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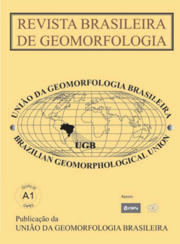

HYDROSEDIMENTOLOGY OF THE PARAGUAY RIVER IN THE CORUMBÁ FLUVIAL REACH, PANTANAL WETLAND

HIDROSSEDIMENTOLOGIA DO RIO PARAGUAI NO TRECHO FLUVIAL CORUMBÁ, PANTANAL

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Resumo:

O Pantanal é um complexo mosaico paisagístico com diferentes compartimentos hidrogeomorfológicos, com processos hidrossedimentares singulares. A compreensão desses processos atrai grande interesse no entendimento de sua dinâmica, tanto na gestão do sistema, quanto no registro geológico legado, no produto de modelos de fácies apropriados. Dados hidrossedimentares no Pantanal ainda são escassos, apesar dos esforços das agências governamentais para a melhoria e ampliação da coleta dos mesmos na Bacia do Alto Paraguai. O presente estudo tem como objetivo ampliar a compreensão dos processos hidrossedimentares existentes em um compartimento hidro-geomorfológico da planície fluvial do rio Paraguai, no trecho Corumbá. Levantamentos hidrossedimentares foram realizados no rio Paraguai e seus afluentes. Esses levantamentos ajudaram a caracterizar a dinâmica hidrossedimentar ao considerar os processos sedimentares que podem estar atuando nesse trecho. O rio Paraguai apresenta interação complexa com sua planície, que funciona como reservatório, retendo a água da enchente e causando distúrbios nas descargas dos rios. Levantamentos batimétricos mostraram que o canal do rio Paraguai apresenta formas longitudinais de barras compostas construídas pela superposição de ondulações. O efeito de remanso, possivelmente relacionado tanto com o regime hidrológico quanto com as características geomorfológicas da área, foi detectado por meio da análise da curva-chave das estações fluviométricas. O fator hidrológico desse efeito é produzido pelo pulso de cheia defasado do Pantanal e o fator geomorfológico pelos gargalos hidráulicos do maciço do Urucum e Bodoquena. Ambos os fatores possivelmente ocorrem simultaneamente. As características hidrogeomorfológicas (morfologia, competência fluvial e potência de canal) do rio Paraguai denotam a necessidade de elaboração de modelos mais adequados ao contexto pantaneiro.

Abstract:

The Pantanal wetland is a complex landscape with distinct hydrogeomorphic compartments, with singular hydrosedimentary processes. Examining these processes draws great interest in understanding Pantanal dynamics for both the management of the system and the geological record predicted by facies models. Hydrosedimentary data in the Pantanal remain scarce, in spite of government efforts to improve and increase data collection in the Upper Paraguay Basin. This study aims to enhance the understanding of active hydrosedimentary processes in the Pantanal Paraguay trunk-river system in the Corumbá reach. Hydrosedimentary surveys were accomplished in the main channel and tributaries of the Paraguay River. These surveys helped characterize the hydrosedimentary dynamics to consider the active sedimentary processes in this reach. The Paraguay River interacts complexly with its floodplain, which functions as a reservoir retaining flood water and disturbing river discharge. Bathymetric surveying showed that Paraguay River channel has longitudinal compound bar bedforms built by superimposition of ripples. The backwater effect, possibly related with both hydrological regime and geomorphological characteristics of the area, was detected by means of rating-curve analysis of the gauge stations. This effect is hydrologically produced by the out-of-phase flood pulse of the Pantanal and geomorphically driven by the hydraulic bottleneck of the Urucum and Bodoquena massifs. Both factors possibly occur simultaneously. The hydrogeomorphic characteristics (morphology, river competence, and stream power) of the Paraguay River denote that the elaboration of models more appropriate to the Pantanal context is needed.

1. Introduction

The Paraguay River is one of the main rivers of the Rio de la Plata drainage basin, whose area surpasses 3 million km² (REBOUÇAS *et al.*, 2002). The Paraguay River Basin covers about 1.095 million km² distributed in Brazil, Bolivia, Paraguay, and Argentina (ANA/GEF/PNUMA/OEA, 2003). The Upper Paraguay River Basin (UPRB) is the area drained by the river from its headwaters to the confluence of the Apa River tributary and encompasses the Pantanal wetland, the world's largest tropical wetland (ALHO *et al.*, 1988; JUNK *et al.*, 2006). The Pantanal is a vast expanse of seasonally flooded river plains, in which the Paraguay River is the trunk-river of a complex depositional tract system of the waters entering from the surrounding plateaus.

The Pantanal wetland is located in an active Quaternary sedimentary basin in which the Paraguay trunk-river floodplains interact with megafans, interfan floodplains, and alluvial floodplains (ASSINE *et al.*, 2015a). Active sedimentation and the presence of a fluvial distributive drainage system make the Pantanal a large natural laboratory to study the hydrosedimentary dynamics of wetland systems. However, hydraulic and sedimentary research in the Pantanal rivers are still scarce, with most studies using low-resolution mathematical models due to limited hydrological and sedimentary data for the entire basin (COLLISCHONN *et al.*, 2007; PAZ *et al.*, 2010; BRAVO *et al.*, 2012; PAZ *et al.*, 2014; BRAVO *et al.*, 2013).

Channel geomorphic behaviors throughout the world are frequently examined by field-based fluvial surveys (e.g. HARVEY, 2001; SURIAN; RINALDI, 2003; RINALDI *et al.*, 2009; CZAPIGA *et al.*, 2015) and by sophisticated hydrodynamic models (e.g. HEC, 1976; BELL; SUTHERLAND, 1983; OLSEN, 2003; ISIS, 2006; LANGENDOEN, 2008; DUAN; JULIEN, 2010; GUPTA *et al.*, 2014). In this scientific scenario, this paper introduces novel information concerning channel hydrosedimentary dynamics and river-floodplain interaction of the Paraguay River in a reach crossing the Pantanal wetland, from the latitude of the Vermelha Lake to the confluence of the Miranda River (Figure 1).

1.1 Regional settings

The Pantanal is a large seasonally flooded area dominated by alluvial sedimentation due to accommodation space generated by tectonic subsidence (ASSINE; SOARES, 2004). The Pantanal is a tectonically active sedimentary basin, which origin is associated with forebulge reactivation during the last Andean compression event (HORTON; DECELLES, 1997; USSAMI *et al.*, 1999; CHASE *et al.*, 2009). The sedimentary infill of the Pantanal Basin is made by deposits of a large depositional tract dominated by alluvial sedimentation (ASSINE *et al.*, 2005; ASSINE *et al.*, 2015a,b,c). The Paraguay River is the trunk-river that collects water from tributary interfan plains and fluvial fans of which the Taquari megafan is well known (ASSINE, 2005; ZANI, 2008; ZANI *et al.*, 2009; ZANI *et al.*, 2012).

The exorheic Pantanal basin and the Paraguay River transfers water and sediment to the Chaco Basin through an outlet located south of the confluence with the Miranda River. However, most of the fluvial sediment load carried to the basin is deposited within the Pantanal, and less than 10% of the load is transported downstream by the Paraguay River (ASSINE *et al.*, 2015a).

