Flow Measurement and Instrumentation 54 (2017) 124–135

Contents lists available at ScienceDirect

Flow Measurement and Instrumentation

journal homepage: www.elsevier.com/locate/flowmeasinst

The ADCP's bottom track capability for bedload prediction: Evidence on method reliability from sandy river applications

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ARTICLE INFO

Keywords:
ADCP
Bedload transport
Bed-particle velocity
Bottom track function
Dunes
Large sandy rivers

ABSTRACT

River processes understanding requires the investigation of sediment transported by the streamflow. To this aim, the use of physical samplers is particularly challenging in large sandy rivers, which pushed the thriving of surrogate methods. The acoustic Doppler current profiler (ADCP) has been recently used to quantify the suspended-load as well as the bed-load. The latter is related to the apparent velocity of particles at the bedload layer as resulting by comparing the ADCP's velocity from its capability to acoustically track the bottom and from accurate GPS recordings. The reliability of this technique depends on instrument frequency, acoustic pulse length used and site-specific properties, such as riverbed composition and bedforms presence that eventually require further research. This work presents ADCP-DGPS measurements in the large sandy Parana River in Argentina, performed with ADCPs operating at 600 and 1200 kHz frequencies and using different acoustic pulse lengths to eventually assess the bedload rate. Combining theoretical parameters and apparent velocity of bed-particles from ADCP, assessed values agree on bedload rate values obtained with the dune tracking method with a discrepancy of 29% on average. The measurements obtained with 1200 kHz and longer pulse lengths deliver better agreements, although variation with longest pulse length was 15% off at most.

1. Introduction

The lack of frequent measurement of sediment fluxes in large alluvial rivers has hindered the full understanding of fluvial processes. This shortage of data specifically refers to an insufficient amount of transport rates of sediment by the river streamflow, classified as suspended- or bed-load depending if the advection of particles occurs in full suspension or close to the riverbed, [13]. These mechanisms must be thoroughly known to calibrate and validate analytical formulas or numerical models for the prediction of river channel morphological changes.

The movement of sediment of various size classes (i.e., grain sizes) at the same time, or the same classes at different times, characterizes the sediment transport mechanisms [13]. In the case of large sandy rivers, the bedload consists of sand coarse particles rolling, sliding, or saltating close to the riverbed over distances that are comparable to their corresponding diameters. The bedload rate usually relates to the shear stress acting over a sandy riverbed, and consequently, to its bedforms and the mean diameter of transported particles. The thickness of the movable layer over the riverbed is on the order of the coarsest grain size of sediment forming the riverbed [3,9,39].

In a large, low-gradient sandy bed river, the estimation of bedload is extremely challenging. The bedload samplers perturb the surrounding flux, which in turn entails an unsafe deployment, and eventually results in a poor time-space resolution for the sediment load assessment [4,6,11,23].

More recently, the acoustic Doppler current profiler (ADCP) has been used to infer the rate of sediment transport. Szupiany et al. [35], Guerrero et al. [17,18] and Latosinski et al. [21] showed a good correlation between sediment concentration of suspended sand and the acoustic signal intensity profiled by the ADCP deployed in the Parana River system. In particular, Latosinski et al. [21] showed that the uncertainty in the assessment of the total transport of suspended sand from the riverbed by applying an ADCP technique is lower than 50% compared to conventional methods.

Although there is a significant amount of work related to sus-

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http://dx.doi.org/10.1016/j.flowmeasinst.2017.01.005
Received 17 June 2016; Received in revised form 23 December 2016; Accepted 7 January 2017
Available online 09 January 2017
0955-5986/

pended-load and acoustic techniques in different rivers [14,35,24,32,16,21, among others], the use of ADCP for bedload assessment in rivers has been developed in few natural streams (i.e., in Fraser River, Canada: [20,29–31,40]; in Missouri River, USA: [10,11,19] and scarce flume experiments [27].

In all these previous studies, the bedload is correlated to the apparent velocity of sediment moving close to the riverbed. This apparent velocity comes from the ADCP's acoustic capability to track the river bottom (known as "bottom track function") and simultaneously to pair the DGPS (Differential Global Positioning System) readings. The actual velocity of the ADCP is usually measured utilizing an accurate positioning system like the DGPS. The acoustically inferred speed, known as bottom track velocity (BT velocity), is the ADCP velocity referred to a reflecting boundary such as the riverbed of an emitted acoustic signal. The difference in the actual instrument velocity and the BT velocity is the apparent velocity of bed-particles. In other cases, the device is maintained steady, and the apparent velocity naturally corresponds to the BT velocity but in the opposite direction (i.e., the sign changes in the same reference system). The technique relating the bedload to apparent velocity of bed-particles from ADCP and DGPS recordings is referred here as ADCP-BT method.

To evaluate the performance of ADCP-BT method in their bedload rate investigations in large rivers, Gaeuman and Jacobson [10,11] reported that bedload sampling is less reliable than dune tracking using repeated bathymetric surveys. In this regard, the inherent inaccuracies of bedload samplers introduce errors that may bias the performance of ADCP-BT technique. The most critical issues using bedload sediment samples are: i) the bedload sampler alignment to flow direction (i.e., horizontal alignment), ii) the position of the mouth because of small perturbations in riverbed (i.e., vertical alignment) and, iii) the sampler actual position with respect to dune shapes and superimposed bedforms that are typical for large sandy rivers [3,11]. Given these limitations, dune tracking methods are eventually applied in large sandy rivers to assess the actual bedload rate. Also, all the contributions relating bottom track measurements and bedload are made without considering the exact position of the ADCP over the dune when bedforms are present, except for the preliminary results of Kostachuk et al. (2005) and the contribution of Villard et al. [40]. These results are relevant because the streamflow horizontal velocities close to the riverbed, and consequently the maximum bed shear stress, occur over the dune crest [7]. Thus, the bedload rate as inferred by dune tracking method, which is an estimated rate for each dune, may be correlated to ADCP values in fixed sections at the dune crest (i.e., static measurements).

Despite the advancement of ADCP-BT method for bedload estimation, the correlation between its outcome and the actual bedload rate largely depend on the coupling between instrument features (i.e., acoustic frequency and pulse length) and in situ properties such as riverbed composition and the position over the bedform where the measurement takes place. This dependence calls for further research to eventually clarifying: i) if the apparent velocity is an unbiased predictor of bedload rate or not, and ii) if the in situ properties and instrument features affect the correlation coefficient.

A concept particularly related to the present work is the effect known as 'water-bias'. Particles transported in suspension within the water column (namely suspended load) close to the riverbed may affect the resulting apparent velocity, which may deteriorate its correlation to bedload rate. This effect comprises i) the acoustic backscatter of suspended particles from the riverbed, which depends on the acoustic frequency applied and the actual particle size distribution [15], and ii) the measurement volume thickness over the riverbed, which is a pulse length function [27]. The experimental work presented in this paper uses a combination of frequencies and pulse lengths for further elucidating the water-bias effect in the case of a sandy riverbed, specifically the Middle Reach of the Parana River. Previous fieldworks studies mostly regarded gravel and sand-gravel riverbeds, while few cases focused on large sandy rivers [10,11,19]. The lack of studies on sandy bed rivers justifies the present research effort, which contributes in clarifying on apparent velocity method reliability about sandy river applications.

This paper presents results from campaigns in the Paraná River using ADCP-BT static measurements and dune tracking techniques with the purpose to clarify the reliability of using the bed particles apparent velocity from an ADCP readings as a predictor of bedload rates in sandy rivers, and its dependence on in situ properties and instrument features. Two different acoustic frequencies (600 and 1200 kHz from ADCPs by Teledyne RD Instrument) were used to infer the velocity of sediment particles transported close to the riverbed at the crest of three large dunes while different pulse lengths were eventually evaluated. Additional measurements were carried out over the dune trough and stoss-side that gave evidence on the importance of ADCP's actual position for the predictor reliability.

Finally, the communication ends discussing the limitations and advantages of using the ADCP-BT function to estimate the bedload in sandy rivers. The approach proposed herein could combine with ADCP surveys of the streamflow velocity field and related sediment concentration suspended in the water column to eventually contribute to the understanding of reciprocal feedback between hydraulics, sediment transport, and the resulting morphology.

2. Study sites, equipment and methodology

The Paraná River watershed comprises parts of Brazil, Bolivia, Paraguay, and Argentina with a total area of 2.3×106 km^2 and an average slope of the order of 1×10^{-5}. The Paraná River has a mean annual discharge of about 18,000 $m^3\ s^{-1}$ [22], and a mean monthly flow in summer (i.e., the wet period) of 22,500 $m^3\ s^{-1}$. For low-level conditions, an average value of nearly 15,000 $m^3\ s^{-1}$ was reported by [2]. The river planform pattern classifies as anabranching with meandering thalweg [22]. This pattern forms a succession of enlargements with narrower, shorter and deeper sectors in between. The enlargements are 2000–3000 m wide with water depths of 5–8 m, and the constrictions are 600–1200 m wide with depths of 15–25 m [2,35,36]. The middle reach is described by suspended-load from the riverbed of about 23×106 t $year^{-1}$ and suspended/bedload ratio of about nine while the wash-load represents 91% of the total sediment transport [1].

