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DYNAMICS OF WATER FLOW AND SEDIMENTS IN THE UPPER PARANÁ RIVER BETWEEN PORTO PRIMAVERA AND ITAIPU DAMS, BRAZIL

Débora Pinto MARTINS [1], Jean-Paul BRAVARD [2] and José Cândido STEVAUX [3]

[1] Université Lumière Lyon 2, France and Universidade Estadual de Maringá/GEMA, Brazil.
E-mail: deby_martins@yahoo.com.br
[2] Université Lumière Lyon 2, France. E-mail: jean-paul.bravard@orange.fr
[3] Universidade Estadual de Maringá/GEMA and UNESP, Rio Claro, SP, Brazil.
E-mail: jcstevaux@uem.br

Abstract: The following paper aims to quantify the bedload transport in the Paraná river in the Porto São José cross section (22°45'52"S; 53°10'34"W), between Porto Primavera and Itaipu dams, Brazil. In the used method, the bedload transport is estimated from the height and the displacement of the dunes along a longitudinal profile. The results were compared with those obtained from classical bedload transport equations. In the Porto São José cross section, the estimated average bedload transport applying the Dune Displacement Method (DDM) was 3,157 t d^{-1}, which corresponds to an average annual bedload transport of 1,152,325 t yr^{-1}. Applying the Van Rijn equation the average bedload transport was calculated in 2,830 t d^{-1} (1,032,950 t yr^{-1}), while using the Engelund-Fredsøe equation the average bedload transport found was 3,135 t d^{-1} (1,144,378 t yr^{-1}). The obtained values using different methods presented some coherence each other, which means that these results can be used as a starting point to establish bedload transport estimations in the Upper Paraná river.

Resumo: O presente trabalho tem por objetivo quantificar o transporte sólido de fundo do rio Paraná, na seção de Porto São José (22°45'52"S; 53°10'34"W), entre as barragens de Porto Primavera e Itaipu, Brasil. No método utilizado o transporte de fundo é estimado a partir da altura e do deslocamento das formas de leito ao longo de um perfil longitudinal. Os resultados obtidos foram comparados com os resultados obtidos à partir de algumas equações clássicas de calculo de transporte de fundo. Na seção de Porto São José, através do método das dunas, o transporte médio de fundo foi estimado em 3.157 t d^{-1}, o que corresponde a uma carga solida anual de aproximadamente 1.152.325 t/ano^{-1}. Quanto aos valores obtidos através da aplicação das formulas pré-selecionadas, à partir do método de Van Rijn chegou-se um transporte médio de 2.830 t d^{-1} (1.032.950 t ano^{-1}) e com o método de Engelund-Fredsøe obteve-se um transporte médio de 3.135 t d^{-1} (1.144.378 t ano^{-1}). Os valores obtidos a partir das diferentes metodologias apresentaram uma coerência entre si, o que pode ser o ponto de partida para estabelecer uma metodologia adequada às condições naturais de fluxo de grandes rios, como é o caso do Paraná.

Keywords: bedload transport, dunes, Paraná River, large rivers
Palavras chave: transporte de fundo, dunas, Rio Paraná, grandes rios

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INTRODUCTION

The fluvial transport is one of the driving factors of the fluvial systems and it reflects the erosive characteristics of the basin through the input of sediments and the hydrodynamics processes of erosion/deposition in the channel. The erosion and sediment transport also are responsible for the reworking of the channel itself and of its morphology.

The amount of variables involved in the solid transport mechanics, as well the complexity of the interactions among the physical processes, makes it difficult to establish a fully satisfactory criteria to determine the solid transport, thus there is not an acclaimed universal method. Throughout the years, many researchers were trying to establish some relations to allow determining the solid transport with precision (Duboys,1879; Straub, 1935; Einstein, 1942, 1950; Kalinsk, 1947; Schoklitsch, 1962; Shields, 1936; Meyer-Peter and Müller, 1948; Levi, 1948; Sato *et al.*, 1958; Yalin, 1972; Pernecker and Vollmer, 1965; Helley and Smith, 1971; Klingeman and Milhous, 1971; Gregory and Walling, 1985, Gomez, 1991; Ryan and Troendle, 1997; Ryan and Porth, 1999). From the methods available in the literature, there are some purely empirical and others theoretic complex models.

