Hydrodynamic and sediment measurements in estuaries of Rio de Janeiro State, Brazil: methodology and application

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Abstract Accurate cross-sectional field data on water currents and sediment concentrations, among other variables, are required to understand and describe hydrodynamic, sedimentologic and morphologic processes in estuarine environments. Hence, cross-sectional field measurements have to be simultaneously and continuously obtained, by a well equipped team, during at least one tidal cycle. Unfortunately, Brazilian hydrometric teams are neither well equipped nor numerous. To address this problem, a new method was developed and applied in Estuaries of Rio de Janeiro State: (a) in the Iguaçu River estuarine stretch, by a team equipped only with one current meter and conventional sediment samplers, and (b) in the São Francisco Channel Estuary, where traditional and modern equipment, such as an Acoustic Doppler Current Profiler – ADCP was used. This method is also applicable for measuring hydrodynamic and sediment phenomena in non-permanent open channels during high-flow events (e.g. during floods).

Key words sediment and morphological processes; fluvial and estuarine morphology; hydrodynamic and sediment measurements; Brazilian estuaries; sediment movements

INTRODUCTION

Hydrodynamic and sedimentologic measurements across an estuarine section are much more complex than measurements across fluvial open channel sections. The presence and interaction of several physical mechanisms causes a substantive distinction between estuaries and any other natural system. The main mechanisms are: (a) tide propagation, influenced by estuarine geometry and at the mouth, tidal amplitude; (b) the appearance of longitudinal, vertical, and eventually lateral salinity gradients, due to density differences between salt water from the sea or ocean, and continental fresh water; (c) the resultant direction of the upstream freshwater towards the estuarine mouth; (d) Coriolis and centrifugal forces inducing secondary currents; (e) marine and continental solid contributions, and (f) sedimentologic and morphologic processes inside the estuary caused by tides and fluvial currents, and consequently, by the water circulation induced by density gradients. As tide amplitude varies continuously between spring maxima and neap minima during a lunar cycle, estuarine water levels and velocities also vary temporally and spatially from the mouth towards the continent. Further, the fluvial discharges that enter the system also vary continuously during the hydrologic cycle, as do all hydrodynamic and sedimentologic variables at every point of the estuarine cross-sections.

Object of investigation

The main purpose of this paper is to present a method for obtaining hydrodynamic and sedimentologic measurements across an estuarine section. Two cases are considered in Rio de Janeiro State (Figs 1 and 2): (a) the complete results and analysis of a field measurement campaign, carried out in the estuarine stretch of the Iguaçu River (23 K 674253.68 m E; 7487020.37 m S) with a mean width of 30.0 m and a mean water depth of 3.2 m, during an 11 hour period, that was collected by a team composed of a senior and two junior hydrometric technicians; and (b) in an estuarine stretch of the São Francisco Channel (23K 629342.76 m E; 7464055.06 m S) with a mean width of 110.0 m and a mean water depth of 5.0 m, collected during two field campaigns conducted for more than 30 hours each, that covered both spring and neap tidal periods.

Fig. 1 Measurements cross-section of the Iguaçu Estuary.

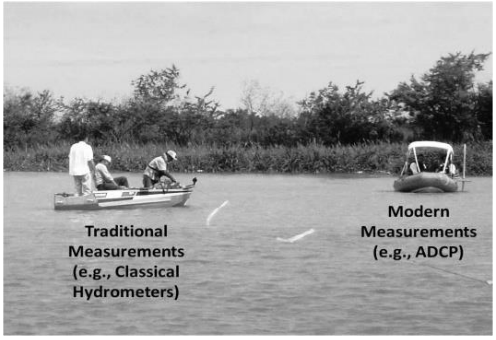

Fig. 2 Measurements cross-section of the São Francisco Channel Estuary.

THEORETICAL CONCEPTS

Fluvial discharge measurements

The discharge Q across a fluvial open flow section may be determined by multiplying the cross-sectional area A by the mean flow velocity U (continuous equation):

$$Q = UA \tag{1}$$

Classical methods of measurements determine Q as the sum of the discharge parcels q_i across area elements A_i of the cross-section A, as illustrated in Fig. 3:

$$Q = \sum_{i=1}^{N} q_i = \sum_{i=1}^{N} U_{mi} A_i \tag{2}$$

where U_{mi} is the mean velocity across the area element A_i, measured at the vertical depth h_i (Fig. 3(a)), and N is the number of elemental sub-sections across the river. Then:

$$A_i = b_i h_i \tag{3}$$

$$b_i = \frac{d_i + d_{i+i}}{2} \tag{4}$$

where b_i is the half-distance between verticals $i - 1$ and $i + 1$; and h_i is the vertical depth of order i.