A set of field campaigns was conducted in the main channel of the middle reach of the Paraná River, including three areas (Fig. 1) with distinct hydrodynamic and bedform characteristics: Lavalle (29° 0′ 59.55" S, 59° 12' 5.14" W), Aguas Corrientes (31° 51′ 21″ S, 60° 28′ 3″ W), and Bajada Grande (3° 44′ 12.7″ S, 60° 39′ 42.6″ O). The flow discharge was 17,100 $m^3\ s^{-1}$, 12,500 $m^3\ s^{-1}$, and 16,000 $m^3\ s^{-1}$ at Lavalle, Aguas Corrientes, and Bajada Grande, respectively, corresponding about to low level conditions. The hydraulic and morphologic variability represented by the three studied zones seeks to sustain the major objective of this paper, which is to improve a methodology for bedload estimations without bias due to site-specific conditions.

At each area, two measurement methodologies were applied. Dynamic measurements were performed by using a moving vessel to infer the bedload rate by the dune-tracking method. These measurements were carried out from 5/31 to 6/2/2011 in Lavalle (near Lavalle City); 4/26/2012 in the Aguas Corrientes zone (near Paraná City) and from 7/24 to 7/26/2012 in Bajada Grande zone (near Paraná City, Fig. 1). Besides applying the ADCP-BT procedure to estimate the velocity of sediment particles transported close to the riverbed, static measurements were carried out in between the dynamic measurements, and on the same dunes, by anchoring the vessel over the dune crest. Additional measurements over the stoss and trough were made to observe the movement of bed-particles at these zones, where they were expected to be slower.

Riverbed sand was sampled by using drag cones in all the analyzed dunes (crest) that resulted in bed sediment distributions. This type of

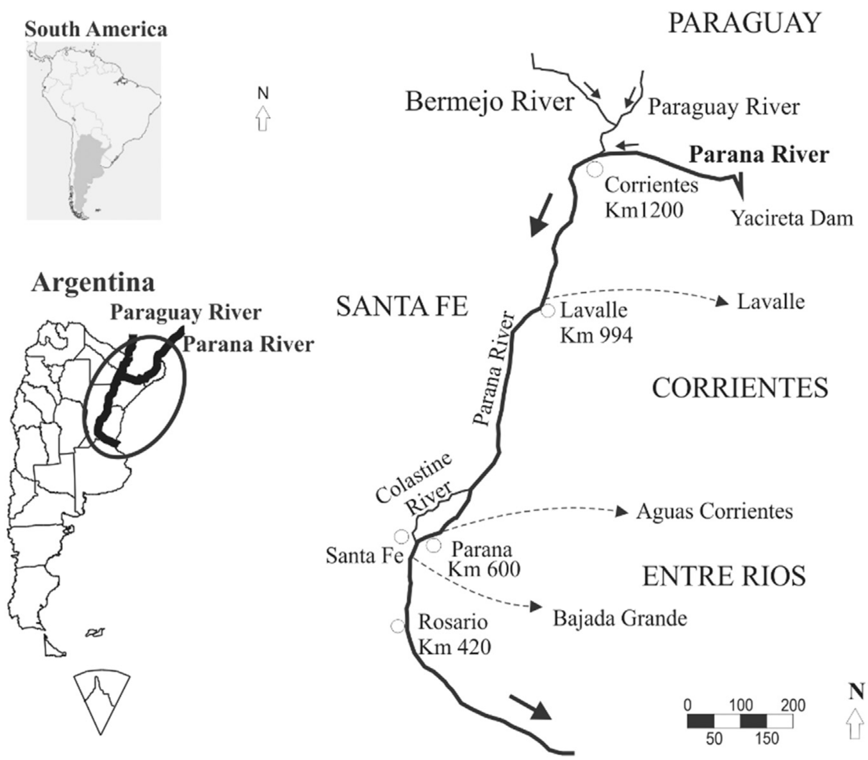

Fig. 1. Location of the study sites along the Paraná River.

samplers, own-made in this case, has a conic shape with 0.15 m and 0.30 m in base diameter and height, respectively. They were operated dredging the bed by drag while the boat was kept drifting. The sampled sand quantities varying from 0.30 to 0.75 kg, were quartered in the lab in order to obtain a proper sample volume for sieving.

2.1. Dynamic measurements

The bedload was calculated applying the dune tracking method [3,11,39] that entails repeating longitudinal tracks over a dune sequence previously identified by exploratory surveys. The procedure eventually results in a time series of bathymetric profiles of bedform sequences. Geographic coordinates were recorded with a frequency of 1 Hz and an accuracy of about ± 2 cm in absolute positioning by using navigation software integrated with a real-time kinematic global positioning system (RTK-DGPS) from Leyca. Water depths at the same frequency were recorded with a single-beam echosounder of 210 kHz from Raytheon. Longitudinal tracks were repeated every 48 h, except Aguas Corrientes, where the repetition period was of 7 h according to the available time. With the aim of maximizing the resolution of recorded bathymetries, dune sequences were tracked from downstream to upstream which resulted in the slowest velocity of the survey vessel (i.e., approximately 1 m s^{-1}) and therefore, a shorter spacing between consecutive bed detections by the sonar. The dune displacement was clearly observed by comparing consecutive profiles. Also, the vessel altitude was continuously measured for all the performed profiles that gave an estimation of the local water slope in the streamline direction.

The use of a single-beam echosounder in longitudinal tracks rather than an ADCP, which corrects for pitch, roll and heading effects, is based on the following facts: i) the 1200 and 600 kHz Rio Grande ADCP models (by Teledyne RD Instruments) do not use a vertical beam to measure the water depth, ii) vertical beam is more appropriate for dune tracking than the averaged information from four beams scanning a large area of the riverbed; and iii) all field works were performed at very calm weather conditions. In spite of the ADCP information can be extracted for each beam individually, negligible differences were found between data from the echosounder and the ADCP individual beam aligned with flow direction.

2.2. Static measurements

The records of geographic coordinates, water velocity, echo intensity profiles, and BT displacements were obtained along 15 min on the stoss side, crest, and trough of individual dunes selected along each longitudinal track (Fig. 4). All measurements were conducted using a 1200 kHz and, eventually, a 600 kHz Workhorse Rio Grande ADCP manufactured by Teledyne-RD Instruments [37]. The ADCPs were set to record the vertical water velocity profile and the corresponding echo intensity with a sampling rate between 1 and 1.7 Hz (depending on ADCP frequency, mean water depths, and mean flow velocities). The profiling resolutions were set in 0.25 m and 0.5 m (depending on ADCP frequency), using the "Water Mode 1", "Bottom Mode 5", and a bottom track pulse length value by default [37]. Both ADCPs were mounted on an aluminum frame (which avoids magnetic effects) fastened to the boat starboard, the draft distances being equal to 0.30 m and 0.20 m for the 1200 kHz and 600 kHz ADCP, respectively. The blanking distance was 0.50 m in Lavalle, 0.50 m and 0.72 m in Aguas Corrientes (for 1200 and 600 kHz, respectively), and 0.49 m in Bajada Grande. The simultaneous deployment of two ADCPs working at 1200 and 600 kHz frequencies in the Aguas Corrientes river section gave evidence of the frequency effect over the BT velocity assessment. Only the 1200 kHz ADCP was active in the other zones. Also, a series of acoustic pulse lengths were tested to measure the BT velocity corresponding to the dune crest location in the Bajada Grande region. The pulse length settings were 10, 20 (default), 30% and 40% of the actual water depth by modifying the '& R' command [37].

2.3. Bed-particles velocity. The ADCP-BT method

The ADCP actual velocity usually refers on an integrated DGPS. In cases of a fixed bed (not bedload transport occurs), the ADCP riverbed relative velocity is measured using an independent acoustic pulse to detect the bottom reflection. This independent pulse eventually provides the water depth and the Doppler effect between a moving ADCP and the reflecting boundary (assumed as a fixed limit), is called bottom track (BT) function. These methods were originally integrated into the current profiler system (i.e., ADCP) to enable water velocity profiling even in the case of a dynamic deployment when the profiled velocity is a relative velocity between the rover-ADCP and the ensonified water column [37].

Afterward, the BT function was also applied to infer the velocity of sediment particles transported close to the riverbed by subtracting the ADCP actual velocity to the BT velocity [29]. The BT function consists in the emission of a long incoherent pulse with the ADCP given frequency. The long incoherent pulse is quite different from the pulse-coherent emission enabling the flow velocity profiling with high resolution and accuracy. The riverbed reflects the long incoherent pulse and, therefore, introduces a Doppler shift that is proportional to the ADCP-riverbed relative velocity, i.e., BT velocity, v_{BT}. Thus, given the ADCP actual velocity, v_{DGPS}, the apparent velocity of bed particles, v_a, (defined as the spatial average velocity of particles moving in the bed over the footprint of transducers) can be inferred as [29].

$$v_a = v_{DGPS} - v_{BT} \tag{1}$$

Fig. 2 shows the alignments of the four acoustic beams as projected from the ADCP and the corresponding footprint over the riverbed (dunes in this case). It is worth noting that the acoustic footprint defines the associated averaging area according to beam divergence (20°) and flow depth. In any case, the averaging areas were an order of magnitude smaller than the dunes wavelength that were scrutinized (Fig. 2).