Most of the methods in the literature were elaborated from data of flume experiments, where the researcher has the control of almost all the variables involved in the transport of the solid material. In the case of natural channels this condition is impossible. Besides, the scarcity of data (historical series) and the relatively short period for field observation are limiting factors for equation calibrations and establishment of a universal model.

Due to the inflow and outflow of water and sediments, in an alluvial channel the sediment movement changes within time and space, shaping the channel morphology. In this context, the understanding of the stream hydro-sedimentological dynamics demands some knowledge of a wide range of interactions among water flow, sediment transport and bed-forms. This paper aims to offer a better understanding of the bedload dynamics in the upper Paraná River applying measurements based on dune displacement (Dune Displacement Method - DDM). This method determines sediment transport based on the size of the bed-forms and its velocity of linear displacement along longitudinal profiles (Stuckrath, 1969).

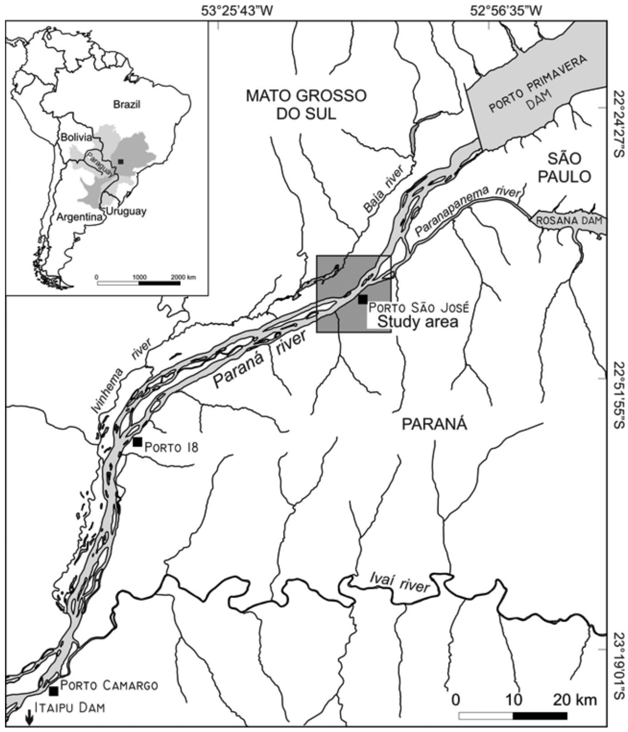

Figure 1. The study area.

STUDY AREA

The study area is a reach of Upper Paraná River, near the town of Porto São José, between Porto Primavera and Itaipu dams, at the border between the states of Paraná and Mato Grosso do Sul, Brazil (Fig. 1). The reach downstream of the Porto Primavera Dam is defined as anastomosing (Stevaux and Souza, 2004) or anabranching (Latrubesse, 2008) with channels divided by long and stable vegetated islands and mobile sand bars. Structural influence generates nodal sections between multichannel reaches. These sections generally present a single channel with a thalweg asymmetrically shifted to the left bank (Stevaux, 1994; Fortes *et al.*, 2005).

At the particular studied section of Porto São José the Paraná River presents a unique channel (node point) with a width of 1,260 m and maximum depth of 10.5 m under normal flow conditions. In this reach the thalweg is displaced to the left side of the channels, with islands upstream and downstream of this node point (Fig. 1). On the left bank of the section the Porto São José gauging station is located. This gauge station is operating since 1964 and has been

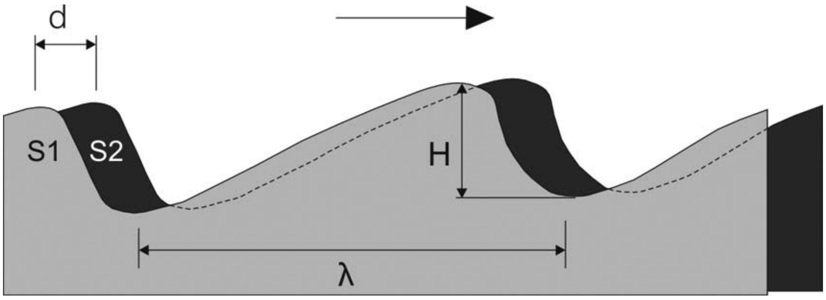

Figure 2. Typical dune from an alluvial river. (d: dune displacement after a time interval (Δt); H: dune height; λ: dune wavelength). Modified from Amsler and Prendes (2000).