This method, named the half sub-sectional's method, consists of measuring the depths h_i of selected cross subsectional verticals, the horizontal distances d_i between these verticals, and the velocities at several points in each vertical. Figure 3(b) shows the measurement point's z_j and the velocity intensities U_j. The median velocities U_{mi} of verticals $i = 1$ to N are determined from these profiles. Water discharge is calculated by equation (5):

$$Q \cong \sum_{i=1}^{N} U_{mi} b_i h_i \tag{5}$$

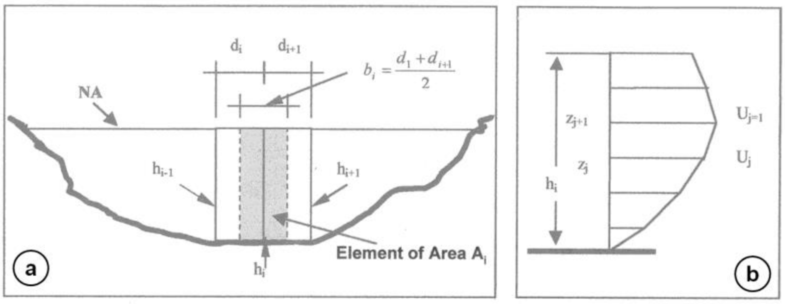

Fig. 3 Cross-section and vertical velocity profile in fluvial open flows (Garcia & Wilson-Jr, 2003).

Estuarine discharge measurements

Water discharge across an estuarine section could be determined in the same way as fluvial discharge by measuring the field of velocities for a precise period of time across a transverse section of the estuary. In a fluvial region, during median and low water seasons, water discharge can be considered constant during the measurements, but during flood season, and in an estuarine region, water discharge varies continuously and so fast that this assumption is no longer valid. In these cases, numerous simultaneous point velocity measurements are required so that the resultant water discharge can be considered constant during these measurements.

Consequently, field work in estuarine regions requires large teams with a substantial amount of equipment. Water levels as a function of time and discharges measurement periods in the Iguaçu estuarine region are presented in Fig. 4, where negative values correspond to flows towards the sea and positive values towards the continent. During the tidal cycle, fluvial discharge remains practically constant.

It is important to note that during non-permanent fluvial flows (e.g. during floods), the same methodology used in estuaries also applies.

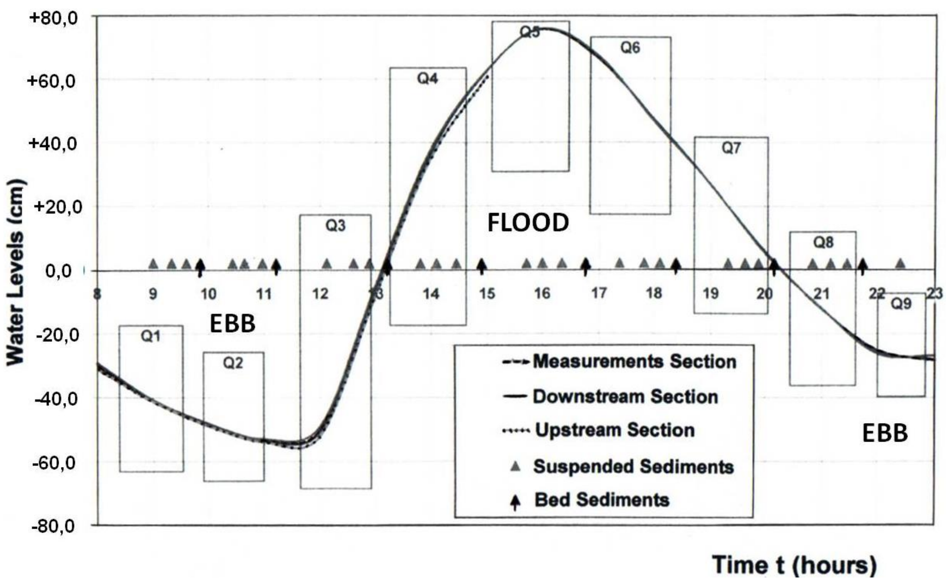

Fig. 4 Water levels and discharges (Q) as functions of time during Iguaçu Estuary work (Wilson-Jr, 1996).