An important aspect of the bottom track acoustic signal is the pulse length of acoustic pings. Long pulses enable the ensonification of the reflective portion of the riverbed with the full cross-section of acoustic beams at the same time. The opening angle of the acoustic beam (i.e., beam width) results in a conic projection over the reflecting boundary that, in the case of short pulses, implies variable leading and trailing angles of the wavefront. This would give rise to a noticeable change in the Doppler shift and eventually introduces a bias in the Doppler velocity assessed [31]. Nevertheless, the accuracy of BT long pulses in the Doppler shift assessment shows a reduced spatial resolution of the vertical profiling (water flow profiling). In the case of a reflecting boundary, like that of the BT capability, this reduced resolution yields a BT velocity influenced by moving particles close to the riverbed in suspension, eventually giving an estimation of particle velocity moving close to the riverbed biased toward the velocity of the water volume above. Therefore, the choice of an adequate BT pulse length could be a compromise solution. The height above the bed of the sample volume is a function of the pulse length, and the beam projection. This thickness is variable during pulse reflection because of simultaneous scatterings produced from the forward and reflected beams. In agreement with Rennie and Millar [31], the actual thickness of the sample volume close to the riverbed corresponds to the maximum overlap between forward and reflected beams that are the highest thickness of the scattering layer occurring in the center of the long pulse reflected. This last definition amounts to $0.5 l_p sen(90 - \chi - \varphi)$, where χ is half of the half-intensity beam width (0.75° for 1500 kHz) and φ is the beam angle with the perpendicular to the reflective boundary, that was considered to be equal to 20° by neglecting dune slope and ADCP axis misalignments from the vertical. In the present cases, using a 1200 kHz RDI-ADCP, with l_p fixed to 20% of the actual water depth (mean value of 10 m), the sample volume was about 1 m thick. All these settings implies that scattering particles as far away as 1 m from the reflective riverbed may affect the BT velocity measured. However, the echo intensity from suspended sediment is usually much lower than the scatter intensity from the reflecting riverbed.

A reduced temporal-spatial resolution of this first modulation combines with long periods of emission and reception that usually yields few estimations of the BT velocity for an individual ensemble, whereas short pulses used for water velocity profiling displays repeated assessments within an individual ensemble that strongly reduces the corresponding standard deviation. However, for Teledyne-RDI ADCPs, Simpson [33] estimated the BT velocity error in the order of 1 mm s^{-1} for a long individual pulse, a discrepancy susceptible of being diminished by including more pulses within a longer ensemble. In addition to that error, the accuracy of the integrated compass into the ADCP must be considered to estimate the total error in velocity assessments eventually. The compass assesses the velocity vector components in the Earth reference system (i.e., North, East, and Vertical) in combination with a DGPS. The compass accuracy reported by the manufacturer is ± 2° [37] while Rennie et al. [29] argued that an error of 2° could generate an error of 3.5% in the BT velocity vector component.

Finally, positioning errors strongly depend on the DGPS system being used. For the present study, these errors gave rise to ADCP actual velocity (v_{DGPS}) errors of about 0.004 m s^{-1} on average and 0.024 m s^{-1} as a maximum for sampling frequencies of 5 Hz that were further reduced to 0.002 m s^{-1} and 0.007 m s^{-1}, respectively at 1 Hz.

2.4. Bedload estimation by means of dune tracking

Dune tracking has been the most widely applied method to estimate bedload in the Paraná River [3], where the deployment of bedload

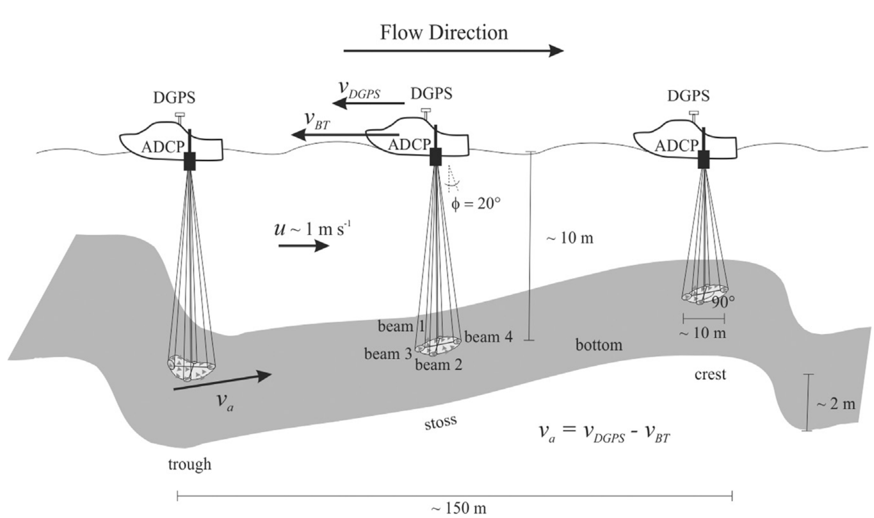

Fig. 2. Location of the static measurements along each dune, ADCP beam alignments, and corresponding footprint at crest, stoss and trough positions. Dune high differs from length scale for a better visualization. Footprints and dune length have approximately the same horizontal scale indicating the ensonified area over the dune resulted from beam spreading.

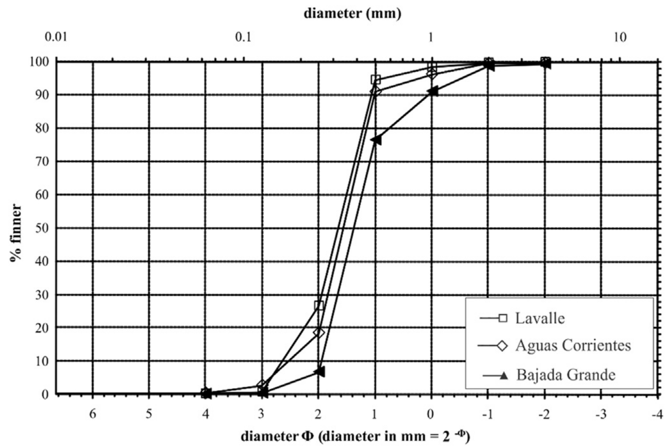

Fig. 3. Grain size distributions of bed sediment for each study zone.

samplers appeared unsafe and in some cases unfeasible [11,23]. This method consists of comparing repeated bathymetric profiles of a dune sequence to infer an average displacement velocity, u_d, and height, H_d, of the measured bedforms that eventually enable the assessment of the bedload rate per unit width [39]:

$$g_{sf} = \alpha(1 - P)H_d u_d + C_1, \quad (2)$$

where P is the porosity of the bed material, α is a shape factor equal to 0.66 according to Amsler and Prendes [3] for asymmetric-triangular dunes in the Paraná River and C_1 represents the portion of the bedload flux that does not participate in the downstream translation of the bedform (i.e., particles that jump from one bedform crest to the next bedform downstream and small superimposed bedforms crossing over lee sides) [11].

2.5. Bedload estimation by the kinematic model

The kinematic model reported herein to validate ADCP data is a function of i) bed-particle velocity of a mean riverbed particle representing the sediment distribution, u_b, ii) the thickness of the bedload active layer, δ_b, and iii) the volumetric concentration of sediment particles in that layer, c_b. Consequently, it amounts to estimate the bedload rate per unit width (g_{sf}) according to the expression

$$g_{sf} = u_b \delta_b c_b, \quad (3)$$

[39,40]. Following Villard et al. [40], there are two possible methods to assess the bedload rate in sandy-bed rivers with Eq. (3). First, Van Rijn [39] expressions were used to compute bed-particle velocity, the thickness of the transport active layer (assuming it equal to the saltation height of particles) and volume concentration of particles in the transport layer. The reader is referred to Van Rijn [39] publication, where all the variables involved expressed regarding the dimensionless particle and bed-shear stress parameters, which, in this case, were obtained from ADCP measurements. The dimensionless particle parameter depends on the mean diameter of bed particles affected by the relative density of bed sediment, gravity and kinematic viscosity of water. The dimensionless bed shear stress parameter is a pondered value of the effective bed-shear stress regarding the Shield's critical value. The effective bed-shear stress was calculated from Van Rijn [39], where the specific weight of water, mean flow velocity and grain-related Chézy-coefficient (as a function of mean depth and $3d_{90}$) take place. The other option to use Eq. (3) is to test the performance of the ADCP for estimating the velocity of particles moving close to the riverbed. In this sense, records of this latter at dune crests were utilized in Eq. (3) (replacing u_b) to estimate the bedload rate. The assumptions were that apparent values were approximately equal to the actual ones ($v_a \approx v_B$) and the maximum rate of bedload may be expected at dune crests, regarded as being responsible for the displacement of dunes [7]. The other method assumes δ_b and c_b as constant values, therefore, the classical values from the literature were employed [5,9], i.e., $\delta_b \approx 2d_{50}$ and $c_b \approx (1 - P)\rho_s$, and $u_b \approx v_B$ again, where $P = 0.4$ for sand. Note that this last method considers the bed-material porosity, rather than a sediment concentration layer above the bed (as Van Rijn suggests) which is equivalent to adopt the maximum possible concentration for a granular bed. Therefore, this is a more rounded approximation in the presence of coarse bed material being transported by rolling and sliding [29].

