The investigation of sediment processes in rivers by means of the Acoustic Doppler Current Profiler

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Measurement of bed-sand transported in river streamflow is desirable for the evaluation of many issues related to rivers evolution. The Acoustic Doppler Current Profiler (ADCP) was used to assess (i) the backscatter from suspended particles to be related to suspended-load, and (ii) the Doppler velocity induced from moving particles at the river-bed thus inferring the bed-load rate. Unfortunately, these techniques strongly depend on acoustic properties (e.g., frequency, pulse length) coupling to in field features (e.g., sediment size, bed sedimentology and roughness). Aiming to reduce the inherent ambiguities in acoustic methods, laboratory and field tests were conducted. Regarding the sediment transported in full suspension, streamflow conditions were simulated in a large flume to compare multi-frequency ADCP to a laser device in sizing suspended sediment. The ADCP method was also applied to assess the sand concentration and grain size in the large Parana River, Argentina. In addition, in the same river, dune displacement was compared to bed induced bias of bed-load on ADCP's bottom tracking (i.e., the instrument ability of measuring its velocity relative to a fixed bottom) aiming to estimate actual rate of transported sand near bed.

Keywords: Sediment transport in rivers, Multi-frequency, Backscatter, Bias in Doppler velocity

1 INTRODUCTION

The transport of sediments from the river bed has been widely studied to understand the alluvial bed dynamics and its reciprocal feedback with the hydrodynamics. The sediment transport is commonly classified basing on the dominant mechanisms: the bed-load is referred to as the transport occurring near the river bed, in which the stream flow sweeps bed particles over the underlying sand bedforms or gravel bed, whereas particles that are transported fully suspended in the water column give rise to the suspended-load.

Obtaining detailed measurements of sediment transport in a river stream-flow is desirable for evaluating many issues related to river hydro-morphodynamics, such as the effects of climate change on river morphology and riverine habitat, the safety of civil engineering constructions (e.g., bridges, embankments), the maintenance of navigation channels and hydropower intakes.

The development of Acoustic Doppler Current Profiler (ADCP) methods capable of estimating significant physical processes has a great potential for the understanding of sediment transport and morphodynamics in sandy rivers.

In particular, the ADCP was successfully applied to non-intrusively characterize the velocity field, suspended sediment patterns, and bed-load rate in the large Parana River nearby the Santa Fe and Rosario cities in Argentina (Figure 1).

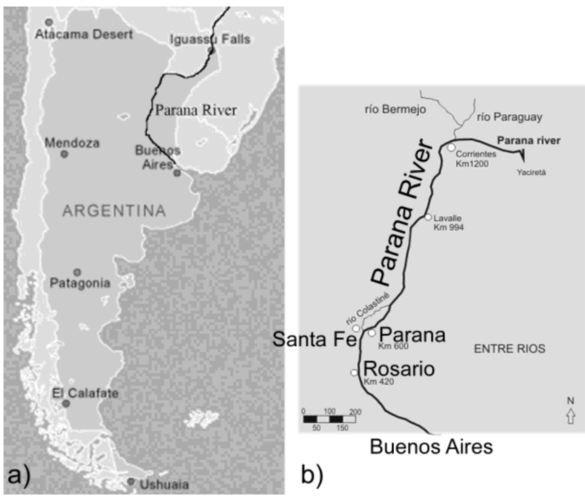

Figure 1: a) Argentina map; b) The Parana River in Argentina.

In more details, a dual-frequency backscatter technique to estimate concentration and grain size of suspended sand was verified under controlled conditions in the large flume of NTNU, Trondheim (Norway) and applied in a cross-section of the Parana river nearby Rosario City. Furthermore, the bed-load was estimated more upstream in the Bajada Grande reach, near to Santa Fe City, by tracking dunes with single-beam sonar along a longitudinal transect, the resulting value was compared to induced bias of bed-load on ADCP's bottom tracking (i.e., the instrument ability of measuring its velocity relative to a fixed bottom).