Residual tidal cycle discharge

Methods used to determine residual tidal cycle discharge, Q_R, across an estuarine section, have to account for the complete period of the cycle and must satisfy continuous equation (6):

$$V_E = V_F + \int_t^{t+T} Q\,dt \qquad (6)$$

where V_E and V_F are equal to the total water volumes which flow across the measured section during the ebb and flood periods, respectively; Q is the fluvial discharge at time t, at the inland extremity; and T is the tidal period (12:25 h for a semi-diurnal tide). Thus, residual tidal cycle discharge can be obtained by equation (7):

$$Q_R = \frac{1}{T}\int_t^{t+T} Q\,dt = \frac{1}{T}\left(V_E - V_F\right) \qquad (7)$$

METHODOLOGY

The methodology for estuarine measurements is based on the principle that the hydraulic and sedimentologic variables, at a given point in an estuary vary continuously with time, in spite of their temporal gradients, eventually reach high values. Periodic measurements of special hydraulic and/or sedimentologic variables performed in the vicinity of a point, permit the determination of the range in these variables as a function of time. Next, the construction of continuous curves of these variables (e.g. the mean vertical liquid velocities and the vertical depths continuous curves, Figs 5 and 6) allow us to obtain values at any given time by interpolation or extrapolation (Garcia & Wilson, Jr, 2003).

Black-filled points in Figs 5 and 6, display the characteristic hydraulic values at the exact time of their measurements. Corresponding values for fixed periods (e.g. each 30 min) can be obtained

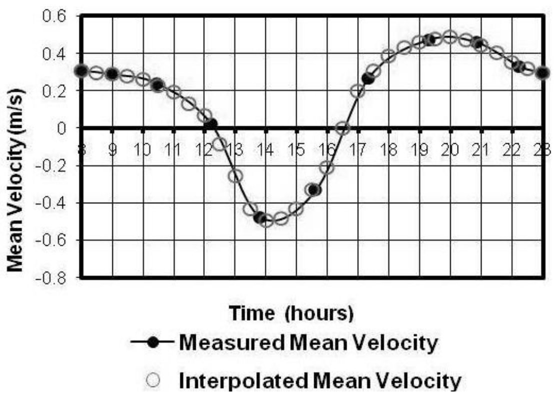

Fig. 5 Mean vertical velocity measured and interpolated values at the distance y = 26.15 m from the Iguaçu River left margin.

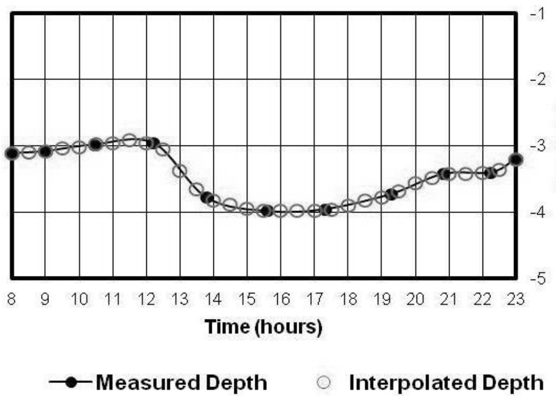

Fig. 6 Depth measured and interpolated values at the distance y = 26.15 m from the Iguaçu River left margin.

by interpolation or extrapolation from the continuous curves corresponding to a vertical profile, as if the variables had been measured simultaneously for all verticals every half hour. During field measurements, the technicians had to conduct the hydraulic and sedimentologic measurements at approximately the same points and verticals, during the tidal cycle.

STUDIES IN THE IGUAÇU RIVER ESTUARY

The 40.4 km long Iguaçu River drains an area of 726.0 km^2 and includes parts of Rio de Janeiro and five neighboring cities; where the population exceeds two million (Wilson-Jr, 1996). The Iguaçu River reaches and pollutes Guanabara Bay, one of the largest tourist sites in the country. Based on numerous visits and field measurements, the causes and consequences of sediment production in the watershed, the forms of solid material transported in both fluvial and estuarine flows, and areas of erosion and sediment deposition have been determined (Wilson-Jr, 1996). The Iguaçu River reach where these measurements were made is located 12.0 km from Guanabara Bay (Fig. 1), midway between two water level gauging stations separated by 645.0 m.

