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STUDIES ON WATER AND SUSPENDED SEDIMENT TRANSPORT AT THE VENICE LAGOON INLETS

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Abstract: Acoustic Doppler current profilers (ADCPs) have been deployed for the continuous recording of the flow at the three inlets of the Lagoon of Venice, providing time series of discharge covering a period of more than three years. In addition, a large series of direct measurement of suspended particle concentration in water samples permitted the calibration of the backscattering signal recorded by bottom-mounted and vessel operated ADCPs by using the Sediview Software. Indirect estimates of the suspended particle concentration for the recorded transects as well as time series of concentration along the vertical profile corresponding to the mid-channel position are obtained. The trend of suspended sediment concentration can now be analyzed with unprecedented resolution both in terms of time, which permits to highlight the effects of sea-weather conditions in the bulk transport, and space, allowing the study of lateral inhomogeneities in relation to the hydrodynamics of the channel.

INTRODUCTION

The water exchanges between the Lagoon of Venice and the Adriatic Sea are ensured by three inlets (Lido, Malamocco and Chioggia) whose depths are at most 20 m. The flow is essentially driven by the tidal excursion, even if wind forcing may strongly affect water circulation during extreme meteorological events. In normal conditions, flow rates as high as of 8,000 m^3/s in a single inlet were estimated by investigators using modeling approaches.

The tidal exchanges are considered the main controlling factor for many of the processes affecting the life and evolution of the lagoon ecosystem. Monitoring the exchanges of water, sediments and dissolved substances at the three inlets of the Venice Lagoon has, therefore, a key role for the preservation of habitats. As many other environmental variables, these evaluations must necessarily be based on sufficiently

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long time series. This permits to identify evolutionary tendencies and minimize the negative impacts of ongoing transformations on the planned interventions.

Acoustic Doppler current profilers (ADCPs) have been employed by the Institute for Marine Sciences of Venice (CNR-ISMAR), jointly with other research institutions, for the continuous recording of the flow at the three inlets of the Lagoon of Venice, permitting the acquisition of a more than three year-long time series of discharge for each of the three lagoon inlets. Data were acquired by bottom-mounted ADCPs in order to derive time series of average current velocity along the vertical profile in the mid-channel region. This latter could be used as a proxy of discharge thanks to an extensive set of calibration measurements performed in different conditions along transects perpendicular to the flow, obtained by vessel-mounted ADCPs (Zaggia et al. 2004). It was therefore possible to investigate the trend of average annual/seasonal fluxes, and the variations induced by particular weather and sea conditions, such as those responsible for exceptional tides and flooding, as well as the hydrodynamics and evolution of velocity fields in the inlet cross-sections (Bianchi et al. 2005).

Based on the results of this investigation, the average magnitude of tidal exchanges between the whole lagoon and the open sea is of the order of 10,000 m^3/s on a half tidal cycle with instantaneous peaks of the same magnitude for a single inlet (Gačić et al. 2002). This has strong implications for the transport of suspended sediments, particularly when wind-induced stress in shallow water areas of the lagoon resuspends large amounts of sediments which can be moved seaward.

The trend of acoustic backscatter recorded by ADCPs showed clear relationships with the occurrence of these processes encouraging our team of investigators to test the calibration procedures for indirect estimates of the suspended particulate matter (SPM) concentration from ADCP data records. The potential of acoustic techniques in obtaining non-intrusive profiles of SPM with high spatial and temporal resolution has been largely demonstrated in the literature of the last decade (Thorne et al. 1994, Holdaway et al. 1999). The recent developments in underwater acoustics provided the tools for advances in the field of SPM monitoring, in comparison with more traditional approaches based on systematic samples collection at fixed stations. For these characteristics, acoustic techniques are more suitable to investigate large- and small-scale (turbulent) suspended sediment processes (Thorne and Hanes 2002), including wave action on sediment transport.

On behalf of APAT, Venice, the procedures for the conversion of acoustic backscattering data into SPM concentration estimates were tested at the Lido inlet from 2002 to 2005. The results of the calibration of field instruments with the Sediview Method (Land and Bray 2000) are here presented and discussed. The method was successfully applied by many investigators for studying both natural sediment transport and the effects of dredging and disposal activities (Puckette 1998) and was preferred among other techniques for the possibility to adjust the calibration in order to account for step changes of physical parameters affecting the backscattering properties.