The Paraguay River has a total length of 2,621 km, from its headwaters in the Parecis plateau to its confluence with the Paraná River near the city of Corrientes, Argentina (INNOCENCIO, 1988). Four very different geomorphic zones with distinct channel patterns and depositional processes were recognized along the length of the river (ALMEIDA, 1945). Within the Pantanal, the Paraguay River was divided into five reaches based on the channel and floodplain morphology (ASSINE *et al.*, 2015a,b,c – Figure 1).

From the latitude of the Lake Vermelha to the confluence of the Miranda River, in a fluvial zone referred as Corumbá reach, the Paraguay River is marked by an active meander belt that crosses a large floodplain with relict geomorphic features created by avulsion processes and changing fluvial discharge that occurred since the late Pleistocene (MACEDO *et al.*, 2014; MACEDO, 2017). The present climate was established during the late Holocene and is more humid than previous Holocene times (McGLUE *et al.*, 2012).

The Pantanal wetland is characterized by the “AW” Köppen-Geiger climate type, defined as tropical wet and dry climate or tropical savanna climate, with mean annual temperatures of approximately 25 ºC. This climate has two well defined seasons, wet summer and dry winter. Precipitation is not uniform across the UPRB, varying from 800 mm near the Brazil-Bolivia border to 2,000 mm in the headwaters of the Paraguay River (CLARKE *et al.*, 2003). Most annual rainfall occurs from November to March, whereas April to September is the driest period (MARENGO *et al.*, 2015).

Fluvial discharge increases downstream in the Corumbá reach, as tributaries (Tamengo, Paraguay-Mirim, Taquari River, Negro, and Abobral) and runoff waters enter the Paraguay River. However, there is no correlation between precipitation and fluvial discharge throughout the year (ASSINE *et al.*, 2015c). During the flood season, this system is affected by water loss to the floodplain, which retains water in several small lakes, and by backwater effect due to hydraulic bottlenecks that decrease fluvial discharge downstream (ASSINE *et al.*, 2015c). The peak flood pulse arrival from north to south is delayed due to both irregular rain distribution (magnitude and frequency) and a low slope floodplain (JUNK *et al.*, 1989). The flood pulse takes approximately four months to cross the entire Pantanal, from the Paraguay River inlet to the Pantanal to its outlet in the southernmost area of Nabileque (KUERTEN, 2010; ASSINE *et al.*, 2015a).

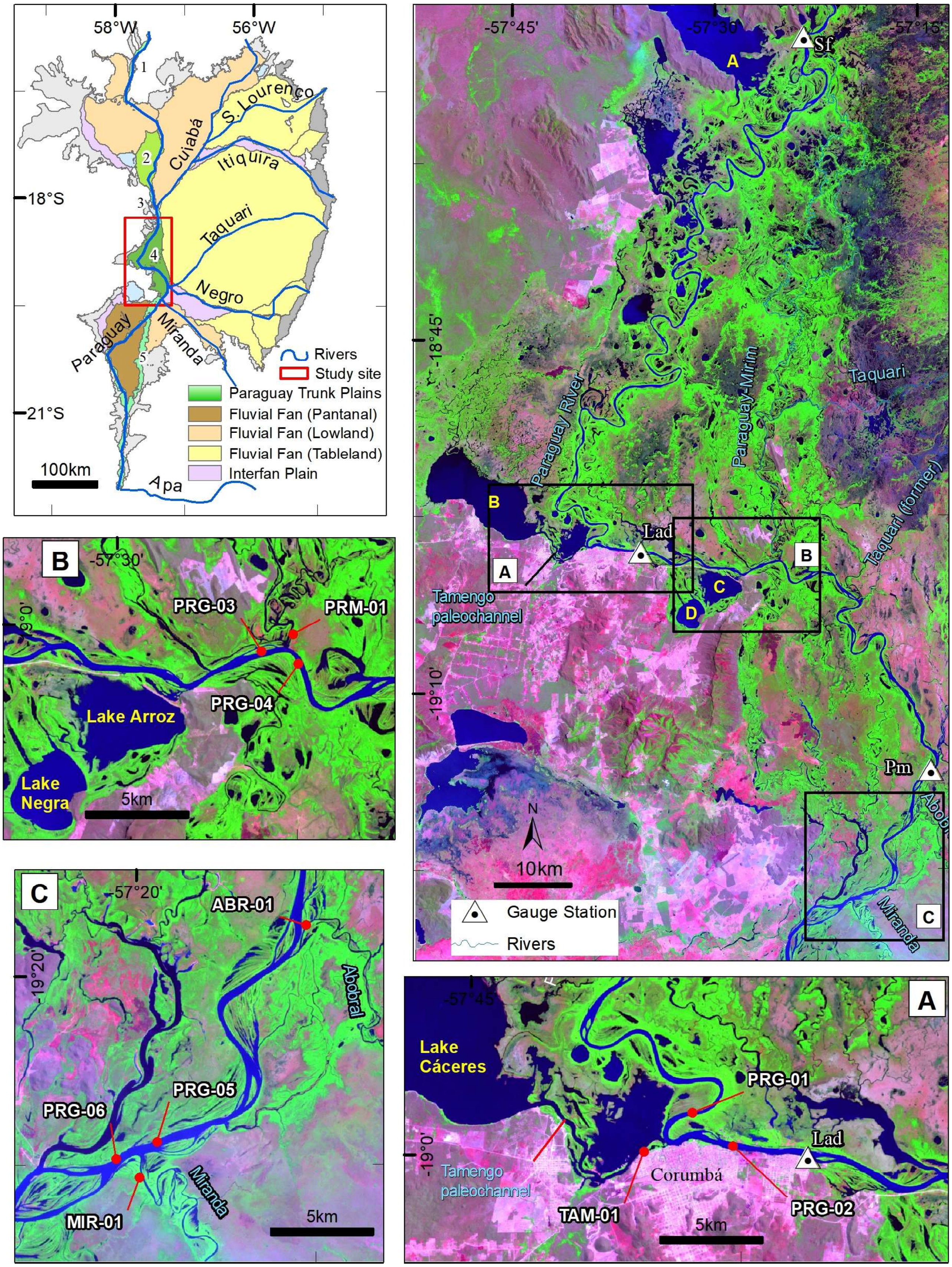

Figure 1 – Pantanal tract system and location map of the study area. Numbers 1 to 5 are Paraguay Trunk Plains: 1) Cáceres; 2) Canzi; 3) Amolar; 4) Corumbá; 5) Nabileque (after Assine et al., 2015a). Lakes: A=Vermelha; B=Cáceres; C=Arroz; D=Negra. Gauge stations: Sf=São Francisco; Lad=Ladário; Pm=Porto da Manga. Landsat 5 TM Image (R7G4B3).

2. Methods and Materials

This study was based on a suite of fieldwork analysis, hydrological data from the National Water Agency of Brazil (ANA), and mathematical equations to calculate Paraguay River hydraulic parameters. Fieldwork was conducted in the Paraguay River and its tributaries to collect hydraulic and sedimentary data.