The temporally consistent data collected and analysed from the Iguaçu site include: topography and bathymetry of the reach, suspended sediment concentration, bed material grain size, water velocity, and depth. Field work extended from 08:00 to 23:00 h. Figure 4 displays temporal variations in water levels in the measured sections, as well as the time periods expended during discharge measurements and the time when sediment samples were collected. Figures 7–10 display examples of hourly transverse profiles and Figs 11–14 display the corresponding hourly values for mean vertical velocities. Similarly detailed temporal sets of hydraulic and sedimentologic variables also were obtained (e.g., transverse profiles of velocities near the water surface and the bed, water areas, water discharges, mean cross-sectional velocities, widths and depths, and mean shear stresses, among others (Garcia & Wilson-Jr, 2003)).

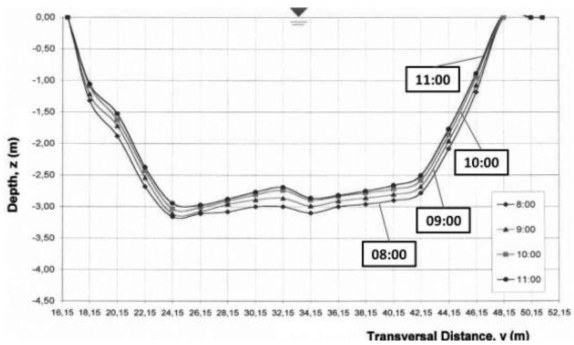

Fig. 7 Transverse profiles of the Iguaçu Estuary section from 8:00 to 11:00 h.

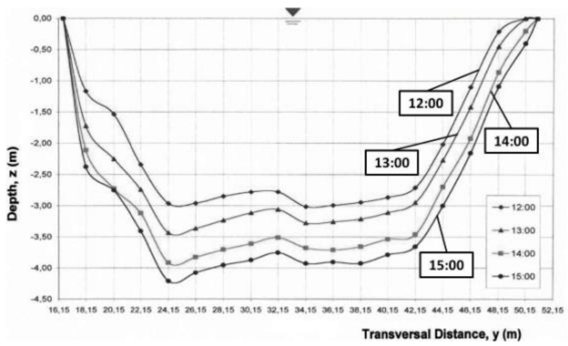

Fig. 8 Transverse profiles of the Iguaçu Estuary section from 12:00 to 15:00 h.

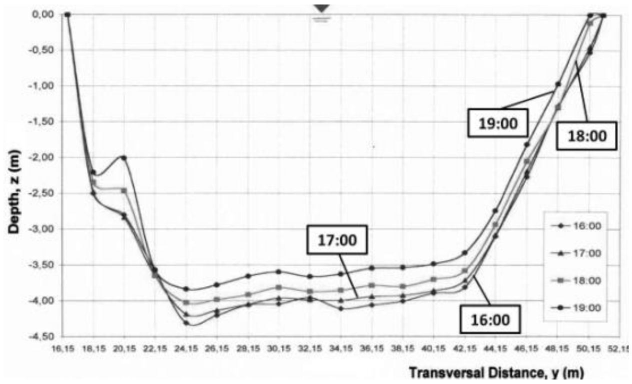

Fig. 9 Transverse profiles of the Iguaçu Estuary section from 16:00 to 19:00 h.

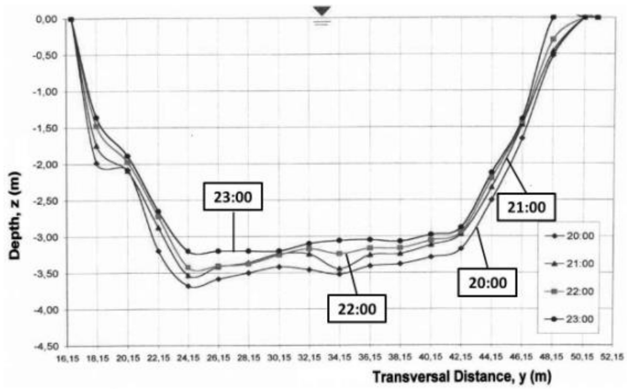

Fig. 10 Transversal profiles of the Iguaçu Estuary section from 20:00 to 23:00 h.