2 METHODS

2.1 Dual-frequency backscatter from suspended sand

The ADCP provides the echo levels from scattering particles, in logarithmic scale. This data can be applied for the indirect measurement of suspended sand concentration and grain size. The method is based on the principle of a frequency-dependent variation in the backscatter of particles, as was first tested by Hay and Sheng [1].

In the river environment, experiments were performed to measure sediment concentrations, together with grain size profiles using a moving vessel equipped with 1200- and 600-kHz acoustic ADCPs by Teledyne RDI to ensonify the same water column (Figure 2).

Figure 2: 1200- and 600-kHz ADCPs (by Teledyne RDI) installation at vessel side; inactive phase before looking-down actual deployment.

The mass of suspended sediments per unit volume, i.e. the concentration M, is related to the backscattering power as reported by Thorne and Hanes [2]:

$$M = \frac{s}{\sigma} \rho_s \frac{4}{3} \pi a^3 \tag{1}$$

where *a* is the particle radius (particles are assumed to be spherical), ρ_s is the particle density, and the ratio s/σ gives the number of particles for unit volume. *s* is the backscattering power, σ is the backscattering power for an average single particle within the measurement volume (namely, scattering size). The scattering size is related to the physical size by the form factor f, that is a function of k times a (the acoustical wave number-particle radius product, i.e. $x = k.a$). The concentration expressions for the two frequencies yield the relationship to solve for grain size (Equation 2):

$$\frac{\sigma_1}{\sigma_2} = \left(\frac{f_1}{f_2}\right)^2 = \frac{s_1}{s_2} = 10^{\frac{S_1 - S_2}{10}} \tag{2}$$

where the subscripts refer to the applied frequencies. Equation 2, which is not dependent on concentration, gives the current mean grain size of an ensonified volume by the two frequencies. The form factors square ratio (in Equation 2) is a function of the sediment grain size and the applied frequencies through x. An advantage of this method is its ability to estimate the mean grain size in the ensonified volume.

The ADCP-measured echo intensity (in a logarithmic scale) is related to the backscattering power as follows:

$$S - S_c = C + K_c(E - E_r) \tag{3}$$

where C and K_c, are calibration parameters, S_c (namely, the backscattering power correction) includes known terms such as the sound dissipations in water; $(E\text{–}E_r)$ is the measured effective echo intensity which also accounts for echo intensity corresponding to the ambient noise level, E_r; and S is the backscattering power in a logarithmic scale.

The sound dissipation due to the presence of suspended sediment is the sum of two terms: viscous dissipation due to the relative motion between sediment particles and water; and sound scattering by particles. Both terms should be accounted in S_c. Various formulations can be found in the literature to assess these losses; among others, Hanes [3] reported a comparison between the two terms as a function of sediment size and applied frequency, showing a negative correlation between scattering and viscous dissipations.

This dual-frequency method was tested under controlled conditions (i.e., with know distributions of suspended sand) in the large flume of the NTNU university (Trondheim), by deploying the two ADCPs by Teledyne RDI and the laser device LISST-SL by Seguoia Scientific suited for grain size assessment in streamflows. The same method was applied in the Parana River to acoustically infer the transport of suspended sand in a river cross-section nearby Rosario.

2.2 Dune tracking and induced bias on ADCP's bottom tracking

Referring to the large Parana River, acoustic technologies were also applied to estimate the bed-load. Dune displacement was assessed along longitudinal transect (i.e., dune tracking) performed both in the Rosario and Bajada Grande reaches, while the induced bias of bed-load on ADCP's bottom tracking (i.e., the instrument ability of measuring its velocity relative to a fixed bottom) gave an estimation of actual rate of transported sand near bed in the Bajada Grande reach.

The dune tracking consisted to apply single beam sonar in repeated surveys to measure dune geometries and their translation lengths. The bed-load rate in m²/day was therefore assessed as suggested in Gaeuman and Jacobson [4]:

$$g_{sf} = 0.66 \cdot (1-P) \cdot H \cdot V_m \tag{4}$$

where 0.66 is a shape factor, P is the sand porosity, the migration velocity, V_m, is in m/day, and H is the average height over two consecutive profiles of the same dune.