Bathymetric surveys were carried out with a Furuno™ echosounder in order to model the Paraguay River bedform size and displacement by longitudinal profiles. A random point mesh was surveyed in an area of approximately 50,000 m² and interpolated by the kriging method on ArcGIS 10 (ESRI, 2010) to generate the channel bottom 3D model.

An acoustic Doppler current profiler (RiverRay™ ADCP) was used to survey six river discharge cross--sections in the Paraguay River and four in the tributaries (Figure 1). Both Paraguay River flow and tributary regime flow were characterized using the data collected. Five bedload samples spaced 50 m apart were collected only in the PRG-02 profile. The Paraguay River competence, capacity, and stream power were calculated for this cross-section.

The suspended load samples were collected with a continuous vertical bottle sampler and were analyzed by a Hach DR2800™ spectrophotometer, which provided results in milligrams per liter of water. The dissolved load samples were collected with the same method of the suspended load. The dissolved sediment concentration was established through the electrical conductivity of the sample with a Multi Probe System (YSI 556 MS ™). We did not ascertain the specific components in the dissolved solids, so the values presented are of the total dissolved solids. The surface sediment samples were collected by a Van Veen jaw sampler, and the particle size analysis was accomplished by sieving. The suspended and dissolved solid discharges were calculated by multiplying the flow rate by the respective sediment concentration and converting units. For the bedload transport calculation, the mathematical model of Van Rijn (1984) was utilized. This task was accomplished with an application developed by Macedo *et al.* (2017), in which the Van Rijn equation was compiled in a Microsoft Excel™ spreadsheet.

Hydrological data from the São Francisco, Ladário, and Porto da Manga gauge stations were downloaded from the ANA webpage (www.hidroweb.ana.gov.br) (ANA, 2012). Discharge and stage (water level) of the Paraguay River were used to build rating-curves for three gauge stations found in the studied reach. The rating-curves were used to calculate the Paraguay River discharge at each gauge station from 2006 to 2011. Cross-section data of São Francisco and Porto da Manga stations were also used to determine the bankfull discharge.

Calculation of hydraulic parameters was carried out to characterize the flow regime of the Paraguay River main channel and tributaries. The distinction between laminar and turbulent flow was determined by Reynolds number (Re), which is a dimensionless coefficient expressed by the equation [Eq.1], $Re=\frac{VR\rho}{\mu}$ where V is the mean flow velocity in ms^{-1}; R is the hydraulic radius in meters; ρ is the density of fluid in $kg(m^3)$-1 which is water temperature dependent (0,000016t3 – 0,006045t2 + 0,024768t + 999,954093); and μ is the dynamic viscosity of fluid in m^2 s-1, which is equal to the product of the density of the fluid and the kinematic viscosity of the fluid (n), which is also water temperature dependent (n = [-0,000138t3 + 0,014617t2 - 0,675197t + 19,106788] x 10-7). Although there are no laminar flows in rivers, this hydraulic parameter (Reynolds number) is important to evaluate the degree of turbulence of a stream.

We also computed the Froude number, which is expressed by the equation $F=\frac{V}{(g.h)^{1/2}}$ [Eq.2], in which V is the mean flow velocity in ms^{-1}; g is the gravitational acceleration in $m(s^2)^{-1}$; and h is the mean depth in meters. This parameter indicates whether the flow regime is critical, subcritical or supercritical.

The stream power (Ω) and specific stream power (ω) were calculated for the cross-section PRG-02 where bedload particle size was measured. These parameters represent the energy lost by the channel due to the flow regime, and they are expressed by the equations $\Omega = \gamma.Q.S$ [Eq.3] and $\omega = \Omega/L$ [Eq.4], in which γ is the specific weight of water in $N(m^3)^{-1}$; Q is the water discharge in $m^3\ s^{-1}$; S is the water surface slope in mm^{-1}; L is the channel width in meters; Ω is the stream power in $W\ m^{-1}$; and ω is the specific stream power in $W(m^2)^{-1}$.

The water surface slope was determined by deduction of other equations. Deducing from the flow velocity equation, we determined that slope is dependent on flow velocity, hydraulic radius, and the Manning roughness coefficient, according to the equation: $V=\frac{R^{2/3}S^{1/2}}{n} \rightarrow S = \sqrt[1/2]{\frac{nV}{R^{2/3}}} \rightarrow \boldsymbol{S} = \left(\frac{\boldsymbol{nV}}{\boldsymbol{R^{2/3}}}\right)^{2}$ [Eq.5], in which *V* is the mean flow velocity in ms^{-1}; *n* is the Manning roughness coefficient; *R* is the hydraulic radius in meters; and *S* is the water surface slope in mm^{-1}. The Manning roughness coefficient is related to the Chezy coefficient: $n = \frac{R^{1/6}}{\left(\frac{C}{1,5}\right)}$ [Eq.6], in which C is the Chezy coefficient defined by equation $C = 8g^{1/2} \times 2 \log\left(\frac{14,84R}{3D_{90}}\right)$ [Eq.7], in which g is the gravitational acceleration in m $(s^2)^{-1}$; and D_{90} is the characteristic particle size in meters at which 90% of all the grains in the sample is finer. Thus, the water surface slope is equal to equation 8.

$$S = \frac{\left(\frac{2,25V^2R^{1/3}}{8g\left[2\log\left(\frac{14,84R}{3D_{90}}\right)\right]^2}\right)}{R^{4/3}} \quad \text{[Eq.8]}$$

Hence, the water surface slope was dependent on the hydraulic radius, gravitational acceleration, D_{90} particle size, and mean flow velocity.

3. Results

3.1 Flow regime, slope and stream power

The flow velocities of all surveyed sections are shown in Figure 2 and Table 1. The discharge values show that the Paraguay River received water from its tributaries and lost water to its floodplain (Table 1). The Tamengo paleochannel had low contribution to the Paraguay River. This input can be observed by a small increase in discharge in the section PRG-02 compared with cross-section PRG-01 (20 $m^3 s^{-1}$).

The Paraguay River discharge decreased in cross-section PRG-03 (40 $m^3 s^{-1}$) due to losses of water through small streams (locally known as *corixos*) and shallow incised channels (locally known as *vazantes*) towards large lakes on its right margin (Arroz and Negra). The river recovered its former discharge in cross-section PRG-04, after receiving the inflow from the Paraguay-Mirim River (PRM-01).

Negative discharge in the Abobral River (ABR-01) was recorded due to inflow of the Paraguay River main channel, which blocked outflow from the Abobral. Despite this small water loss to the Abobral River, the Paraguay River experienced increased discharge in section PRG-05 (80 $m^3 s^{-1}$) due to the discharge of both the Negro River and an abandoned channel of the Taquari River. This increase may also be explained by the Paraguay-Mirim River inflow. In section PRG-06, the Paraguay River increased 190 $m^3 s^{-1}$ after the confluence with the Miranda River (MIR-01).

The Reynolds number calculated for all surveyed sections (Table 1) was >2,500, indicating turbulent flow regime in the Paraguay River and tributaries. The Froude numbers were <1, indicating subcritical flow in all surveyed rivers (Table 1).