Results of these three alternatives for each dune, frequency, and pulse length variation, were compared with those obtained by the dune tracking method (Eq. (2)), eventually indicating the reliability of the ADCP method for the estimation of bedload transport.

3. Results

3.1. Riverbed grain-size distributions

The grain-size distributions of bed material sampled by means of drag cones are reported in Fig. 3 for each surveyed dune. Fine material, i.e., finer than 62 µm, is negligible in the bed of large alluvial rivers [22]. This is particularly true in the main channel of the Paraná river where the volume of fine fraction resulted lower than 0.1% [3]. The corresponding characteristic diameters d_{16}, d_{50}, d_{84}, (i.e., 16%, 50%, and 84% finer) and geometric deviations (σ_g) are summarized in Table 1. These values reflected well-sorted sediment forming the riverbed with spatial homogeneity considering the distance among the sections. Due to the technique used and the complexity to sample the bed material in a large river like the Parana, the exact position of each sample along the dunes was not possible to determine. However, these values were in agreement with several studies regarding the riverbed sediment in the main channel of the Parana River [3,8] which reflected a weak variation of grain size along dunes.

3.2. Dune morphology and bedload rates

Table 2 includes measured dune length (λ_d) and height (H_d) and the angle of the lee side of the dune for the three river sections studied. The dune length was measured between two consecutive troughs while dune height was considered as the perpendicular distance between the crest level and the dune length segment as sketched in Fig. 4-a. By the same token, Table 2 presents the corresponding flow discharge (Q) at the cross section, mean overall water depth (h) and flow velocity (u) along the dunes, measurement period (dt) between consecutive bathymetric records, and the resulting dune-velocity (u_d) and bedload rate (g_{sf}) assessed with Eq. (2), where C_1 was assumed equal to zero based on low values of the dune lee-side angles and the fact that no small superposed bedforms were observed over lee sides of the dunes analyzed.

Values of g_{sf} in Table 2 were obtained considering quartz sediment density (ρ_s equal to 2,650 kg m^{-3}) which was previously documented in the literature for the investigated Parana River section [3]. Fig. 4

Table 1
Characteristic diameters (mm) and geometric deviations of bed grain size distributions at study zones.

	d_{50}	d_{16}	d_{84}	σ_g
Lavalle	0.31	0.19	0.44	1.52
Aguas Corrientes	0.34	0.22	0.48	1.48
Bajada Grande	0.39	0.29	0.7	1.55
Average	0.35	0.23	0.54	1.52
Standard deviation	0.04	0.05	0.14	0.04

Table 2
Dune characteristics, mean flow parameters from ADCP profiling and assessed bed-load rate by applying Eq. (2) considering quartz sediment.

Zone	Date	Discharge m³ s^{-1}	λ_d, m	H_d m	Lee side angle °	h, m	u m s^{-1}	dt hours	u_d m d^{-1}	g_{sf}, kg (ms)$^{-1}$
Lavalle	6/2/11	17,100	185.3	2.35	8	9.17	1.05	42.2	2.8	0.09
Aguas Corrientes	4/26/12	12,500	134.3	2.38	9	18.5	1.45	6.5	3.9	0.11
Bajada Grande	7/26/12	16,000	138.7	1.78	5	9.51	1.18	48.5	2.6	0.06

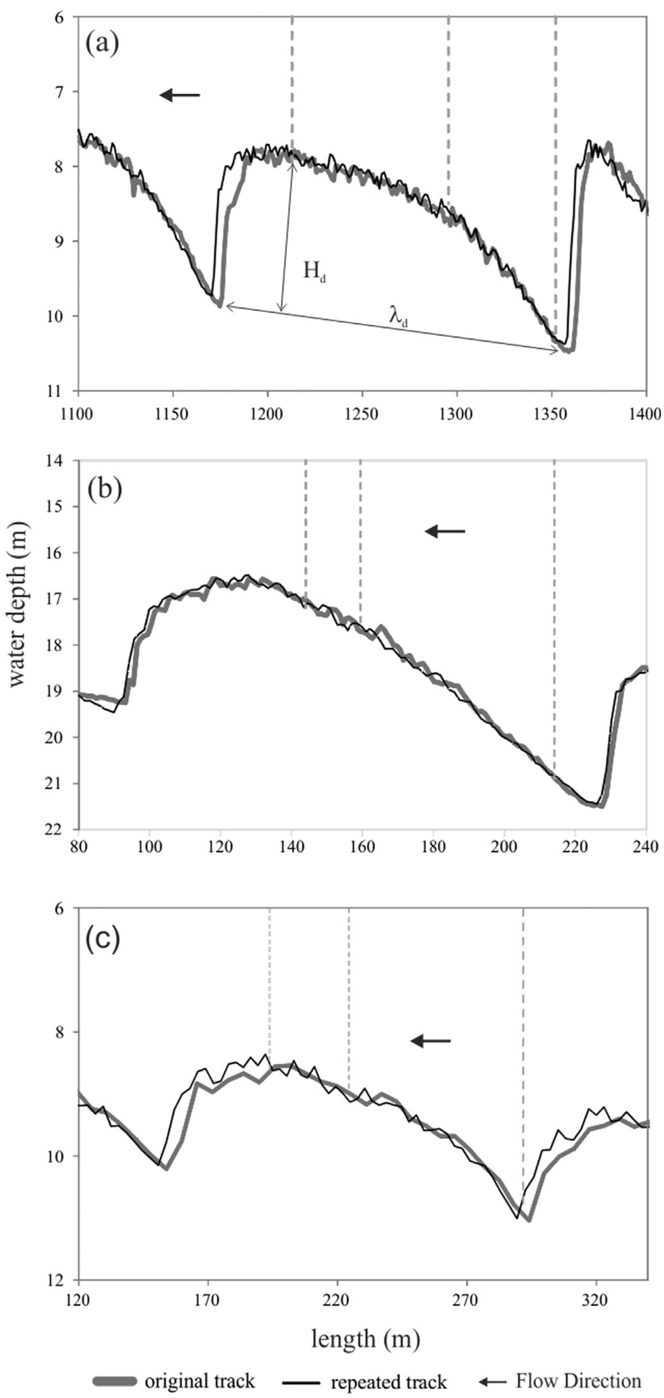

Fig. 4. Bathymetric profiles from dynamic measurements in (a) Lavalle, (b) Aguas Corrientes and (c) Bajada Grande. Vertical dashed lines show fixed positions where ADCP static measurements were performed.

displays the dune morphology profiles.

Next, a brief description is provided for the observed hydraulics over the dunes at all zones just to contextualize the results within the framework of the intended acoustic methodology. There is no attempt to advance knowledge about the dynamics of flow over dunes.

The resulting mean water surface slopes along the dune profiles investigated were in the order of 10^{-5}, which agrees with previous findings regarding the Parana River [3,22,25]. The lee side angle corresponding to the upstream side of dune trough was equal to 8°, 9° and 5° for those found at Lavalle, Aguas Corrientes, and Bajada Grande, respectively. Small bedforms superimposed to the dunes were also observed (Fig. 4), and characterized by an increasing wavelength in the direction of the streamflow acceleration towards dune crests. These small bedforms were not observed on the lee side of all studied dunes, which may be an evidence of flow separation and no overestimation of g_{sf} computed from Eq. (2) [26,34]. The observed superimposed bedforms have average wavelengths of 4.7, 5.4, and 8 m and mean heights of 0.19, 0.40, and 0.3 m in Lavalle, Aguas Corrientes, and Bajada Grande, respectively. Particularly relevant for the application of BT function, these small bedforms may interfere with the acoustic beams footprint; indeed, each beam may encompass a part of, an entire or a couple of these bedforms, eventually resulting in a spatial average from high and low-velocity zones.

Rennie et al. [29] reported the ADCP measurement volume over the riverbed as a function of the transducer radius, the half-intensity beam width, the flow depth and the beam angle. The projected area over the riverbed of the BT sample volume corresponded, consequently, to a quasi-elliptical footprint for each acoustic beam with an equivalent circumference having a diameter of 0.29, 0.55 and 0.31 m for Lavalle, Aguas Corrientes, and Bajada Grande, respectively. Moreover, the overall ensonified areas between beams footprint were enclosed in a circle with a diameter of 6, 13.9 and 6.2 m at crest zone in Lavalle, Aguas Corrientes, and Bajada Grande, respectively. Those were of the same order of magnitude as the wavelength of superimposed bedforms in the corresponding zones.