surveyed by the energy company CESP. The mean annual discharge for the 1964-2006 period is 8,780 $m^3 s^{-1}$ and the extreme records in this section are: minimum daily discharge of 2,551 $m^3 s^{-1}$, observed in September 1969, and maximum daily discharge of 34,912 $m^3 s^{-1}$, observed in February 1983.

Even though it is the third largest river in South America, the studies concerning the hydrosedimentological dynamics of the Paraná River are scarce. There are some studies of this nature in the middle course, in Argentina, mainly in the reaches close to the cities of Corrientes and Santa Fé. In the Corrientes reach, Bonetto and Orfeo (1984), Orfeo (1995) and Orfeo and Patiño (1998) worked mainly with the suspended load. In the Santa Fé region, Stuckrath (1969), Lima *et al.* (1990), Trento *et al.* (1990), Amsler and Gaudin (1994), Amsler and Schreider (1999) worked with the quantification of the bedload transport. About the Upper Paraná River in Brazil, during the years of 1986 and 1987, the Itaipu Binacional Company, responsible for the Itaipu Dam, developed some studies devoted to sediment transport in the reach upstream the dam lake. In these studies was observed that bedload discharge was inferred indirectly, assuming that it could represent 20% of the suspended load.

Presently, the hydro-sedimentological dynamics of the Paraná River is under the control of a series of dams, which transformed the main channel of the Paraná River into a sequence of lakes. According to Itaipu Binacional (1990) the correlations between the suspended solid concentration and the discharge in Porto São José section became precarious, because both the discharge and hydro-transported solids are very controlled by the upstream dams. In this context, Martins (2004) and Martins and Stevaux (2005), based upon the first studies made in the Argentine reach of the Paraná River (Amsler and Gaudin, 1984; Amsler and Schreider, 1999; Amsler and Prendes, 2000), determined the bedload transport of the last natural-like reach of the Upper Paraná River in Brazilian territory. In this paper we present results on the Paraná River downstream Porto Primavera Dam, which was constructed from 1989 to 1998 generating one of the largest dam lakes of the world that spread on 2,250 km^2.

METHODOLOGY

The DDM method has been used for estimating the bedload in mobile bed channel, assuming a permanent and "almost" uniform flow in the study reach of an alluvial river (Hubbell, 1964; Simons *et al.*, 1965; Fredsøe, 1981; Engelund and Fredsøe, 1982). In this method, the bedload transport is given by the size of the dunes and by the velocity of displacement of those dunes along a longitudinal profile through the channel (Fig. 2). The quantification of the transported bedload is made using the Stuckrath's equation (1969), as follows:

$$Cf = (1-p)H\,k\,ud \qquad (1)$$

where Cf is the transported bedload; p is the porosity of the sand, H is the mean dunes height, ud is the velocity of displacement of the dunes and k is a coefficient related to the shape of the dunes. The value of porosity depends on the bedload texture, used in the study case (fine to medium sand) the value of 0.6, as it has been suggested by Amsler and Prendes (2000), Stevaux and Takeda (2002), Orfeo and Stevaux (2002). Considering that the longitudinal section of the natural dunes is not a perfect triangle, a coefficient of shape (**k**) is used in order to minimize the errors issued from this variable. According to Stukrath (1969) and Lima *et al.* (1990), this coefficient generally varies between 0.50 and 0.66. In this paper we adopted **k** = 0.67, according to the most recent study carried out by Amsler and Prendes (2000).

The application of this method considers that the bedforms are in equilibrium, which means that the set of dunes must keep its shape while it displaces downstream. This condition, observed by Lima *et al.* (1990), Stevaux. (1994), Martins (2004), Martins and Stevaux (2005). Cheng and Shen (1975), and Strasser (2008), showed that, even if the shape of an individual dune changes during its displacement, the set of dunes tends to present a morphological constancy. In this study, the morphology of the bed and the morphological constancy of the shapes were determined from bathymetric charts and from three-dimensional bathymetric models prepared along this research.