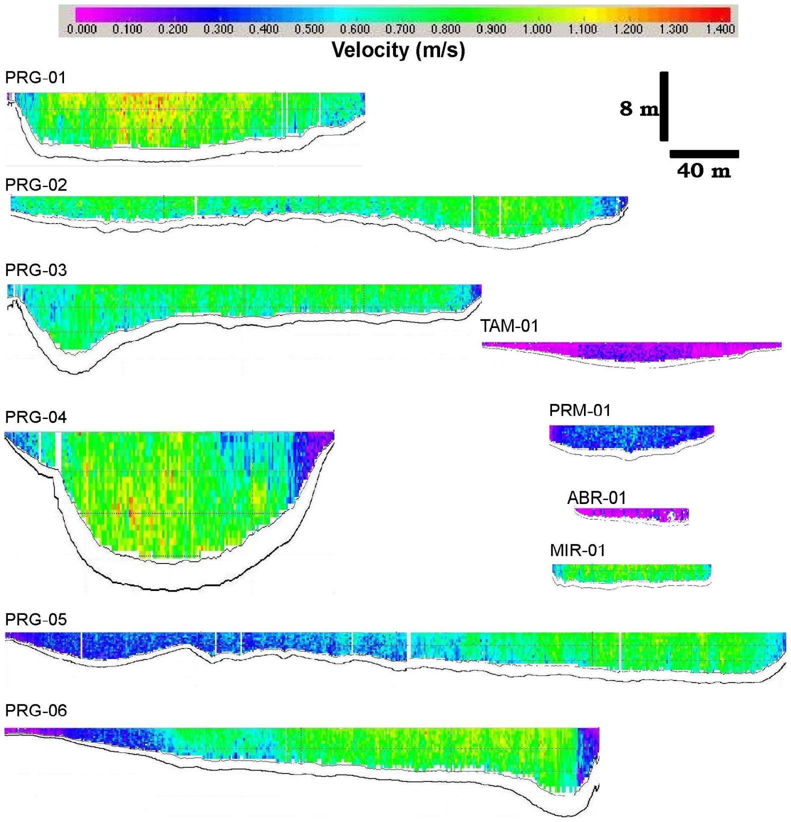

Figure 2 – Surveyed sections using ADCP and showing the flow velocity and channel geometry.

The surface water slope was 3x10^{-5} m m^{-1} in section PRG-02, calculated solely for this unique section where bedload samples were collected. The stream power and specific stream power of the Paraguay River were calculated as 312.955 W m^{-1} and 0.835 W m^{-2}, respectively. In this section, the Chezy and Manning coefficients were 89.736 and 0.021, respectively.

Table 1: Hydraulic parameters of the surveyed sections. Surveyed sections location in Figure 1.

Section	Hydr. ration (m)	Mean depth (m)	Mean velocity (m s^{-1})	Disch. (m^3 s^{-1})	Water temp. (°C)	Rey	F
PRG-01	6.37	6.32	0.791	1110	30.80	6.17x10^9	0.100
TAM-01	2.23	2.18	0.016	6.52	31.25	4.41x10^7	0.003
PRG-02	4.19	4.19	0.672	1130	30.73	3.44x10^9	0.105
PRG-03	6.00	6.00	0.637	1090	30.80	4.68x10^9	0.083
PRM-01	3.17	3.19	0.302	106	30.75	1.17x10^9	0.054
PRG-04	12.59	11.90	0.430	1130	30.80	6.63x10^9	0.040
ABR-01	1.84	1.,98	0.035	-4.80	32.51	8.17x10^7	0.008
PRG-05	4.78	4.91	0.537	1210	30.77	3.14x10^9	0.077
MIR-01	2.72	2.79	0.738	193	30.08	2.42x10^9	0.141
PRG-06	5.93	5.95	0.653	1400	30.50	4.71x10^9	0.085

3.2 Hydrosedimentary regime of the Paraguay River floodplain and hydraulic geometry of the channel

The São Francisco and Porto da Manga gauge station rating-curves showed that discharge and water level were directly related. However, the Ladário station (Figure 3) discharge deflects downwards when the river stage reaches 3.50 m, reaching a maximum discharge of 1,200 m^3 s^{-1}. When the river reaches this stage, the discharge decreases up to ~800 m^3 s^{-1} at a river stage of 6.10 m (Figure 3).

A one-month delayed flood pulse occurs between São Francisco and Porto da Manga (Figure 4). A significant decrease in water discharge is observed between São Francisco and Ladário during the flood season, due to water loss of the Paraguay River to its floodplain. The discharge at São Francisco and Ladário gauge stations are similar from October to December, representing the dry season when the water is confined into its main channel. However, a noticeable difference arises between March and August. In May, the Paraguay River discharge reaches around 2,700 m^3 s^{-1} at the São Francisco gauge station, while at the Ladário gauge station the discharge is just 1,104 m^3 s^{1}.

Bankfull discharge rates of 2,245 m^3 s^{-1} and 2,093 m^3 s^{-1} were calculated, respectively, for São Francisco and Porto da Manga gauge stations (Figure 5). The highest mean annual discharge in the studied reach was measured at Porto da Manga gauge station with ~1,715 m^3 s^{-1}. Between April and June, however, the São Francisco discharge > 2,700 m^{3}s^{-1} due to brief floods from March to May surpassed that of Porto da Manga (Figure 4). The minimum discharge recorded at São Francisco between 1995 and 2011 was 815 m^3 s^{-1} at a stage of 3.82 m, and the maximum discharge was 4,089 m^3 s^{-1} at a stage of 8.53 m (Figure 5A). In the Porto da Manga station, the minimum discharge recorded was 953 m^3 s^{-1} (at a stage of 2.86 m), and the maximum discharge was 2,604 m^3 s^{-1} at a stage of 7.84 m (Figure 5B).

The hydraulic geometry of three gauge stations on the studied reach are shown in Figure 6.

3.3 Bedform and sediment transport

Bedforms were recognized in a straight reach near the PRG-02 section (Figure 7). Megaripples (ripples > 0.50 m but < 1 m) were the main bedform, but the displacement of these bedforms could not be measured due to the small dimensions and irregular form (Figure 7). Alternatively, a mathematical model of bedload transport was used to show a bedload transport rate of 204.0 ton day^{-1}. Since the flow regime of the Paraguay River is subcritical turbulent, the cross-section PRG-02 showed competence to transport fine sand. Hydrosedimentary surveys at the same cross-section revealed suspended solid discharge of 1,273.6 ton day^{-1} and dissolved solid discharge of 3,142.7 ton day^{-1}, which resulted in 4,620.2 ton day^{-1} of total sediment transport, showing a river dominated by both dissolved and suspended load.