3.3. Apparent bed-particles velocity resulting from the ADCP-BT method

The tracks of ADCP displacement, recorded during static measurements, were different (Fig. 5) as resulting from the DGPS recording and by using the BT function capability. These tracks correspond to ADCP measurements performed in different positions along the dune profiles (i.e., crest, stoss side and trough); the exact positions of these static measurements along dune profiles can be seen in Fig. 4. It is worth noting that the boat anchoring produced a lateral movement perpendicular to the streamflow direction. This lateral movement was accurately recorded with the DGPS, which resulted in less than 10 m in most of the cases (Fig. 5) and gave the ADCP actual velocity, v_{DGPS}. Aiming to estimate the velocity of particles moving close to the riverbed, the DGPS recording (i.e., v_{DGPS}) was applied to Eq. (1), eventually inferring the apparent velocity of bed-particles,v_a. Fig. 5 compares ADCP tracks corresponding to crest, stoss side, and trough positions, which turns out particularly relevant for verifying the reliability of the ADCP-BT method to estimate bedload rate. The spatial variability should provide evidence on the method applicability in positions with different bed dynamics.

In the trough position at Aguas Corrientes, the anchoring was particularly challenging because the high flow velocity ($u \geq 1.45$ m s^{-1}) and considerable water depth (> 20 m). The helmsman managed to

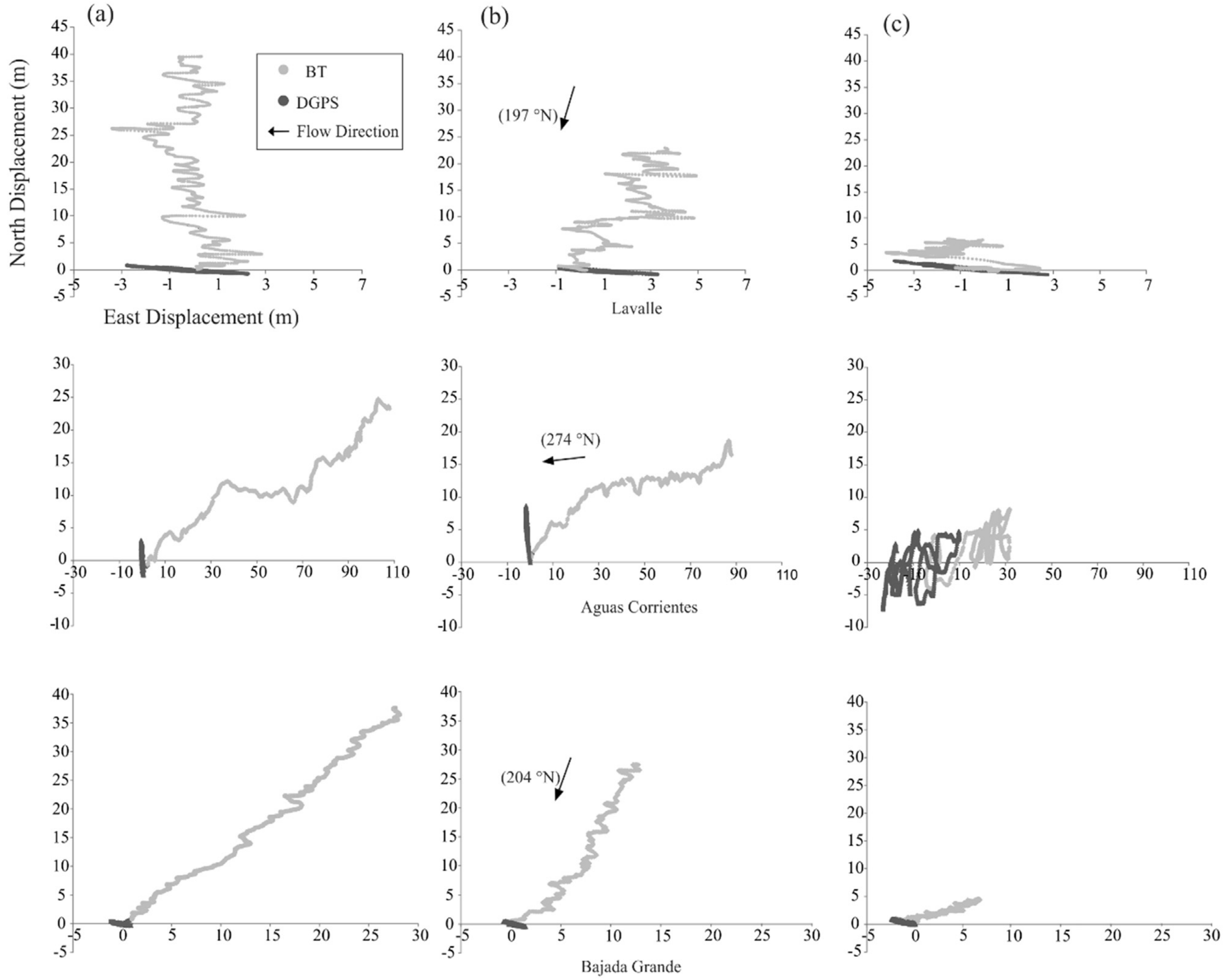

Fig. 5. ADCP tracks inferred by using the BT function of the ADCP and DGPS real time positioning during measurement periods of 15 min. Fixed positions corresponding to dune a) crest, b) stoss side and c) trough in Lavalle, Aguas Corrientes, and Bajada Grande.

maintain the boat as steady as possible. The largest apparent displacements were observed at dune crest locations while they systematically reduced when passing through the dune stoss side and trough. These visible changes of the ADCP position were 40-25-9 m, 113-92-30 m and 50-33-9 m in the upstream direction for dune crest-stoss-trough positions in Lavalle, Aguas Corrientes, and Bajada Grande, respectively.

The ADCP actual tracks measured with DGPS were depicted on geographic axes eventually assessing v_{DGPS} vector components according to Eq. (1), where the v_{BT} components corresponded to ADCP displacements from BT capability (Fig. 5). A reliable predictor of the bedload was consequently the magnitude, $v_a = v_B$, and direction, θ, of the apparent velocity. These features of the sediment flux would reflect a more homogeneous velocity field over dune crests rather than for corresponding troughs (Fig. 6). For example, the streamflow resulted pretty well aligned with the bedload velocity; i.e., the corresponding directions were similar at dune crest positions (197° in Lavalle, 274° in Aguas Corrientes and 204° in Bajada Grande). Although instrumental inaccuracies may hinder the investigation for very low velocities, e.g. within the dune trough, a low-frequency period characterized the time series assessed for dune trough in Aguas Corrientes (Fig. 6-b, right). This low-frequency period may reflect the oscillation induced by a large rotating flow structure [26,34], although the boat drift may also have affected the resulting values.

Table 3 reports the estimated magnitude and direction of time averaged values of bed particles velocity ($\overline{v_B}$) over the dune crests, stoss and lee sides. The reported values are both for the 1200 kHz and 600 kHz ADCPs in the case of Aguas Corrientes and for the &R10 and &R40 pulse lengths in the case of Bajada Grande (the &R30 pulse length measurement was discarded due to anchoring problems).

Table 3 also includes the standard deviations values for $\overline{v_B}$, obtained by summing the corresponding vector component variances [19]. Time-averaged velocity was higher in Aguas Corrientes, where both mean flow velocity and depth were the highest recorded by the ADCP (Table 2). Bed-load rate from dune tracking was also the highest in this zone, thus corroborating the reliability of the bedload rate predictor using the ADCP method.

Relevant deviations arose for bed-particle displacements (magnitude and direction) in the stoss and trough positions when compared to values in the dunes crest. These deviations reflected different velocity values of particles transported throughout the trough (low-zero velocities), stoss side (medium velocities) and crest (highest velocities) positions. All these observations confirmed the behavior of bed-sediment transport along dunes and the capability of the ADCP-BT method to register the bed-particle displacements (magnitude and direction) in crest versus the stoss and trough positions. Moreover, the differences registered at each zone along the studied dunes suggest the importance of the static measurement location to quantify $\overline{v_B}$ in order to predict g_{sf}.