It is interesting to note that changes in the direction of water velocity due to the tidal cycle do not occur simultaneously in the transverse section (Figs 11–14). At noon (Fig. 12) the velocities obtained at the two sides of the cross-section had opposite directions, which characterizes the pattern of circulation in this estuary. As a consequence, a temporary longitudinal sediment bar formed in the centre of the cross-section (Fig. 8).

Similar studies and figures permit the precise description of water, sediment, and pollutant behaviour in an estuary (e.g. the Iguaçu River's bed sediment grain-size properties and movement as functions of time during the tidal cycle). Hourly values for the main hydrodynamic and sedimentologic variables obtained between 08:00 to 23:00 h, at the central vertical of the Iguaçu River cross-section, are presented in Table 1. Further, the bed sediment grain-size results were plotted on Shields' (1936) diagrams to analyse the threshold of bed movements (Figs 15–16).

The dimensionless shear stress θ and the grain Reynolds number, Re_*, values were defined and calculated using the following equations:

$$\theta = \frac{\tau}{(\gamma_s - \gamma) D_{50}} \quad (8)$$

$$Re_* = \frac{u_* D_{50}}{\nu} \quad (9)$$

where: γ_s and γ are the specific weights of the sediment grains and of the fluid, respectively, and ν represents the kinematic viscosity of the fluid.

Figures 15–16 indicate that during periods when the tides change from ebb to flood and *vice versa*, the bed is stable. However, during the ebb and flood tides bed sediments are remobilized (e.g. from 08:00 to 11:00 h; from 13:00 to 16:00 h, and from 17:30 to 23:00 h).

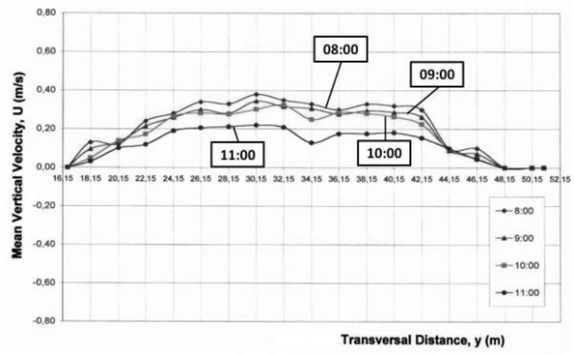

Fig. 11 Mean vertical velocities of the Iguaçu Estuary section from 8:00 to 11:00 h.

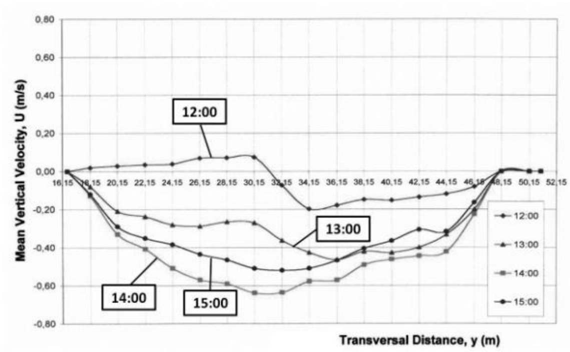

Fig. 12 Mean vertical velocities of the Iguaçu Estuary section from 12:00 to 15:00 h.

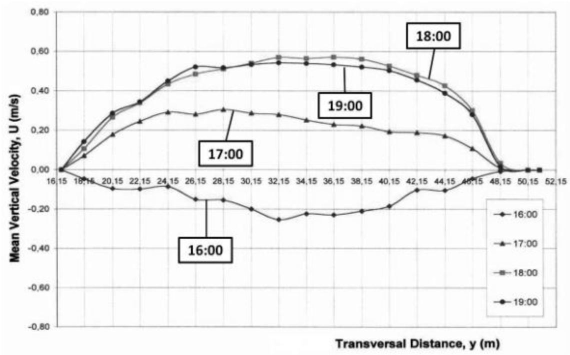

Fig. 13 Mean vertical velocities of the Iguaçu Estuary section from 16:00 to 19:00 h.

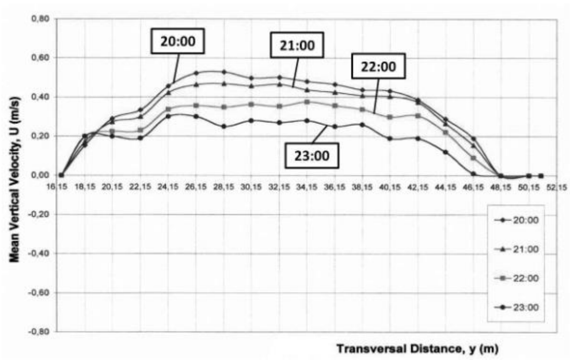

Fig. 14 Mean vertical velocities of the Iguaçu Estuary section from 20:00 to 23:00 h.