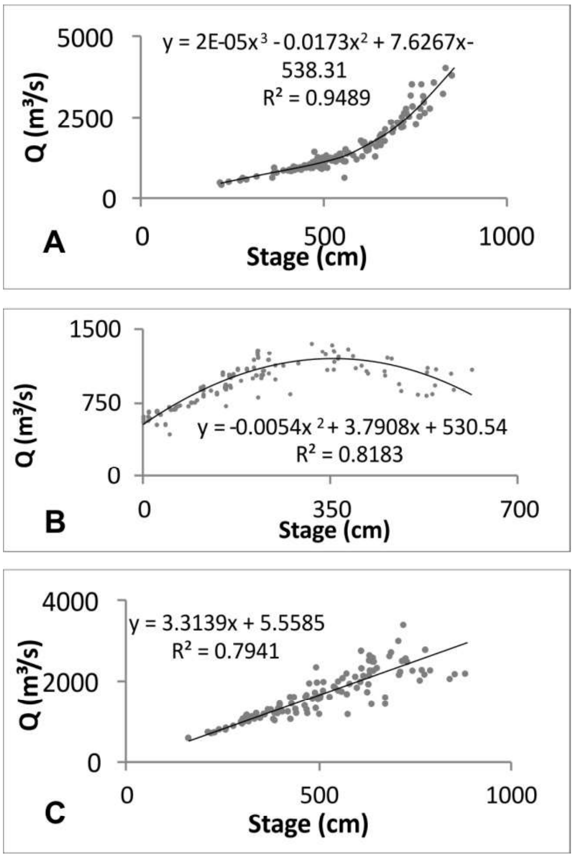

Figure 3 – Rating-curve of the Paraguay River in the studied reach. A) São Francisco; B) Ladário; C) Porto da Manga (Gauge stations location on Figure 1)

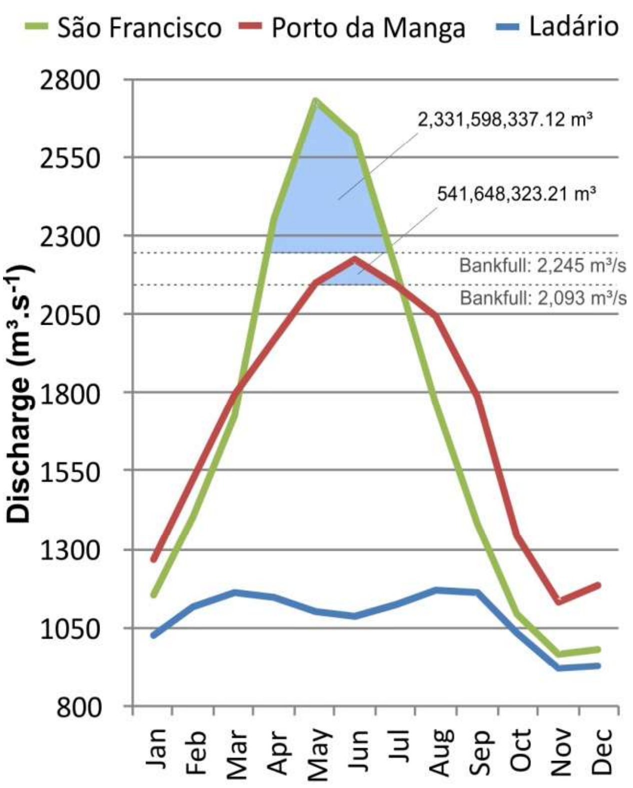

Figure 4 – Mean monthly water discharge of the Paraguay River on studied reach from 2006-2011 (Gauge stations location on Figure 1). The blue area above the bankfull discharge corresponds to the amount of water which overflow onto floodplain.

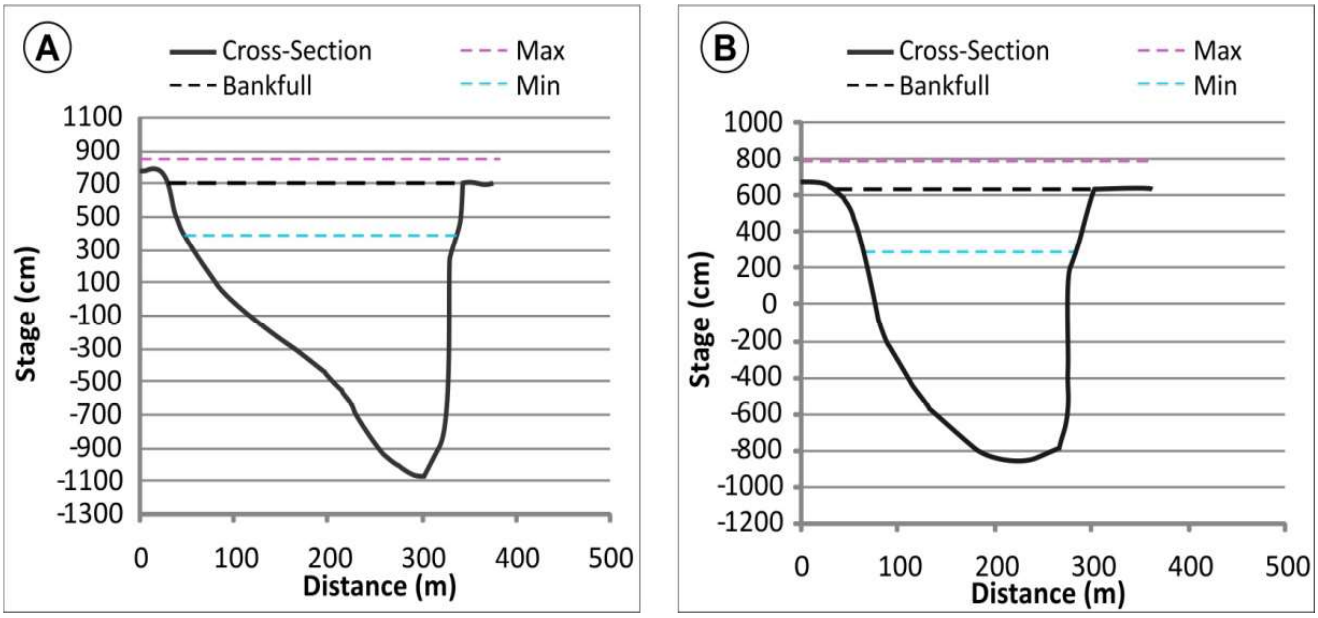

Figure 5 – Cross-section of São Francisco (A) and Porto da Manga (B) gauge stations. Minimum and maximum stage calculated between 1995 and 2011. Source: ANA (2012).