Data acquisition

Dune velocity is obtained through successive bathymetric surveys. As the first step, it is necessary to determine the study period according to the hydrological regime (high and low water level), and to establish the time interval between the two successive bathymetric surveys. This interval depends of the bedform displacement velocity and the potential of dune shape preservation. On this study, field work was performed during 2005, 2006 (medium water level) and 2007 (in flood stage). For each field season two bathymetric surveys were made at an interval of 10 to 15 days as recommended by Stevaux and Takeda (2002), Crispim (2001), Martins (2004) and Martins and Stevaux (2005). A set of 2 km-long longitudinal profiles, 100 m equidistant from each other was obtained (Fig. 3).

Bathymetric data was acquired by a Furuno GP-1650F echo-sounder/GPS system, and recorded in a portable PC, through software *Fugawi3*. Data was exported and treated with *MS Excel®, Surfer® 8.0* and *AutoCAD® 2000* software.

Bathymetrical data was completed by a zigzag track over the study reach, in order to produce a large dataset for 3-D bathymetric models elaboration. Instantaneous discharge, flow velocity and direction data were collected by an ADCP – Acoustic Doppler Current Profiler. Channel bottom sediment was sampled for textural analyses.

Data Treatment

The estimation of the bedload transport begins with an individual identification of each dune along each longitudinal profile. The dune's height (h) is obtained by the mean height of one specific dune in