Table 1 Hourly hydrodynamic and sedimentological variable values obtained in the central vertical of the cross-section of the Iguaçu estuary (Wilson-Jr, 1996).

T h	*B* m	*H* m	*S* m/m $\times10^{-05}$	u_* m/s $\times10^{-02}$	*T* t/m² $\times10^{-05}$	U_m m/s	D_{10} µm	D_{16} µm	D_{35} µm	D_{50} µm	D_{60} µm	D_{65} µm	D_{84} µm	D_{90} µm
8:00	28.24	3.10	2.14	3.10	9.73	0.31	160	175	240	300	305	320	360	380
9:00	28.04	2.99	–0.14	2.80	7.93	0.28	170	190	260	310	320	340	380	390
10:00	27.75	2.89	0.82	2.50	6.58	0.25	178	200	285	320	340	350	390	410
11:00	27.61	2.86	–0.72	2.00	4.04	0.18	182	220	315	343	362	372	413	505
12:00	28.24	3.02	–4.45	0.40	1.80	–0.05	173	200	273	302	330	340	385	462
13:00	29.18	3.28	–4.24	–3.60	1.32	–0.38	160	173	216	245	283	298	358	380
14:00	29.98	3.68	–2.80	–4.10	1.67	–0.47	155	160	185	205	233	240	290	317
15:00	30.44	3.93	–0.31	–3.90	1.53	–0.43	160	173	220	258	292	305	388	430
16:00	30.68	4.11	–0.31	–3.60	1.30	–0.23	208	255	400	565	700	770	1210	1360
17:00	30.70	4.00	–2.17	0.80	5.73	0.20	207	280	462	680	850	945	1530	1720
18:00	30.19	3.86	1.71	3.80	1.43	0.43	102	165	225	292	340	375	530	580
19:00	29.72	3.63	–0.31	4.00	1.59	0.46	095	138	159	195	202	208	240	253
20:00	29.86	3.52	1.24	4.20	1.81	0.43	158	165	205	285	312	322	385	418
21:00	29.11	3.44	–0.31	3.60	1.28	0.38	165	172	218	282	318	328	398	425
22:00	28.69	3.24	2.91	2.90	8.57	0.30	158	170	218	260	290	305	375	395
23:00	28.34	3.06	–4.04	2.20	5.11	0.19	145	150	200	230	265	280	350	370

T: time; *B*: wet surface width; *H*: mean depth; *S*: longitudinal water surface slope; u_*: shear velocity; τ: shear stress on bed of river; U_m: mean water velocity; D_i (i = 10, 16, 35, 50, 60, 65, 84, 90) = particle sizes for which *i%* by weight of sediment is finer.

Shields' (1936) criterion, as well more recent ones (e.g. Paphitis, 2001; Beheshti & Ataie-Ashtiani, 2008; Van Rijn, 1984) accurately reflect the sedimentary dynamics of the Iguaçu estuarine region, as shown in Figs 15–16 (Souza & Wilson-Jr., 2011). In fact, sediment grains which were in movement since 08:00 h, start to deposit at 11:30 h, in such a way that at 12:00 h, bed sediment movement ceased (Fig. 15). At 12:30 h, with an increase in the hydrodynamic flood forces, the fine and medium sand bed layer started to move. From 13:00 to 16:00 h (Fig. 16), the bed sediments were still moving. They started to deposit around 16:30 h, when only 35% of the bed sediments still were moving. At 17:00 h, bed sediment movement was negligible, but at 17:30 h it was observed that 100% of the bed sediment could be moving, a situation that lasted until 23:00 h.