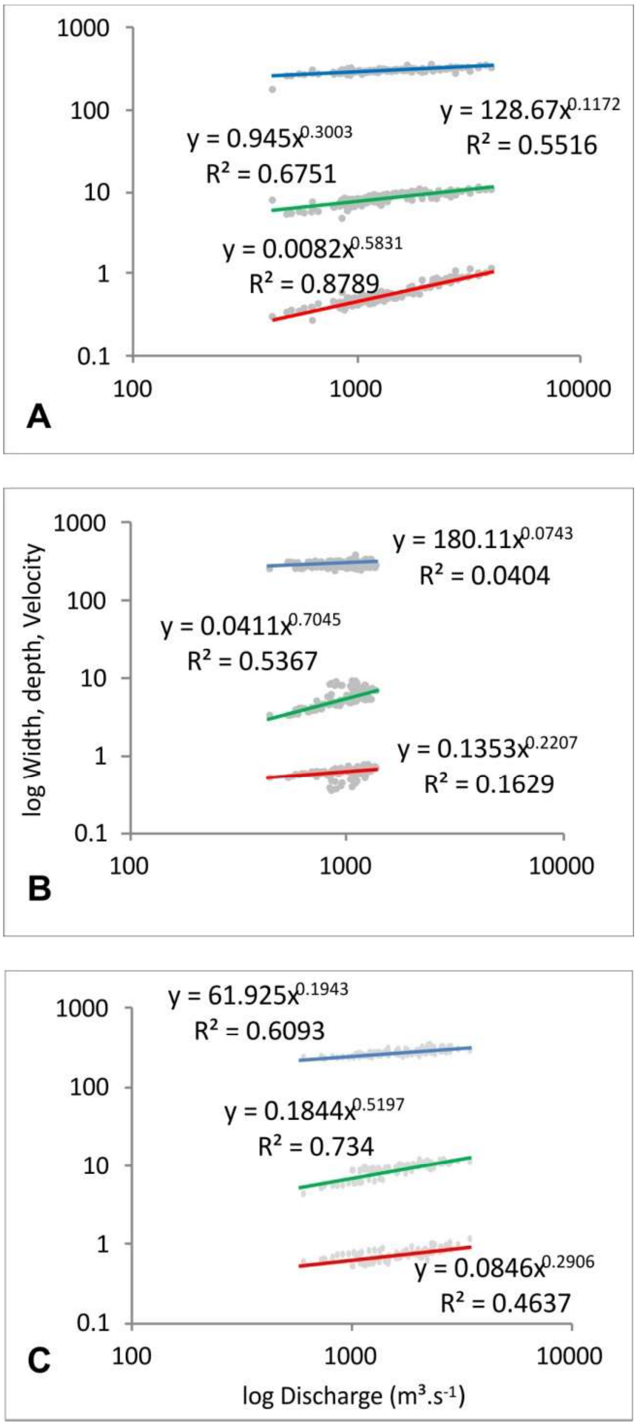

Figure 6 - Hydraulic geometry of the gauge stations found in studied reach. A) São Francisco; B) Ladário; C) Porto da Manga. Blue line= width; green line= depth; red line= velocity.

Longitudinal bar with ~ 200 m width, 1,400 m length, and ~ 4 m height was recorded in the cross-section PRG-02 (Figure 7). The texture of the bedload, which decreased in size from the right toward the left bank, varied according to the flow speed (Figure 2 – PRG-02; Figure 8).

The suspended and dissolved sediment concentration, discharge data, channel geometry, and suspended and dissolved sediment transport of cross-section PRG-02 are shown in Table 2. The bedload transport was calculated for each part of cross-section PRG-02 and is presented in Table 3.

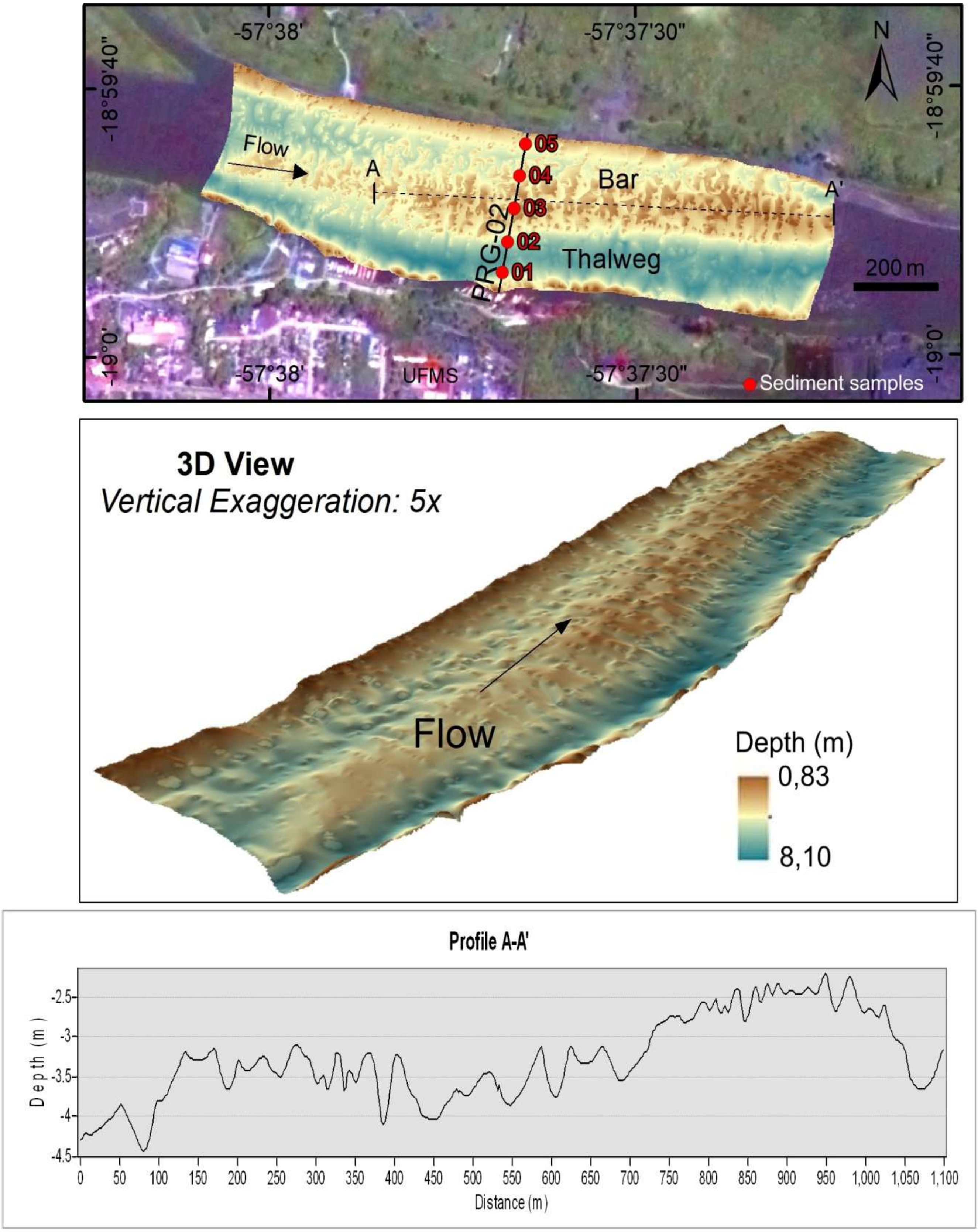

Figure 7 – Bedforms mapped into Paraguay River near the Ladário gauge station. Landsat TM5 image fused with the CBERS-HRC image. The points surveyed were interpolated by kriging method using ArcGIS 10 (ESRI, 2010).

The channel thalweg was displaced to the right bank, with a submerged longitudinal bar on the left bank. The ripples were more common on the bar in formation, which indicates that the bar was built by superimposition of the bedforms. These bedforms were small with ~ 0.60 m height and ~ 30 m length (H/L ratio = 1:50). The H/L ratio of the mapped bedforms were well beyond those of Ashley (1990). According to the interpolation (Figure 7), the bedforms can be classified as two-dimensional forms (Ashley, 1990).