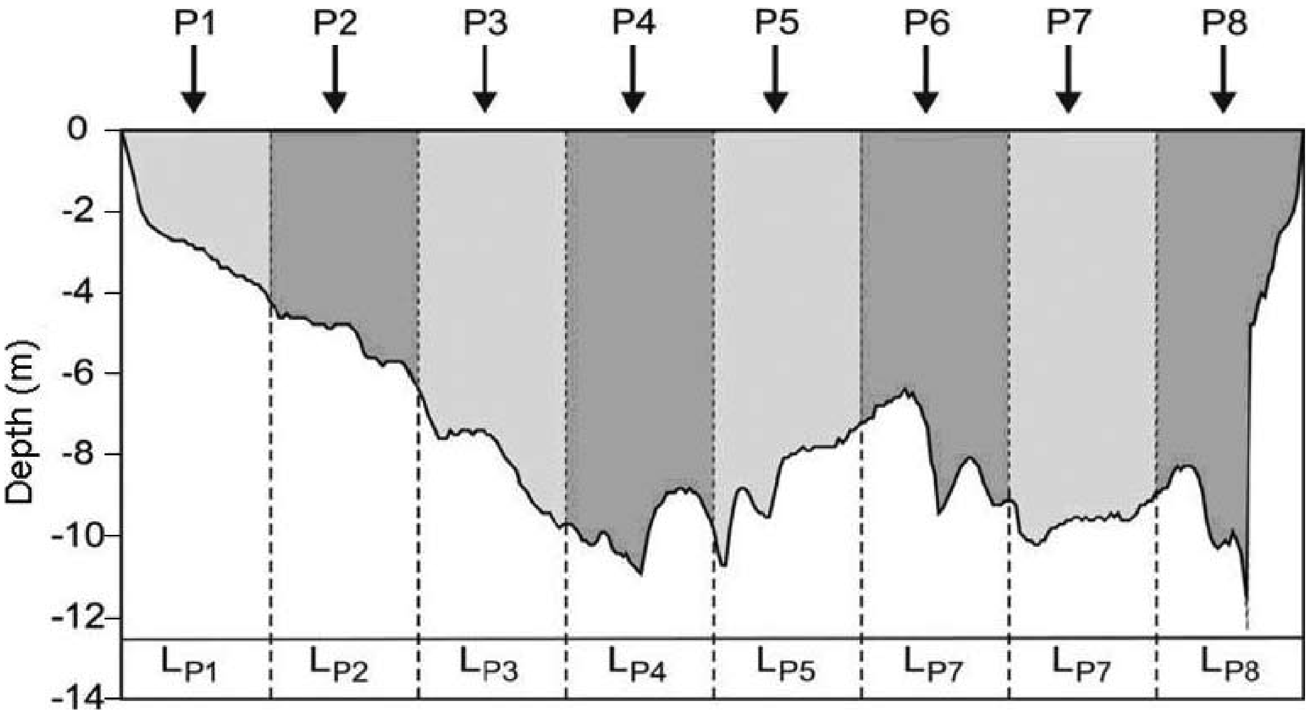

Figure 3. Influence width (Lp1 to Lp8) of each longitudinal profile (P1 to P8) in the Paraná River channel cross-section at Porto São Jose.

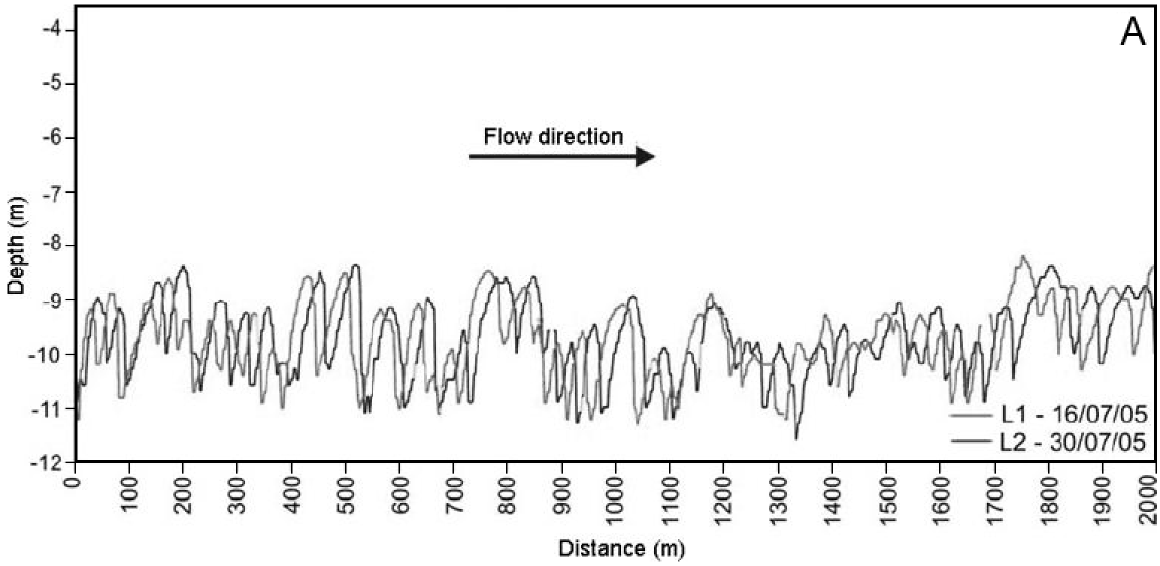

Figure 4. Longitudinal bathymetric profile of the Paraná River at Porto São José section under medium flow discharge stage.

both measurements (h1 and h2). The displacement (d) is done by the difference of position of the dunes crest in the two successive measurements. Bedload is determined individually for each dune, and then by the mean for the entire profile as the equation:

$$CfPi = \Sigma\ Cfdi/n \quad (2)$$

where CfPi is the estimated bedload for the entire profile Pi, Cfdi is the bedload estimated for each dune and n is the number of dunes considered in the estimative. The total bedload for the entire section (Cf Total) is obtained by the sum of CfPi for each longitudinal profile multiplied by its width of influence (Lpi) (Fig. 3):

$$Cf\ Total = \Sigma(CfPi * LPi) \quad (3)$$

RESULTS

Bedload transport

The bathymetric profiles show the dunes as the predominant bedform in the Paraná River channel at Porto São José (Fig. 4). Bedforms are regular in shape and maintain their morphology while moving downstream. At medium discharge stage, dune height varies from some centimetres to 2.5 m (Fig. 4). During the flood season, it is common to find mega-dunes up to 5 m high with superimposed dunes (Fig. 5).