MATERIALS AND METHODS

The investigated area, shown in Figure 1, includes the section where one of the bed-mounted ADCPs is monitoring the flow since 2001 (Latitude: 45° 25.350′ N, Longitude: 12° 25.593′ E), in the framework of the research program “Qualità e Quantità degli Scambi tra Laguna e Mare” (CORILA 2000-2003, linea 3.5).

Starting from July 2004 four acoustic surveys, covering a complete tidal cycle were carried out under different tidal conditions. Daily surveys corresponding to particular meteorological events were also performed in order to investigate the effects of sea-weather conditions on water circulation and suspended load.

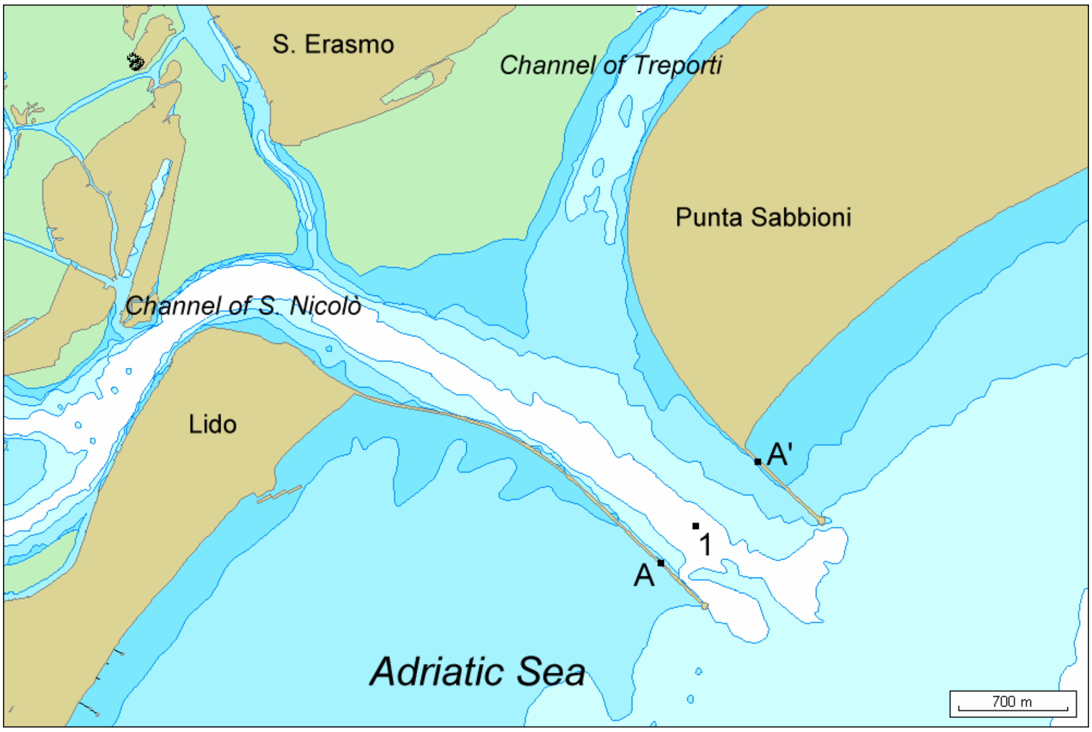

Fig. 1. Schematic map of the study area. In brown the littorals (Lido and Punta Sabbioni) and lagoon islands. A-A' identifies the investigated section, the position of the bottom-mounted current meter (1) is also indicated.

The equipment used during the monitoring includes an ADCP (600 kHz Workhorse Rio Grande - River Direct Reading ADCP, RD Instruments, CA-USA), a CTD probe supplemented by an Optical Backscatter Sensor and a Rosette sampler for the collection of the water samples at predetermined depths on the water column.