4. Discussion

The studied channels were asymmetric with sinuous thalweg in the straight reaches. The section PRG-05 had a wide low-velocity area on the left bank (Figure 2) where the Paraguay River waters are dammed by the Miranda River flow. The Paraguay River flow is instead concentrated on the right bank (Figure 2 – PRG-05), which provokes asymmetric channel geometry (Figure 2 – PRG-06).

Table 2: Concentration and solid discharge of suspended (Css and Qss) and dissolved load (Cds and Qds), and channel geometry and water discharge at section PRG-02. See Figure 7 for sample locations.

Sample Nº	Css (mg l^{-1})	cds (mg l^{-1})	disch (m^3 s^{-1})	Width (m)	Mean Depth (m)	Qss (t day^{-1})	QDS (t day^{-1})
01	12	32	404.06	105.00	5.00	418.929	1117.145
02	14	30	215.56	65.00	4.26	260.741	558.731
03	12	32	137.22	60.00	3.22	142.270	383.332
04	13	32	177.78	60.00	4.11	199.682	479.010
05	13	32	224.33	78.81	3.80	251.967	604.435
Total			1130.22	368.81		1273.589	3142.653
Total						**4416.242**	

Table 3: Bedload transport of section PRG-02. See Figure 8 for granulometric curve.

Sample	Wetted area (m^2)	Wetted perimeter (m)	Mean velocity (m s^{-1})	D90 (mm)	D50 (mm)	Qbl (t day^{-1})
01	550.689	113.095	0.679	0.2263	0.1613	76.192
02	274.792	73.849	0.660	0.1767	0.1485	39.685
03	192.281	67.095	0.633	0.1715	0.1438	32.340
04	243.909	68.476	0.653	0.1714	0.1371	30.460
05	320.969	89.418	0.651	0.1549	0.0943	25.297
Total	1582.640	411.933				203.974

The Pantanal floodplain experiences a seasonal flood regime with a flood pulse (or flood wave) that peaks asynchronously in different areas of the wetland. (JUNK *et al.*, 1989). The Paraguay River collects water and sediment from fluvial fans and interfan systems (ASSINE *et al.*, 2015b). The Paraguay River floodplain configuration interferes with river discharge, since the floodplain works as a reservoir, storing a large amount of water that gradually returns to the channel during the dry season.

The Paraguay River experiences constant water exchange with the lakes on the floodplain (lakes Cáceres, Arroz, and Negra), where the Paraguay River loses water to these water bodies during a specific period. In the flood season, flow inversion in the Tamengo paleochannel may occur, when the Paraguay River feeds Lake Cáceres. The same phenomenon may be true for lakes Arroz and Negra.

The Paraguay River hydrological pattern at the Ladário gauge station is unique due to its lower discharge compared to other gauge stations, particularly São Francisco. This disparity is higher from March to September, with the greatest difference occurring in June.

Due to its downstream location, the Porto da Manga gauge station receives inflow from the Paraguay-Mirim and Negro rivers in addition to the former Taquari channels. This accounts for the disparity relative to Ladário in the dry season (October to March) but does not explain the difference found in the flood season (April to September), which may be the result of the floodplain reservoir effect. When the Paraguay River overflows to the floodplain, the water is stored and slowly released to the river by both hortonian and base flow. Abandoned meander belts on the Paraguay River floodplain confine a major volume of overflowed water during the flood season, channeling the water to the Paraguay River downstream of the Ladário gauge station (MACEDO, 2013; MACEDO *et al.*, 2014) so that the increased discharge is only recorded at Porto da Manga. In addition, both the Taquari and Negro rivers drain substantial flow towards the Paraguay River during the flood season, contributing significantly to the difference of discharge rates between Ladário and Porto da Manga. This difference is better explained by a backwater effect near the city of Corumbá. This effect is observed on the Ladário gauge station rating curve (Figure 3B). The backwater effect can be generated by hydrological and geological factors. The fluvial inflows of the left margin of the Paraguay River (Taquari, Negro and Miranda rivers) reach the Porto da Manga region earlier than the flood pulse caused by the northern Pantanal inflows (Cuiabá, Jauru, and Sepotuba rivers). When the northern flood pulse reaches the cities of Corumbá and Ladário, the water level is already higher than baseflow due to the eastern flood pulse, causing the Paraguay River to dam waters at Ladário. Additionally, the Urucum bottleneck formed by the mountains of the crystalline basement rock present in this reach of the Paraguay River increases the backwater effect (ASSINE *et al.* 2015a,b). The backwater effect extends from Ladário to Porto da Manga, which lacks an inverted rating curve but has scattered data (Figure 3C). Other authors have noticed the backwater effect in this Paraguay River reach (COLLISCHONN *et al.*, 2005). More detailed studies about the hydrology and geomorphology may confirm this idea, which seems sufficiently plausible due to the geomorphological and hydrological characteristics of the area.

4.1 Estimation of overbank deposits on the Paraguay floodplain

The waters of the Paraguay River overflow to the floodplain when discharge exceeds the bankfull stage, carrying the sedimentary load (suspended and dissolved) as shown in Figure 4. When the Paraguay River discharge exceeds 2,245 m^3 s^{-1} at the São Francisco gauge station, waters overflow the levees and inundate the floodplain, which will retain and return the waters to the river by sheet flow. This hydrological behavior is similar to a reservoir effect, which is shown by the discharge difference between the São Francisco and Ladário gauge stations (Figure 4).

More than 2 billion cubic meters of water overflow to the floodplain, carrying more than 29 thousand tons of sediment (value calculated for estimated mean concentration of 12.68 mg L^{-1}, according to HidroWeb – ANA, 2012) that are deposited by vertical accretion on the floodplain near the São Francisco gauge station from April to July. The same phenomenon occurs at Porto da Manga gauge station, where more than 500 million cubic meters of water carrying more than 8 thousand tons of sediments (considering a mean concentration of 15.64 mg L^{-1}) overflow to the floodplain.

These quantities may represent between 0.006-0.01 mm of mean sedimentation per year, based on the overflow area. These values can be better estimated by hydrologic models which calculate the flood surface (e.g. PAZ *et al.*, 2010; RICCARDI, 2001; GARCIA *et al.*, 2013), providing a more precise quantitative measurement of overbank deposits on the Paraguay River floodplain.

4.2 Hydraulic geometry and stream power and their relation to geomorphology

Within natural channels, the discharge is controlled by the relationship of width, depth, and flow velocity. Discharge can be graphically represented as a simple potential function represented by a straight line on a logarithmic scale. The sum of the exponents and the product of coefficients must be nearly 1 (LEOPOLD; MADDOCK, 1953). The values of exponents indicate the slope of the regression curve, which is an index for how much the variable is affected by the discharge. For example, the increase of the São Francisco discharge is produced mainly by increased flow velocity, whereas at Ladário and Porto da Manga, depth is the main variable (Figure 6). The channel width is least affected by the river discharge among the three gauge stations (Figure 6). The lower variation of channel width may be explained by the U-shaped cross-section channel morphology at the Porto da Manga (Figure 5B) and Ladário (recent fieldwork survey) gauge stations but is also affected by the low water level variation of the Paraguay River when the São Francisco station has a V-shaped cross-section (Figure 5A).