During the first fieldwork (July 2005), dunes presented an average height of 1.5 m and a linear displacement velocity of around 1.44 m d^{-1}. On that occasion, flow velocity varied among 0.22 m s^{-1} and 1.18 m s^{-1} (mean of 0.80 m s^{-1}). The bedload transport was estimated in 0.96 m^3 d^{-1} m^{-1} (0.024 kg s^{-1} m^{-1}), which represents a total volume of 1,062.52 m^3 d^{-1}, or 2,815.67 t d^{-1}. During that period, the average discharge of the Paraná River at Porto São José gauging station was 9,769 m^3 s^{-1}.

During the second fieldwork (May 2006), the dunes presented an average height of 1.28 m and an average displacement velocity of 1.72 m d^{-1} at a flow velocity varying between 0.5 m s^{-1} and 1.30 m s^{-1} (medium flow velocity of 0.80 m s^{-1}). The estimated bedload for that period was 0.98 m^3 d^{-1} m^{-1} (0.030 kg s^{-1} m^{-1}), which correspond to a total volume of 1,219.28 m^3 d^{-1}, or 3,258 t d^{-1}. The average discharge on that period was 7,953 m^3 s^{-1}.

During the third fieldwork (January and February 2007), because of the high magnitude of this event (2.5 times the mean discharge) and the bedform morphology, the solid transport was estimated through the velocity of displacement of the mega-dunes. They presented an average displacement of 6.30 m d^{-1}, to a flow velocity varying between 0.5 m s^{-1} to 2.0 m s^{-1} (medium flow velocity of 1.5 m s^{-1}). Bedload transport was 3.3 m^2 m^{-1} day^{-1} (0.11 kg m^{-1} s^{-1}), which corresponds to 3,757 m^3 d^{-1} or 9,956 t d^{-1}. During that period the Paraná River presented a discharge of 18,136 m^3 s^{-1}, 2.5 times the average discharge, and the flow velocity two times higher than that at mean water discharge. Bedload transport

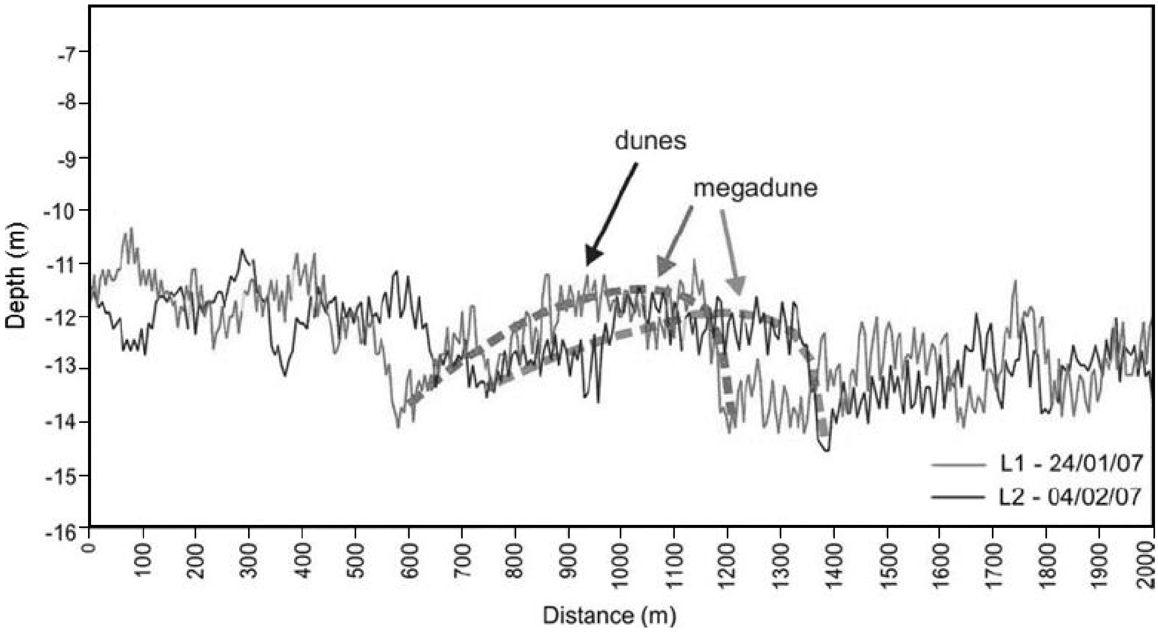

Figure 5. Longitudinal bathymetric profile of the Paraná River at Porto São José during flood discharge stage.

was approximately three times the transported bedload under average flow conditions.