Current velocity data were acquired using a vessel-mounted ADCP (Simpson 2001), while the boat was covering transects across the inlet channel. At the end of each transect, CTD profiles were acquired at specific stations along the transect path. Simultaneously, water samples were also collected through the water column by firing the Rosette sampler at different depths. SPM concentrations were obtained by filtration of the water samples on pre-weighed polycarbonate membranes of 0.4 µm pore size and determination of weight loss after drying at 105 °C.

The acquired ADCP data sets were analyzed using Sediview Software (Dredging Research LTD, UK) which converts the acoustic backscatter data obtained by the ADCP to SPM estimates (Land and Bray 2000). This conversion is carried out after the calibration against the concentrations obtained by the collected water samples. Both temperature and salinity profiles were used in the calibration module in order to correct the acoustic energy absorption coefficient in water.

The software examines and fixes the differences between the estimated and bottle sample concentrations using an optimization procedure, which corrects the attenuation and absorption parameters through the water column and computes the site-specific relationship between the corrected backscatter intensity and the sample concentrations. The computation is iterated along the vertical profile and the acoustic attenuation coefficient is refined stepwise until concentrations no longer change.
The same methodology was applied to the time series acquired, by the bed-mounted ADCP (600 kHz Sentinel, RD Instruments, CA-USA) from July 2004 to January 2005 with a sampling frequency of 10 minutes. In this case, backscatter intensities were converted into SPM concentrations after calibration against the SPM estimates provided by the vessel-mounted ADCP at the corresponding depths along the same vertical. A time series of concentration was therefore obtained allowing the analysis of the temporal variability of the suspended sediment transport at the Lido inlet for a period of about nine months.

RESULTS AND DISCUSSION

The results of the calibration of acoustic backscattering from the vessel-mounted ADCP, relating to the average of the four transducers beams, with SPM concentration in bottle water samples are shown in Figure 2. A good correlation was found throughout the whole range investigated, even if most of data pairs are localized in the lower part of the calibration plot. Suspended sediments in the water column of the Lido inlet are, in fact, typically low and values above 30 mg/l are quite uncommon in fair weather and sea conditions.

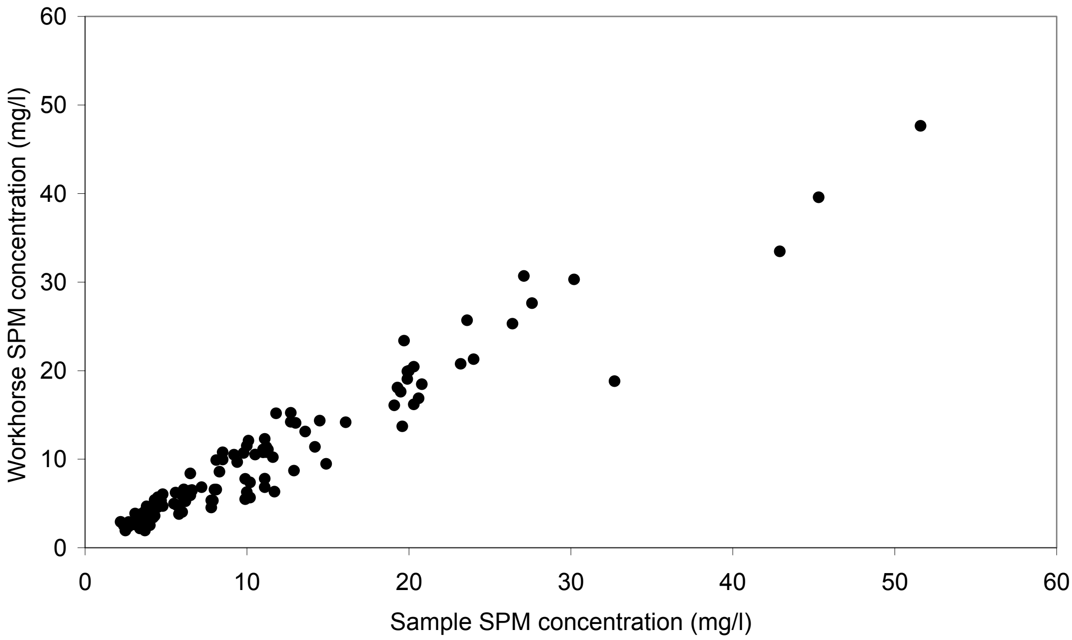

Fig. 2. Calibration of the boat-mounted ADCP (Workhorse). SPM concentration estimates obtained from instruments backscatter data and corresponding water sample measurements (Oct 2004 – Jan 2005).