The observed flow velocities corroborate the findings regarding bed

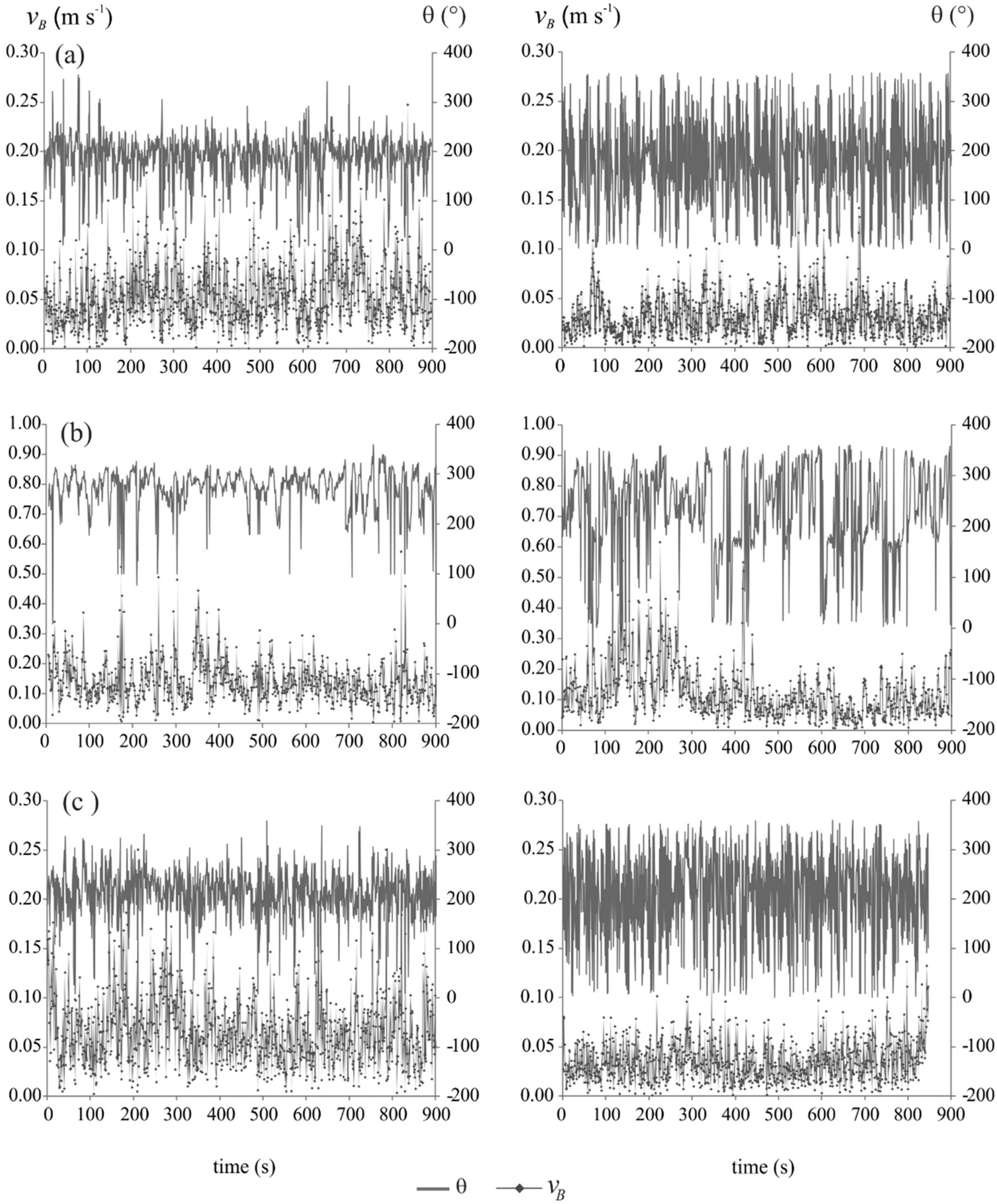

Fig. 6. Magnitude and direction of bed-particle velocity vectors assessed by applying Eq. (1) for dunes crest (left) and trough (right) in (a) Lavalle, (b) Aguas Corrientes and (c) Bajada Grande.

particles velocity. Table 4 shows time-averaged values of the depth-averaged flow velocity, u, and the corresponding standard deviations, σ_u, at the crest, stoss side, and trough of the studied dunes. In addition, time-averaged flow velocity values and standard deviation are reported for the deepest bins measured by ADCPs, which were approximately in the 10% of water depth at bottom, $u_{O.1h}$ and $\sigma_{O.1h}$, respectively in Table 4. In any case, velocity values systematically reduced when passing from crest to dune stoss side and trough. Furthermore, near-bed velocities appeared more biased than depth averaged values, which reflected acoustic beams divergence in the acoustic far range.

Finally, to evaluate the measurement period, a simple analysis using running averages of bed particles velocities obtained from BT measurements showed that a period of 8–9 min gets ± 10% of the mean value for 15 min (Fig. 7).

3.4. Effect of ADCP frequency on bed-particles velocity

In Aguas Corrientes, mean bed-particles velocities, $\overline{v_B}$, inferred by applying the 1200 kHz ADCP were 2.4, 1.9 and 3.5 times the corresponding values derived from 600 kHz data recorded above dune crest, stoss and trough, respectively (Table 3). Though those ratios in $\overline{v_B}$ were close to a multiple of two, they were not linearly correlated with the given frequency change [12]. These deviations were likely related to the changing sensitivity of applied frequencies with the actual grain

Table 3
Time-averaged magnitude of bed-particle velocity vector v_B (m s^{-1}), direction θ (degrees [°] referred to North) and standard deviations using different acoustic frequencies and pulse lengths.

Zone	Crest				Stoss				Trough			
	$\bar{v}_B$	σ_{v_B}	$\bar{\theta}$	σ_θ	$\bar{v}_B$	σ_{v_B}	$\bar{\theta}$	σ_θ	$\bar{v}_B$	σ_{v_B}	$\bar{\theta}$	σ_θ
Lavalle[a]	0.045	0.04	187	47	0.027	0.04	206	68	0.006	0.04	189	99
Aguas Corrientes[a]	0.124	0.10	270	42	0.099	0.12	260	62	0.050	0.15	227	91
Aguas Corrientes[b]	0.053	0.06	200	50	0.053	0.06	201	45	0.014	0.05	165	86
Bajada Grande[a]	0.052	0.05	212	49	0.036	0.05	200	60	0.009	0.04	204	92
Bajada Grande[c]	0.046	0.06	214	65	–	–	–	–	–	–	–	–
Bajada Grande[d]	0.061	0.05	213	40	–	–	–	–	–	–	–	–

[a,b] 1200 and 600 kHz-ADCP, respectively, with & R20 pulse length.
[c,d] & R10 and & R40 pulse lengths, respectively, for 1200 kHz.

Table 4
Time-averages and standard deviations of depth-averaged flow velocity u (m s^{-1}) and near-bed flow velocity $u_{O.1h}$ (m s^{-1}) for different locations. Near-bed flow velocity corresponded to ADCP bins at ~0.1 of the water depth.

Zone	Crest				Stoss				Trough			
	u	σ_u	$u_{O.1h}$	$\sigma_{O.1h}$	u	σ_u	$u_{O.1h}$	$\sigma_{O.1h}$	u	σ_u	$u_{O.1h}$	$\sigma_{O.1h}$
Lavalle	1.123	0.200	0.893	0.233	1.019	0.213	0.877	0.193	0.912	0.213	0.478	0.274
Aguas Corrientes	1.479	0.233	1.187	0.267	1.410	0.254	1.131	0.324	1.375	0.248	0.805	0.390
Bajada Grande	1.247	0.208	1.008	0.237	1.204	0.206	0.934	0.242	1.018	0.200	0.694	0.221

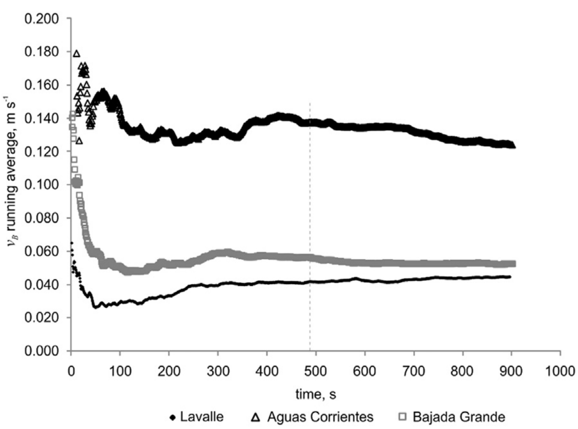

Fig. 7. Running averages of v_B at the crest of the dunes analyzed.