Some control measures were taken in the section of Porto Camargo, located about 100 km downstream Porto São José section (Fig. 1). During the first fieldwork at Porto Camargo (July 2005) the dunes presented an average height of 1.35 m and a displacement of 1.65 m d^{-1}, to a flow velocity varying between 0.31 m s^{-1} to 1.5 m s^{-1}. The value of bedload transported was 647.32 m^3 d^{-1}, which represents a total weight of 1,715.4 t d^{-1}. In the second fieldwork (May 2006), the dunes presented an average height of 1.42 m and a displacement velocity close to 1.80 m d^{-1}, under a flow velocity that ranged from 0.5 m s^{-1} to 2.0 m s^{-1}. The estimated transport was 712 m^3 d^{-1}, which means 1,887.86 ton d^{-1}.

During the third fieldwork (flood season of January and February 2007), the dunes at Porto Camargo presented an average height of 1.56 m and an average velocity of displacement of 3.32 m d^{-1}, under a flow velocity of 2.0 m s^{-1}. Bedload transport was 1,925 m^3 d^{-1} or 5,101.36 t d^{-1}.

A comparative analysis of the data obtained in the two sections indicates that the bedload transport at Porto São José was 1.68 times higher than that at Porto Camargo. During the flood season the value at Porto São José was 1.95 higher than at Porto Camargo.

At Porto São José, three other surveys were performed by Martins (2004) and Martins and Stevaux (2005) during 2002 and 2003. In those surveys, bedload was estimated in 2,940 t d^{-1} (November/December 2002), 2,710 t d^{-1} (June/July 2003), and 2,812 t d^{-1} (November/December 2003). In all those surveys, field work has been done under average discharge conditions.

Comparison with bedload transport equations

Values of bedload transport estimated through the dune DDM were compared with those obtained by the application of some classical bedload transport equations chosen from the specific literature. The equations of Engelund-Fredsøe, Van Rijn, and Meyer-Peter & Müller were selected because they have already been used in the middle Paraná, in

Bedload	DDM	Van Rijn	Meyer-Peter & Müller	Engelund-Fredsøe
kg m^{-1} s^{-1}	0.029	0.023	0.016	0.028
t d^{-1}	3,157	2,830	1,741	3,135
t yr^{-1}	1,152,325	1,032,950	635,465	1,144,378

Table 1. Average bedload transport in the Paraná River at Porto São José estimated from different methods.

Argentina (Amsler and Prendes, 2000). The values estimated by the different equations presented some coherence among the values estimated using the DDM (Table 1). This coherence is more expressive with the results estimated using the equations of Engelund-Fredsøe and Van Rijn, while the equation of Meyer-Peter e Müller has resulted in lower values of bedload transport when compared with the results obtained with the method of dunes displacement.

CONCLUSION

The estimation of bedload transport in the upper Paraná River has been a need in terms of hydro-geomorphologic, ecologic and engineering studies. The effect of dams on solid discharge was rapid an intensive (Stevaux *et al.*, 2009), but the adjustment of the alluvial channel in response to these changes are totally unknown. We provided the first systematic analysis of bedload transport downstream the huge Porto Primavera dam. In the Porto São José section, the average bedload transport was estimated in 3,157 t d^{-1}, which corresponds to 1,152,235 t yr^{-1}. The bedload transport estimated by using the method of the displacement of the dunes is coherent with the results obtained when applying the Engelund-Fredsøe and Van Rijn equations.

The advantage of using the method of dune displacement is given by its relative feasibility for field measurements (through bathymetric surveys) mainly in large alluvial channels. These are the first systematic results obtained on bedload transport in the Paraná River in Brazilian territory. Our results can be considered a starting point to elaborate a new method to estimate the bedload transport for the Paraná River or even to create a rating curve for the upper course.

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