Despite the experimental data so far obtained cover a period of several months when different conditions were found, the calibration does not show considerable time dependence and the whole range of values can be represented by a single regression line with a reasonable accuracy. According to Gartner (2004), this indicates that variations in size distribution during our investigation are narrow and limited to a few percent in the contents of fine silt sand and very fine sand.

Acoustic sensors slightly underestimate when the particle distribution shifts toward silt, as in the case of wave resuspension over shallow-water areas of the lagoon, which yield larger amount of silt than normal tidal currents. This can explain the little underestimation visible in the higher concentrations region of the plot, whose data mainly refer to measurements performed under these conditions.

The two examples of transect shown in Figures 3 and 4 represent the distribution of the SPM concentrations corresponding to two specific situations. They refer to the early flood (Figure 3) and late ebb (Figure 4) phases on two different days of the same field survey in January 2005. The current speed in the two transects averages to -0.10 m/s and 0.55 m/s, respectively, with peak velocities up to -0.35 m/s and 1.35 m/s.

Average concentrations are less than 7 mg/l in Figure 3 and more than 15 mg/l in the case of Figure 4. The generally higher concentrations measured on January 19th reflect the different sea-weather conditions. During the acquisition of the transect of Figure 4, the Northern Adriatic Sea was affected by a strong *bora* wind (approximate direction 50°) which caused sediment resuspension on the littorals and in the shallow-water areas of the lagoon. Waves are clearly traced in Figure 4 by the oscillatory trend of the yellow line, which represents the bottom tracking signal recorded by the instrument, while the survey boat was crossing the inlet section. A visual estimate of these oscillations gives an approximate wave height of 1 to 1.5 m.

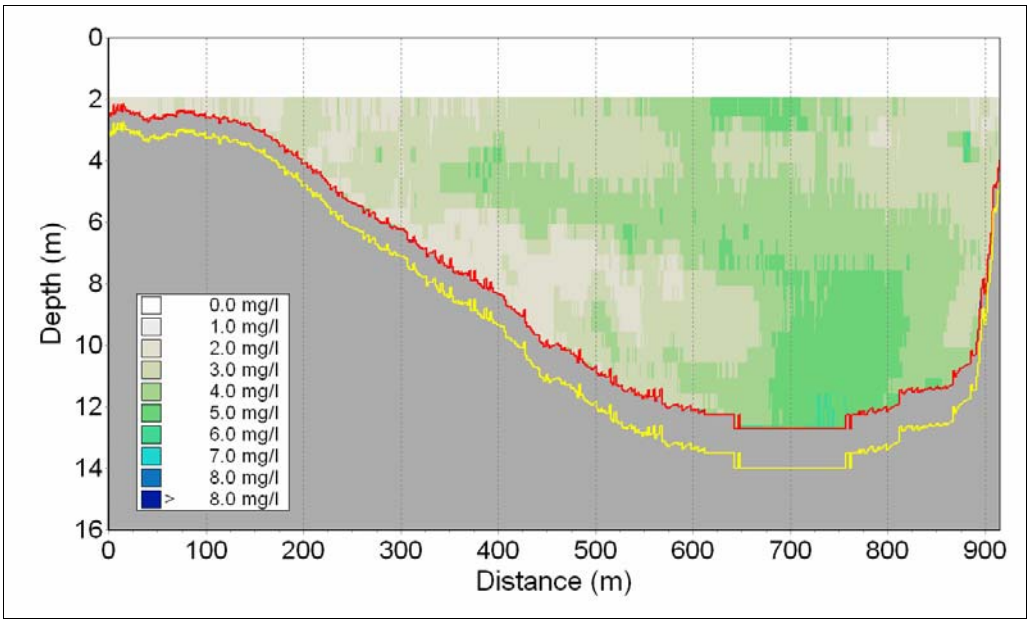

Fig. 3. Distribution of SPM concentrations across the A-A' section in the early flood phase. Transect acquired on January 17th 2005 at 13.57 UT.