A 1200 kHz ADCP by Teledyne RDI was deployed in three sections to estimate the bed-load rate in the trough, stoss-side and crest positions (Figure 3).

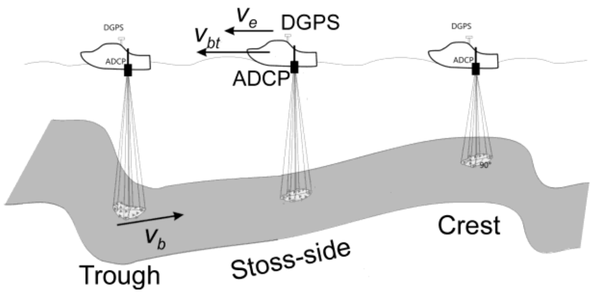

Figure 3: ADCP deployment in the trough, stoss-side and crest of a dune.

The ADCP has the capability of measuring its velocity by detecting the Doppler effect on acoustic beams scattered by a fixed bottom (i.e., bottom tracking capability). The sand that moves near the bottom induces a deviation between the instrument velocity as measured by a Differential GPS and the bottom-tracking, i.e., $V_b = V_e - V_{bt}$ in Figure 3. This deviation was correlated to bed-load as suggested by Rennie et al. [5]:

$$g_{sf} = \rho_s \cdot (1-P) \cdot d \cdot V_b \tag{5}$$

where d is the thickness of the moving layer.

3 RESULTS

3.1 Suspended-load

The laboratory verification of the dual-frequency method for grain size assessment gave an average difference between the measured by LISST-SL and acoustically inferred grain sizes of about 19%. This result is pretty good when considering the velocity and concentration fields variations in the flume. Indeed, the grain size assessments by ADCPs presented a larger variability than the LISST-SL measurements (Figure 4). The low accuracy of the echo measurement and the smaller measurement volume for laser scattering most likely played relevant roles in producing the observed variability. Fortunately, concentration and grain size gradients in a river occur along distances that are some orders of magnitude larger than the volume of punctual sampling (such is performed by LISST-SL) but may be comparable to ADCP profiling cells.

The same method was applied to a cross-section of the Parana River nearby Rosario City, resulting in flow velocity, grain size and concentration typical patterns reported in Figure 5, that corresponded to the hydrological condition of about 14500 m^3/s as assessed for the Rosario gauge station. These patterns are limited to the measured area from ADCPs that does not include a relevant layer close to the river bottom because of side lobes interference.

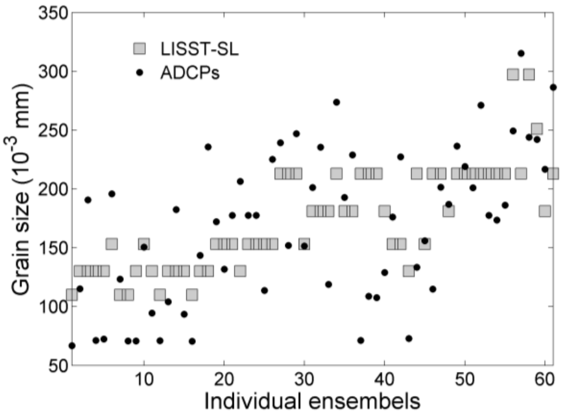

Figure 4: Grain size assessment by dual-frequency method application (ADCPs) and the laser device (LISST-SL).