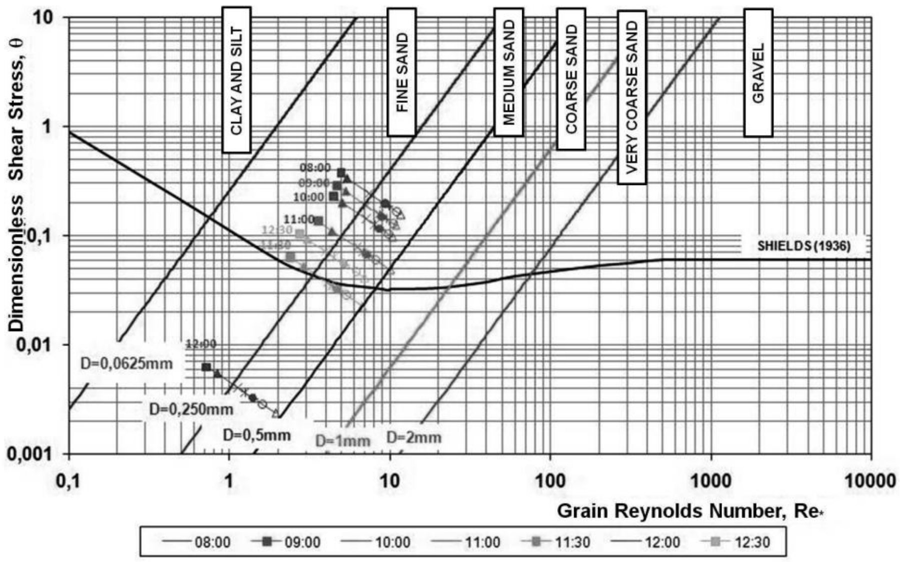

Fig. 15 Dimensionless shear stress θ, as function of the grain Reynolds number, Re_*, from 08:00 to 12:30 h, in the central vertical of Iguaçu estuary cross-section (Souza & Wilson-Jr, 2011).

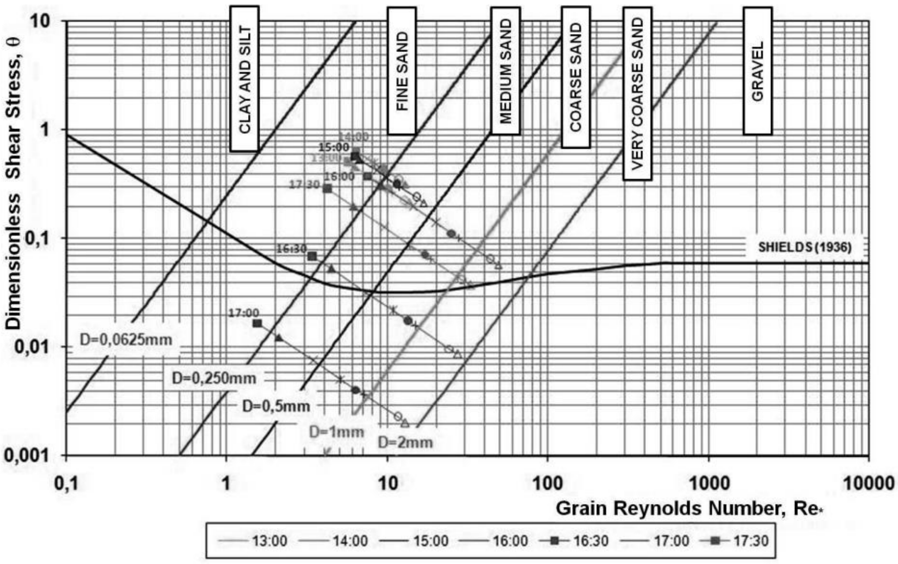

Fig. 16 Dimensionless shear stress, θ, as function of the grain Reynolds number, Re_*, from 13:00 to 17:30 h, in the central vertical of Iguaçu estuary cross-section (Souza & Wilson-Jr, 2011).

Between 13:00 to 17:00 h (Fig. 16), the moving bed sediments were predominantly composed of coarse and very coarse sands. In the period that followed, hydrodynamic force intensities were reduced, and these coarse sediments were immobilized on the bed and subsequently covered by finer-grained sediment (Souza & Wilson-Jr, 2011).

To synthesize, flood tide velocities were sufficient to move even the coarsest-grained bed sediments (Fig. 16) which, in combination with remobilized fine sediments from the same source, increased the overall concentration of suspended sediments. Contrariwise, ebb tide velocities were only sufficient to remobilize fine and medium sand-sized particles (Fig. 15).