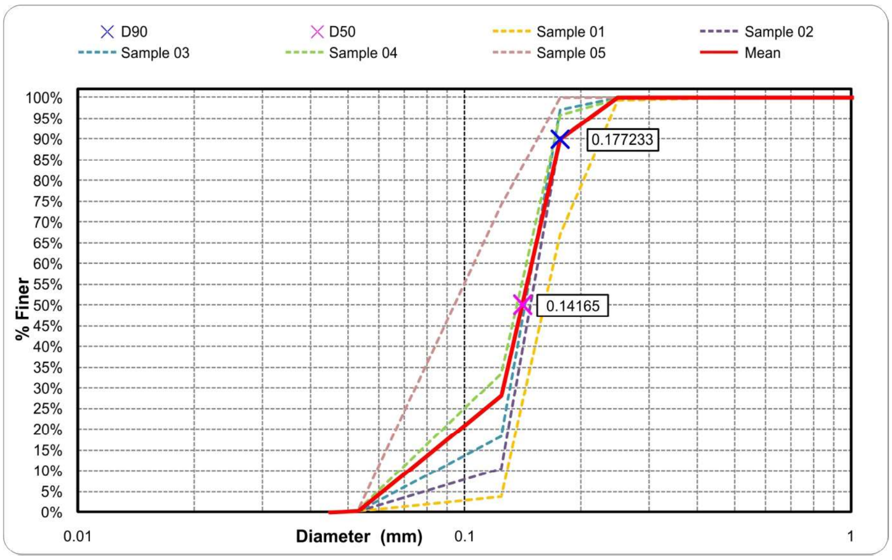

Figure 8 – Particle size analysis of Paraguay River bedload samples. See Figure 7 for sample locations.

The stream power calculated for the Paraguay River indicates that the floodplain would be formed by a low energy river with cohesive sediment following the Nanson and Croke (1992) classification scheme. Nonetheless, the morphological settings of the studied area suggest a floodplain built by an intermediate energy river, composed of non-cohesive sediment. The value obtained in the hydrological characterization disagree with current system morphology, denoting that the Paraguay River in the past experienced higher stream power to build the current morphology features. However, models such as Nanson and Croke (1992) often are produced from contexts very different from Pantanal, which could cause a divergence of classification. Studies contributing to models more closely based on the conditions in this region are needed.

4.3 Bedforms migration and evolution

Several islands are present in the Paraguay River channel (MACEDO *et al.*, 2014), some of which are situated on the channel bank, leading to the interpretation that the river cut through the floodplain. However, bedforms recognized in the Paraguay River channel, which generate submerged bars built by overlapping ripples, indicate that the islands were built by deposition of bedload, leading to the formation of longitudinal bars, which evolved to islands.

The low slope of the Paraguay River defines the small stream power calculated for this river. With low stream power, the Paraguay River can only carry fine sand-sized debris. The low stream power is also reflected in the low Froude number (0.083 to 0.105), conditioning subcritical turbulent flow. These hydraulic characteristics dominate the bed topographic model of the Paraguay River. These characteristics represent only the straight reaches of the river and do not represent curved reaches. The curved reaches were not mapped, as we initially intended to compare the bedload discharge calculations with the displacement of bedforms.

The overlap of smaller bedforms produces larger bedforms (compound bars) with irregular displacement, which prevented the measurement of bedform displacement. The Van Rijn mathematical model for the calculation of bedload transport (MACEDO *et al.*, 2017) was used, and its results were in agreement with the flow regime of the Paraguay River. In his work, Van Rijn utilized a 0.2-2.0 mm particle size range and flows with Froude number < 0.9. However, the 0.1 to 0.5 mm particle size range were best estimated. This method seemed most appropriate to calculate the bedload discharge in rivers of the Pantanal since these rivers have hydraulic and sedimentary characteristics similar to the model. However, the measurement of real bedload transport should be carried out by direct methods (e.g. measurements done by Delft Nile Sampler – Fattah *et al.*, 2004) since the mathematical model needs verification.

4.4 The complexity of the Pantanal hydrologic dynamic

Despite the lack of hydrological data for the UPRB, several researchers have proposed mathematical models to understand the hydrologic and hydraulic behavior of rivers and floodplains of the Pantanal wetland. For example, Bravo *et al.* (2012) modeled a rainfall-runoff process and flow direction on the UPRB. Paz *et al.* (2010) carried out large-scale modeling of channel and floodplain flow dynamics in a coupled 1D/2D model. The authors emphasized the complex channel-floodplain interaction of the São Lourenço and Piquiri rivers where water overflows the São Lourenço levee, inundating the floodplain and propagating towards the Piquiri River channel. In another study, Paz *et al.* (2014) demonstrated the influence of the vertical water balance (precipitation – evapotranspiration) in the hydrological cycle of the Pantanal wetland, simulating the lateral exchanges of water between main channel and floodplain. Their results showed no lateral exchanges of water in the reach between São Francisco and Porto da Manga. However, the data provided by our research confirmed this interaction (Figure 4 and Table 1).

These researches show the scant data and complexity of the hydrologic and hydraulic dynamic of the Pantanal wetland. Studies such as those cited above introduce new research perspectives on the hydrosedimentary field across the Pantanal. Opportunities abound for studies dealing with the hydrologic dynamic of the Paraguay River and its tributaries to advance our geologic, hydrologic, climatic, and geomorphic understanding of the system. Consequently, additional studies focused on these areas are needed to aid in understanding the hydrosedimentary dynamics of the Pantanal wetland.

5. Conclusion

A complex relationship between the river channel and its floodplain was detected in the Corumbá reach of the Paraguay River. The river loses water to its floodplain when flow exceeds bankfull condition, and the water gradually returns to the channel by baseflow and Hortonian flow. The floodplain functions as a reservoir that stores water during flood seasons, which resulted in the fluvial discharges recorded at the São Francisco, Ladário, and Porto da Manga gauge stations. In addition, the Paraguay River experiences a backwater effect, which also causes contrasting values of fluvial discharge between these gauge stations.

The Paraguay River stream power is inconsistent with floodplain characteristics. The stream power of the Paraguay River indicates a floodplain composed of cohesive material (clay), built by channel-levee rivers without scroll bars, which does not represent the morphologic characteristics of this area of the Pantanal. The stream power produces a subcritical turbulent flow regime, with low competence (fine sand) and capacity (~204 ton day^{-1}). Hydrosedimentary characteristics of the Paraguay River dominate the bed topographic model, which is formed by submerged compound bars built by smaller overlapping bedforms (megaripples) that can evolve to islands. Channel bedforms did not allow measurement of bedform displacement, so the bedload transport could not be calculated by this method.

Improving and expanding the amount of data regarding all these issues would provide a better understanding of the hydrologic dynamic of this huge alluvial plain. Thus, our work helps clarify issues such as the classification divergence and enhances the hydraulic modeling of the Pantanal rivers. This work is the first attempt to understand the hydrosedimentary dynamic of this area, and more studies must be conducted about this issue. The initial considerations have not exhausted additional research about this issue since this subject has great potential to answer more questions about the Pantanal.

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