which is not only very well defined by field equipment (ADCP), but it is visible on the water surface as well. Flow separation generates double flow lines with secondary flows diverging 47° to 87° from the mainstream direction, generating a "shadow zone" around the island. Velocity in this zone ranges from zero, near to maximum in the limit with normal channel flow (Figure4).

Three conditions concerning shear stress relation were found: $\tau cr:\tau 0 > 1$ near the island, $\tau cr:\tau 0 = 1$ at zone boundary with normal channel flow and $\tau cr:\tau 0 < 1$ in the channel. Bedload moves along the channel through mega-ripple and dunes with their crests perpendicular to flow direction at a τcr:τ0 < 1 condition. When transported, bedload reaches shadow zone boundary τcr:τ0 = 1, particle deposits and an attachment bar begins to be constructed. This condition also generates the bar-island channel in the τcr:τ0 > 1 sector. Unlikely the origin of other bars, as postulated by Ashworth *et al.* (2000), Sarma (2005) and Njenga *et al.* (2013) and others, attachment bars do not arise from mega bedforms such as dunes and sand waves. A rather complex process is involved though. In-transit bedforms in the study area move about 2-3 md^{-1} at medium water levels. To obtain this displacement, flow velocity has to be around 0.8 to 1.2 m s^{-1} for an average depth of 4-5 m over fine to medium sand grains (Gon, 2012).

Under this condition, bedforms normally migrate as mega-ripples and dunes with approximately straight crests perpendicular to higher velocity water flow. When an end of a bedform crosses the borderline of the low velocity zone, part of the bedform deposits while the rest continues its migration downstream. However, the crest shifts diagonally with the higher water flow line by anchor effect. In the course of time, it tends to form a shoestring sand bar grossly parallel to the island (Figure11).