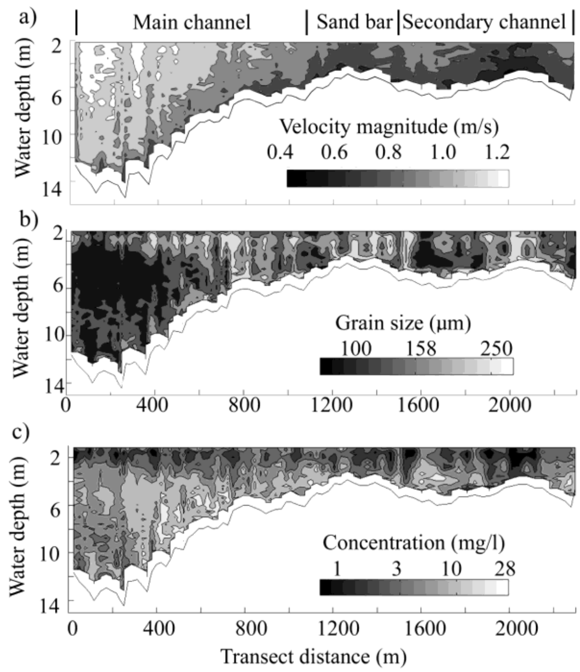

Figure 5: Velocity magnitude, grain size and concentration of suspended sand from the 2-ADCPs method application in the Rosario cross-section.

3.2 Bed-load

Dune tracking along the 15-m- and 10-m-deep channels of the Rosario and Bajada Grande reaches gave average rates, V_m, of forms displacement equal to 2.7 and 2.6 m/day, respectively. The observed dune height and length resulted equal to 1.5-1.8 m and 130-140 m.

The Rosario reach data refer to the same flow discharge characterizing the suspended-load survey (i.e., 14500 m^3/s), while the flow discharge was estimated around 17900 m^3/s (from Rosario gauge station) in the case of Bajada Grande campaign. The corresponding bed-load rates were equal to 1.7-1.9 m^2/d by applying Equation 4, that, considering the sand weight of 2650 kg/m^3, are 0.051-0.060 kg/m/s.

The velocity deviation, V_b, induced on the ADCP bottom-tracking by sand that moves over a dune resulted equal to 0.01-0.04-0.05 m/s for its trough, stoss-side and crest respectively. These velocities were measured in the 10-m-deep main stream of Bajada Grande. Accounting of a layer thickness, d, equal to two times the d_{50} of the observed sand distribution (Van Rijn [6]), the application of the measured velocity deviations in Equation 5 gave a change of bed-load rate from 0.005 to 0.026 kg/m/s when passing from the dune trough to its crest.

4 DISCUSSION

The integration and extrapolation to the not measured areas from ADCP of the observed velocity and concentration fields (Figure 5) gave a rate of about 150 kg/s for suspended transport of sand from the river bed (i.e., in the range of 80-300 μm). Dune tracking along the channel thalweg resulted in 0.05 kg/m/s as bed-load rate that, considering a 1km wide stream, would lead to a total rough estimation of 50 kg/s for the Rosario reach cross-section during the same campaign. Indeed, a lower value is expected accounting of the change of dune features with water depth across the channel.

A further campaign was conducted in the reach of Bajada Grande close to Santa Fe City that was characterized with a larger discharge. The rate of bed-load transport over a dune crest resulted near to 0.03 kg/m/s by applying the ADCP bottom-track capability, and the double from dune tracking. In addition a large variability was observed along the dune profile for the assessed sediment velocities. One critical issue is the scattering sensitivity to grain size variation; this sensitivity was exploited to map suspended-load grain size by applying the dual-frequency method. The same frequency-dependent variation in the backscatter of particles may be further exploited to achieve better predictors of suspended and bed-load in sandy rivers. At the same time, the ADCP may be modified to reduce the unmeasured area near the bottom that, typically, is the portion with the larger concentration of sand forming the bed.

5 CONCLUSIONS

ADCP methods show a relevant potential for the study of fluvial processes. In particular the multi-frequency backscatter method was applied to assess the flux of suspended sand in the Parana River. In addition, the Doppler velocity induced by moving sand close to the river bed resulted pretty well correlated to the bed-load, which gave reliable values when compared to the sediment flux estimated from dune tracking.

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