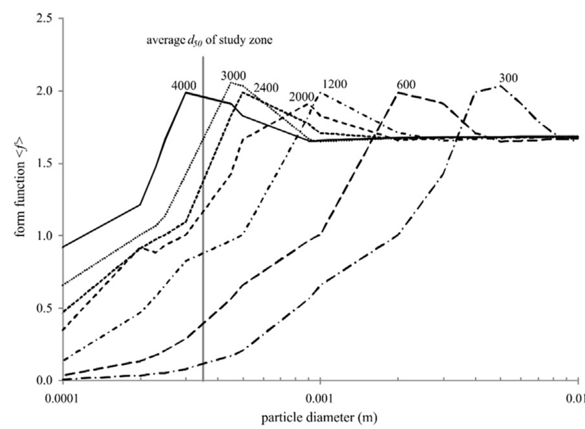

Fig. 8. Backscatter form function $\langle f \rangle$ for different acoustic frequencies and bed-particle average size.

size distribution of sediment forming the riverbed and dominating the laden fluxes close to the riverbed. This distribution included particle diameters in the range of 0.06–2 mm (Fig. 3). Using 1200 and 600 kHz frequencies entailed a noticeable decrease in the backscatter form function $\langle f \rangle$ [38] for particles finer than 0.38 and 0.77 mm respectively, which is related to the transition from Rayleigh to geometrical scattering. Indeed, assuming negligible sound attenuations along short paths (i.e., the movable sediment layer thickness, δ_b), the observed deviation from frequencies should be only produced by the form function change. Therefore, $\langle f \rangle$ values were assessed following Thorne and Meral [38], and considering a normal distribution, which represented the well-sorted sediment forming the Parana riverbed. These values were 1.23, 0.72 and 1.08 for 1200 kHz in Lavalle, Aguas Corrientes, and Bajada Grande, respectively. Meanwhile, $\langle f \rangle$ was equal to 0.27 for 600 kHz (used in Aguas Corrientes only). In other words, the 1200 kHz ADCP acoustically sampled a broader range of particles corresponding to the actual distribution of sediment forming the Parana riverbed. On the contrary, the 600 kHz frequency is sensitive to coarser fractions, characterized by particles moving at slower velocities, which biased its measuring in the Paraná riverbed.

Fig. 8 shows $\langle f \rangle$ as a function of sediment particle size for different acoustic frequencies. This was assessed under Thorne and Meral [38], by assuming the normal distribution of sediment grain sizes with $\kappa = 0.4$, where κ is defined as the ratio of the mean size of particles to standard deviation [38]. Given the observed d_{50} of 0.35 mm, a frequency close to 4000 kHz would correspond to the maximum value of the form function value, which may improve the performance of the ADCP-BT method to predict bed particles velocity though this high frequency is not available for commercial ADCPs. This frequency would correspond to Rayleigh-geometrical scattering. Indeed, geometrical scattering is not dependent on the frequency that may produce a frequency-unbiased assessment of bed particles velocity.

In this case study, the 1200 kHz reduced backscatter sensitivity in the Rayleigh regime corresponded to the fine sizes of sediment forming the riverbed that eventually underestimated the actual bed-particles velocity. In other words, the 1200 kHz backscatter was mostly due to the coarse particles of the real grain size distribution forming the riverbed. This frequency dependence corroborates the thesis that the ADCP-BT method underestimated the actual bed-particles velocity. Indeed, coarse particles giving the most of the backscatter are poorly loose particles among the sediment forming the riverbed. This echo response from bed-particles also agrees with even lower velocities inferred from 600 kHz data. In this case, the maximum of backscatter

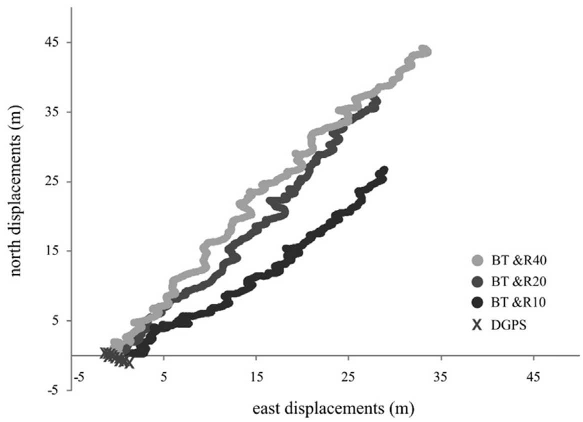

Fig. 9. Relative boat displacements according to BT function and DGPS of static measurements over the dune crest in Bajada Grande, for different acoustic pulse lengths (& R).

is expected for particles larger than 0.7 mm, which corresponded, for example, to d_{84} in Bajada Grande (Table 1).

3.5. Effect of ADCP pulse length on bed-particles velocity

Differences in the bed particles velocity were observed among different pulse lengths (& R10, & R20 and & R40) in Bajada Grande (Table 3). The effect of these deviations was also reflected in the boat displacement which is referred to bottom by BT function with changing pulse length (Fig. 9). Observed deviations were equal to −12% and +17% of the value corresponding to the default setting (i.e., & R20) for & R10 and & R40 pulse lengths, respectively. The observed increment of bed-particle velocity with pulse length corroborates the effect of water bias as defined by Gaeuman and Jacobson [10], i.e., particles transported in full suspension above the riverbed and much faster than bedload particles affect the ADCP capability of tracking the river bottom. Indeed, the increase in pulse length thickened the sample volume, which embedded heavily laden flux of full-suspended sediment close to the riverbed, therefore biasing the actual bedload flux. Thus, the present results confirm that the water bias [27,29] may deteriorate the reliability of ADCP method to predict the bedload rate in sandy rivers. This result requires the assessment of the correlation between pulse length and predicted bedload rate, as further clarified in the next section.

3.6. Comparison of bedload rates

With the aim to evaluate the performance of the ADCP-BT method in predicting the bedload rate in sandy rivers, Table 5 compares the kinematic model results, Eq. (3), with $u_b \approx \overline{v_B}$ (labeled b) and considering $\delta_b \approx 2d_{50}$ and $c_b \approx (1-P)\rho_s$ (marked c), both against values obtained by the dune tracking method (marked d), as described in Section 2.5. For the sake of comparison, the performance of Van Rijn semi-empirical model (labeled a) was also evaluated, which represent a standard application for river morphodynamics assessments. In that regard, the resulting bedload rates of methods b and c underestimated the values from Van Rijn semi-empirical model (compare methods a with b and c, Table 5). Moreover, for this semi-empirical model (method a) deviations of matching values from dune tracking (method d) changed from 6% to 305% from Lavalle to Bajada Grande. Better performances with deviations ranging between −86% to −53% and −52% to 14% resulted when computing δ_b and c_b from Van Rijn (method b) and considering as constant values ($\delta_b \approx 2d_{50}$ and $c_b \approx (1-P)\rho_s$) (method c), respectively. No improvement in bedload estimates was achieved using the lower frequency in Aguas Corrientes, where the deviations of matching values from dune tracking reduced from −32 to −71% to 20 to −49% when using the method b and c, respectively. Finally, the best performance may be argued for the shorter pulse length (i.e., & R10) applied in Bajada Grande, although the resulting deviations from dune tracking poorly changed when combining the bed-particle velocity to Van Rijn estimations of method b. On the contrary, these variations passed from 33% to 14% and 1.8% when changing the pulse length from 40% to 20% and 10% of the water depth (at the given frequency of 1200 kHz) and considering a constant active layer of sediment and bed concentration.

4. Discussion

The apparent velocities of bed particles measured with the ADCP-BT procedure were appreciable and aligned with the mean flow in sections located on dune crests, whereas lower velocities were measured at dune troughs with time averaged values close to zero. These small values are evidence of random recirculation and/or flow stagnation at that sites though the overall direction remained downstream oriented. Therefore, the exact positions along the observed dunes where the ADCP-BT procedure was applied were extremely relevant to make up consistent comparisons with bedload rate values from dune tracking. Indeed, dune tracking technique appeared feasible and accurate to yield matching values for point estimations of bedload rate from ADCP-BT method, although the first delivers average bedload rate values over a dune wavelength. These values must be compared to point bedload rate values from ADCP-BT method applied on dune crests, which apparently best represent bedform displacement rates. This correlation between bedload and bed displacement rates along the investigated dunes agrees well with flow velocities gradients observed by means of ADCPs. In fact, both the depth-averaged and near-bed flow velocities were maximal at dune crests.

Table 5
Comparison of g_{sf} values in kg $(ms)^{-1}$ from the kinematic model applications (Eq. (3)) and using dune tracking method (DT).

Zone	u_b [α]	δ_b [α]	c_b [α]	g_{sf} [a]	g_{sf} [b]	g_{sf} [c]	g_{sf} [d]	Deviation from DT (%)		
	m s^{-1}	m		kg s^{-1}	kg s^{-1}	kg s^{-1}	kg s^{-1}	(g_{sf} a/d)	(g_{sf} b/d)	(g_{sf} c/d)
Lavalle[e]	0.3396	0.0010	0.1034	0.097	0.013	0.044	0.092	6	−86	−52
Aguas Corrientes[e]	0.4688	0.0015	0.1500	0.284	0.076	0.135	0.112	155	−32	20
Bajada Grande[e]	0.4502	0.0018	0.1087	0.228	0.026	0.065	0.057	305	−53	14
Aguas Corrientes[f]				–	0.032	0.057	0.112	–	−71	−49
Bajada Grande[g]				–	0.024	0.058	0.057	–	−59	1.8
Bajada Grande[h]				–	0.031	0.076	0.057	–	−45	33

[a] following Van Rijn (1993) [39],
[b] following Van Rijn (1993) [39] with $u_b = \overline{v_B}$,
[c] assuming $\delta_b = 2d_{50}$ and $c_b = (1-P)\rho_s$ and $u_b = \overline{v_B}$,
[d] dune tracking values.
[e,f] 1200 and 600 kHz-ADCP, respectively, with & R20 pulse length.
[g,h] & R10 and & R40 pulse lengths, respectively, for 1200 kHz.