STUDIES IN THE SÃO FRANCISCO CHANNEL ESTUARY

The field measurements obtained in the estuarine reach of the Iguaçu River were collected by a team composed of a senior and two junior hydrometric technicians, during an 11 h period. They only used one hydrometer in conjunction with a bed sampler and a suspended sediment sampler. This approach generated precise measurements of water discharge, as well as the passage of sediment, pollutants, and the salt wedge across the measured section. However, the ebb and flood periods of the tidal cycle are not symmetrical in this region (Fig. 4). As such, to obtain a complete data set for suspended and bed sediments, measurements had to be obtained during a period greater than 24 h 50 minutes, the residual tidal cycle discharge, as defined by equation (7), and calculated for T = 24.83 h.

The methodology used in the Iguaçu River was also applied to the São Francisco Channel Estuary, in Rio de Janeiro State (Fig. 2), in a section with a mean width of 110.0 m and a mean depth of 5.5 m. Two continuous 30 h field campaigns were conducted covering both spring and neap tidal periods. In this case, unlike the Iguaçu River estuarine program, both traditional and modern equipment was used (e.g. classical hydrometers, bed and sediment river samplers, turbidity meters, and Acoustic Doppler Current Profilers – ADCP).

This work was performed as part of a Federal University of Rio de Janeiro (COPPE-UFRJ, 2004) project to study alternative sites for water intakes for the Santa Cruz Thermal Power Plant. Field studies included estuarine measurements of water levels, water discharge, vertical and longitudinal salinity profiles, water quality parameters, wind, and humidity. They were made at the mouth of the estuary and at a 10 km upstream section (SM1). The main measurement area, (SM2) was near the Thermal Plant. Water level recorders also were installed in these sections.

To illustrate the results, graphs for the SM2 section of water level and cross-sectional water discharge for the spring tidal period, as a function of time, are presented in Fig. 17. Currently, ADCP point measurements as a function of time, obtained at the same verticals in the SM2 section are being analysed and compared to determine measured field velocities during the tidal cycles.

CONCLUSIONS

The methodology presented in this paper is based on the principle that the hydraulic and sedimentologic characteristics, at a fixed point in an estuary, vary continuously with time. Measurements must be obtained at fixed vertical points over a complete tidal cycle to generate continuous curves representing hydraulic and sedimentologic data. Subsequently, these curves may be used for inferring values for non-measured periods.

For large and/or deep estuaries, or for better precision during the measurements, two or more field teams are recommended. After the first team moves a certain distance from the margin, the second team would follow measuring and sampling across the same section, always occupying the same verticals. Both teams would use classical equipment, such as hydrometers and sediment samplers. Alternatively a smaller single team, using modern equipment such as ADCP and turbidity meters, would be able to conduct similar estuarine surveys during a tidal cycle. In other words, the proposed method permits estuarine measurements either with several teams using classical equipment, or with a single team using modern equipment.

Finally, this method also can be adapted to measure hydrodynamic and sedimentologic phenomena for non-permanent open channel flow events (e.g. in fluvial systems during floods).

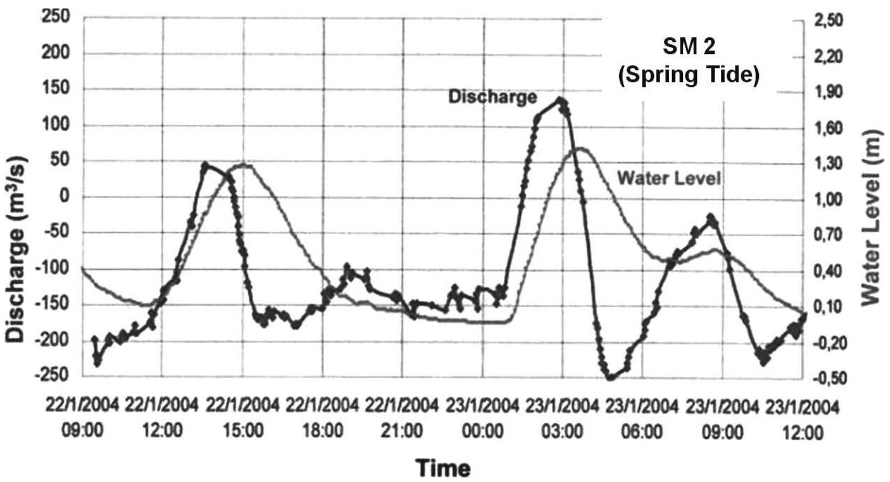

Fig. 17 Water level and discharge of the spring tide period (COPPE-UFRJ, 2004).

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