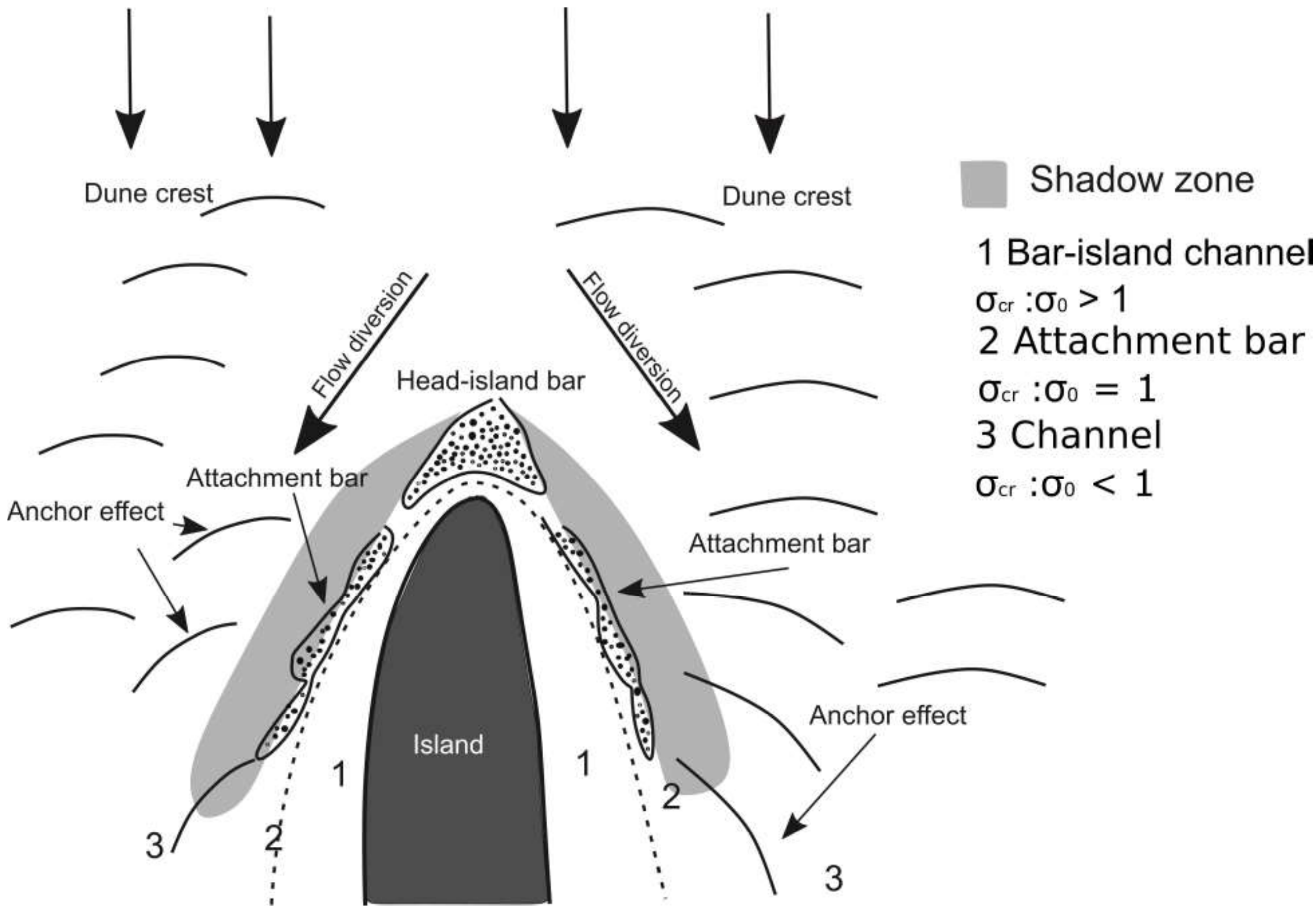

Figure 11 - Flow separation, shadow zone and attachment bar formation. Upstream (top), bedform crests migrating parallel to the higher velocity flow line. Downstream (bottom), the effect anchor in low velocity zone (U shape traced line) shifts bedform crests to grossly parallel to the island, forming attachment bars. The area between traced line and island marks the bar-island channel.

The continuous deposition of the attachment bar propagates downstream the shadow zone and, consequently, stabilizes the attached bar. Although these bars are reworked annually during floods, they also tend to increase vertically by aggradation, which improves their morphological stability. In secondary channel bars, the stability is such that allows grass vegetation to develop. This tendency reflects reports by Nicholas *et al.* (2013), which show that bar and island stability may be sensitive to hydrologic regime, especially because greater variability in flood magnitude encourages the formation of emergent bars that can be converted into stable islands by vegetation colonization.

Bedload material is predominantly sand, except for the island-bar channel where silt and clay are also found. According to the grain-size relation (Figure9), it is possible to observe that fine particles are distributed in places of higher velocity and depth (thalweg) in both water level periods. On the other hand, medium and coarse sand is distributed along both secondary channels during high water level periods and in shallow sub-environments (bar and right channel) at the medium water level.

Rocha and Souza Filho (2005) suggested that during the floods in the study reach, large bedforms (dunes and mega-ripples) composed of fine to medium sand are formed and overlain the coarse bed deposits. In medium water periods, the finer grains continue to be transported and the coarser ones remain as lag deposits. This may explain why in regions of higher flow velocity, at medium water levels, it is possible to find finer sediments (Figure9). As previously seen, medium and coarse grains are being deposited in the head of RSI (head-island bar of Drago *et al.*, 2013) and in the secondary channel, but they are not being removed.

Therefore, the formation and maintenance of attachment bars in SRI are related to the reduction of flow competence and occurrence of divergent currents. The bar-island channel keeps flow active up to its upstream closing. Vegetation cover and flow regime control the permanence of the attachment. Depending on sand availability, the attachment bar can be formed laterally and in front of the island.

The Upper Paraná River anabranching channel pattern is formed by long and narrow islands, whose formation is controlled by attachment bar processes. In this type of channel pattern, a straight and relatively narrow channel forces the formation of long islands and, therefore, the attachment bars as seen in this case. Dunne and Aalto (2013) have emphasized the importance of bar formation and maintenance of anabranching channels, especially in rivers with high sediment: water discharge such as the Ganges and the Upper Paraná. Actually, most islands that compose the studied anabranching reach are formed by processes involving attachment bars.

6. Conclusions

Results showed that attachment bars are lateral and/or head-island bars formed by flow division by the Santa Rosa Island, so this type of bar can be more expressive in anabranching rivers.

Bar deposition is caused by a zone of low flow velocity developed by flow separation. In this zone, flow can diverge 47° to 87° from original direction, and velocity reaches gradually to zero from the zone limit to the Island's bank.

Bar sedimentation occurs within shadow zone, where the flow velocity decreases at the transport particle limit. When the bed-form entrainment enters in the shadow zone deposition occurs forming the attachment bars.

Bar morphology is directly related to the Paraná River regime. During the flood, bar is usually reworked and remain stable in medium/low water level. Major modifications in bar morphology are found in the deepest places while deposition is more intensive in shallow parts.

The flow diversion generated secondary channels with different specific stream power and shear stress, being the left one that presents major values.

Bed load material is predominantly sand, except for the island-bar channel, where silt and clay also be found. According to the grain size relation, it is possible to identify that fine particles are distributed in places of higher velocity and depth (thalweg) in both water level periods. Although it seems a paradox, medium and coarse sand is distributed along in both secondary channels during the high water level period and in the shallow sub-environment (bar and right channel) in the medium water level. We attribute this fact to a lag effect that carries out finer particles, resting the large one.

Based on stream power and critical shear stress it was possible to define that erosion and transport are more active in the left channel in both periods. In the right channel, these values are lower, with much more active deposition generating a larger bar in it.

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