The results of Table 5 suggest some observations that encourage the discussion about the performance of different methods to estimate the bedload rate. The Van Rijn semi-empirical expressions assume that bed sediments are transported mostly by saltation. This mode of sediment transport occurs when the values of the parameter w_s/u_* (i.e., bed-sediment settling velocity over shear velocity) range between 0.6 and 2.0 according to Raudkivi [28]. Values within this range are obtained in the Paraná River when the parameter is computed with the mean diameters of its bed sediment. The ADCP-BT method biases the results towards the coarse fractions of the actual distribution of sediment forming the riverbed; in part due to the dominant backscatter effect of those fractions as discussed in Section 3.4. Thus, considering representative sizes of coarse fractions (i.e., d_{90} and d_{95} from Fig. 3, as reference sizes for settling velocities), w_s/u_* values reaches and exceeds (respectively) the threshold of 2, which means rolling and sliding mechanisms in bed load transport according to Raudkivi [28]. This correspondence would explain the underestimation of resulting bedload rates from BT methods (b and c) compared to Van Rijn values (method a).

Using the measured bed particles velocity instead of the semi-empirical expression of Van Rijn for u_b yielded a more reliable predictor of the bedload rate. Indeed, the g_{sf} values in alternative b which combined the ADCP-BT method with δ_b and c_b of Van Rijn were more consistent with deviations up to 86%, although systematically underestimated the dune tracking results. Deviations of method c peaked 52% with underestimations (Lavalle) and overestimations (Aguas Corrientes and Bajada Grande). A simple test for proving an unbiased predictor consisted in verifying a constant deviation from matching values (% columns in Table 5) whatever the application (i.e., Lavalle, Aguas Corrientes, Bajada Grande), in other words, a constant calibration factor may be applied to reduce predicted to actual value deviations. This calibration test was clearly not the case for Van Rijn semi-empirical model. As said, better performances resulted when computing δ_b and c_b from Van Rijn (method b) and considering as constant values (method c), respectively. Based on those ranges, a constant calibration factor would result in maximum expected errors of 29% and 46% for predicted to matching values, which indicate a better performance when combining bed-particle velocity from ADCP-BT method to Van Rijn semi-empirical estimation of δ_b and c_b. Nevertheless, the surrogate method should yield higher or equal rates of bedload compared with dune tracking because the effects of resuspension occurred downstream of the crest and/or the crossing of small bedforms superimposed over the lee side of the dune (i.e., $C_1 > 0$ in Eq. (2)). Both of these process may be responsible for lower bedload rates determined by dune tracking; therefore, method c seems more reliable than b, because of the overestimation. Synthesizing, results of both alternatives, b and c, show the possibility of using the ADCP-BT procedure as an unbiased predictor of bedload rates with better performance than semi-empirical formulations as the one of Van Rijn´s.

It is important to highlight that alternatives b and c imply dissimilar conceptions of the same phenomenon. The first one accounts for the bed particles saltation height δ_b and the volume bedload concentration c_b varying according to Van Rijn [39] formulations. In the case c, both parameters are nearly constant values, i.e. $\delta_b \approx 2d_{50}$, where d_{50} has small variations in the Paraná River (see Table 1 and Fig. 3, and Drago & Amsler [8]) and c_b was equal to ~0.60 which is the maximum possible concentration in a granular fixed bed. Comparing alternatives b and c, it is satisfied (with a high probability) that $\delta_b > 2d50$ and $c_b <<< 0.6$. Indeed, focusing on the physics of the phenomenon, empirical methods (e.g. [28]) show that saltation does exist in a mobile sandy bed composed of fine and medium sand and subjected to bed shear velocities as those in the Paraná River bed, even though saltation were small, i.e., on the order of a few diameters. On the other hand, the expected porosity of moving bed particles of a sandy bed, even with coarser sizes, should be higher than 0.4. That is, a compensation of differences exists in such a way that the results were improved in alternative c but without a clear physical meaning. The thickness of the active bedload layer and its concentration especially in sandy rivers, are topics which still remain without a complete understanding. Thus, further research is needed especially in laboratory, if reliable values of these variables are intended to use in Eq. (3).

The underestimations of the apparent velocity when using the 600 kHz ADCP are due to the biasing towards the higher geometrical backscatter of coarse fractions of the riverbed. The threshold between Rayleigh and geometrical regimes of this frequency is a larger particle size (i.e., 0.7 mm) which is more sensitive to particles transported by sliding or rolling than by saltation. The result is lower apparent velocities. A higher frequency ADCP (e.g., 3000 kHz) would likely give more accurate values by limiting the backscatter of coarse fractions (see Fig. 8), although this underestimation of the apparent velocity does not appear as relevant biasing since the texture of a sandy river remains homogeneously distributed among the investigated regions. Also, a high frequency, such 3000 kHz, would noticeably reduce the water profiling range to shallower streams, i.e., 5 m water depth. However, in terms of bedload rates, it could be assumed that uncertainties of the ADCP-BT method scale with the observed deviations from dune-tracking values. Therefore, using the lower frequency in Aguas Corrientes the performance of the bedload rate predictor was clearly poorer. Note that deviation reduced from −32 to −71% and from 20 to −49% when using the method b and c, respectively.

Smaller BT pulse lengths yielded lower bedload rate deviations for the same location and frequency (i.e., 1200 kHz). A small pulse length reflects a thinner measurement layer over the riverbed thus reducing the contribution to backscatter of sediment in full suspension close to the riverbed. This source of water bias affects particularly the actual velocity of bed-particles over dunes. Note those deviations of estimated bedload decreased from 33% to 14% and 1.8% (Table 5) for &R40 to &R20 and &R10, respectively (i.e., pulse length equal to 40%, 20% and 10% of the water depth) in Bajada Grande. This improvement was verified in the results of alternative c, i.e. with constant values of c_b and δ_b. It remains to check this reduction of deviations by using actual values of these two variables. Table 5 shows that deviations maintained near equal to 50% whatever the pulse length in alternative b which combines the apparent velocity with values of δ_b and c_b from the Van Rijn semi-empirical model.

Summarizing, to use a shorter acoustic pulse length to measure the bed particles velocity and combine it with the other two variables in Eq. (3) predicted from a model like the Van Rijn´s, would not be appropriate up to now to estimate bedload rates in the Paraná River. Apparently, constant values of the active layer thickness and bedload concentration seem to be more adequate (though a physically poor based artifact) to use fully the ADCP-BT capability. However, the results obtained therewith are a first verification of the thesis that the apparent velocity may be used as an unbiased predictor of the bedload rate in a large sand bed river.

5. Conclusions

The ADCP-BT technique used to measure the apparent velocity of bed-particles already tested in gravel bed rivers, was applied herein in a large sandy bed river at different sections, flow conditions, ADCP frequencies (1200 and 600 kHz) and pulse lengths. The objective was to investigate its potential use as an unbiased bedload rate predictor under sand bed conditions. The results of experiments were tested against dune tracking values (i.e. matching values) and the Van Rijn semi-empirical model assessments. When compared to this model the average errors by using the ADCP-BT method reduced from about 150–25%, which illustrates its potentiality to obtain reliable bedload values.

The knowledge of the sand bed texture may improve the bed load predictions since enables to select the best ADCP frequency by assessing the particles most affecting the overall backscatter from bedload content. The water bias from sediment transported in full suspension close to the bottom was noticeably decreased by reducing the BT pulse length which further contributed to improving the bedload predictor performance.

Though the results of these field experiments corroborate the thesis about using the apparent velocity as an unbiased predictor of bedload rate in large sandy rivers with bedforms, additional investigations are required to elucidate further the role of bed composition on the apparent velocity for a wider sample of river flows and particle sizes. Moreover, field, as well as experiments, should also be conducted to include traditional topics in fluvial hydraulics do not still completely clarified concerning the active layer thickness and bed load concentration in sand-bed channels.

Finally, it is important to remark that the improvement of the ADCP-BT technique for bedload rate assessments closes the circle of basic flow measurements possible to perform with a unique ADCP, i.e. flow, suspended bed-sediment and bed load transports. This combination implies a substantial advance since enables future detailed field investigations of intricate processes such as interactions of sediment particles with flow structures and morphodynamic changes over dunes in large rivers.

Acknowledgments

The authors would like to acknowledge gratefully the help supplied by Roberto Mir and Santiago Cañete during the field measurements. This research was funded by the Secretary of Science and Technology, Universidad Nacional del Litoral, Santa Fe, Argentina [conducted within the framework of the research grant CAI+D 2011 "Analysis of construction processes in the floodplain of a large river: the Rio Paraná in its middle reach" and CAI+D 2011-Proyecto Joven "Sediment transport in alluvial rivers: development of methods for measurements based on acoustic Doppler technology"]; financial support from CONICET is also gratefully acknowledged.

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