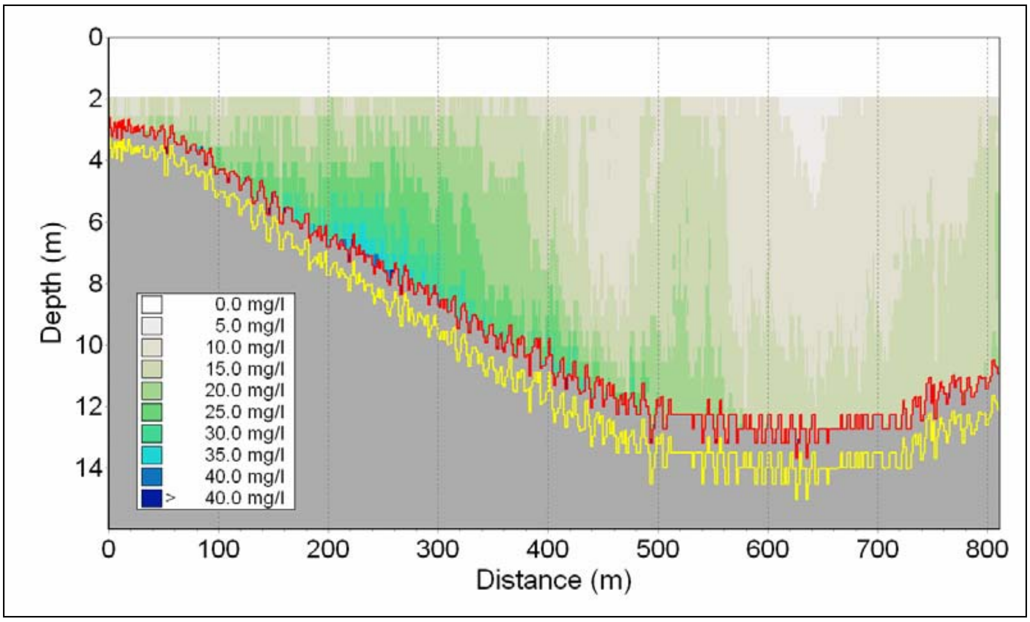

Fig. 4. Distribution of SPM concentrations across the A-A' section in the late ebb phase. Transect acquired on Jan 19th 2005 at 09.39 UT.

The northern side of the Lido inlet section, close to the Punta Sabbioni littorals (Figure 1), is frequently characterized by a strong resuspension, clearly visible in Figure 4. This spatial inhomogeneity of the SPM distribution is the effect of the interaction between bottom morphology and hydrodynamics. Scouring at the bottom with high velocity fields is, in fact, more intense in the shallower part of the channel section and the described effect is commonly observable even in the absence of waves.

The distribution of SPM concentrations in the Lido Inlet also depends on differences on sediment transport in the channels of Treporti and S. Nicolò (Figure 1), which originate from the Lido inlet and drain lagoon areas with different morphological characteristics. The basin of Treporti channel is characterised by the presence of larger salt-marsh surfaces and receives the inputs of the two major rivers of the lagoon catchment (Dese and Silone), approximately accounting for 50 % of the total watershed discharge (Zaggia et al. 2004). Consequently, the waters of the Treporti channel may transport larger amounts of suspended particles, as observed in the field during specific surveys (unpublished data). In the ebb tide phase the water masses of the two channels can flow through the inlet without a significant mixing giving rise to a marked differentiation in the distribution of SPM concentrations.

The results of the calibration of the bottom-mounted ADCP with concentration estimates provided by the vessel-mounted ADCP are shown in Figure 5. The SPM estimates obtained by the two instruments are in good agreement in the whole concentration range and are comparable to that of Figure 2, even if these are based on a data set covering a longer period.

By using this calibration, the time series of backscattering intensity of the bottom-mounted current profiler was converted into a time series of the SPM concentration for each of the 10 depth-measurement cells. In Figure 6, the trend of the average SPM concentration is compared to the curve of tidal level measured at the inlet for a period of about two weeks. The trend of suspended particle matter shows a strong dependence

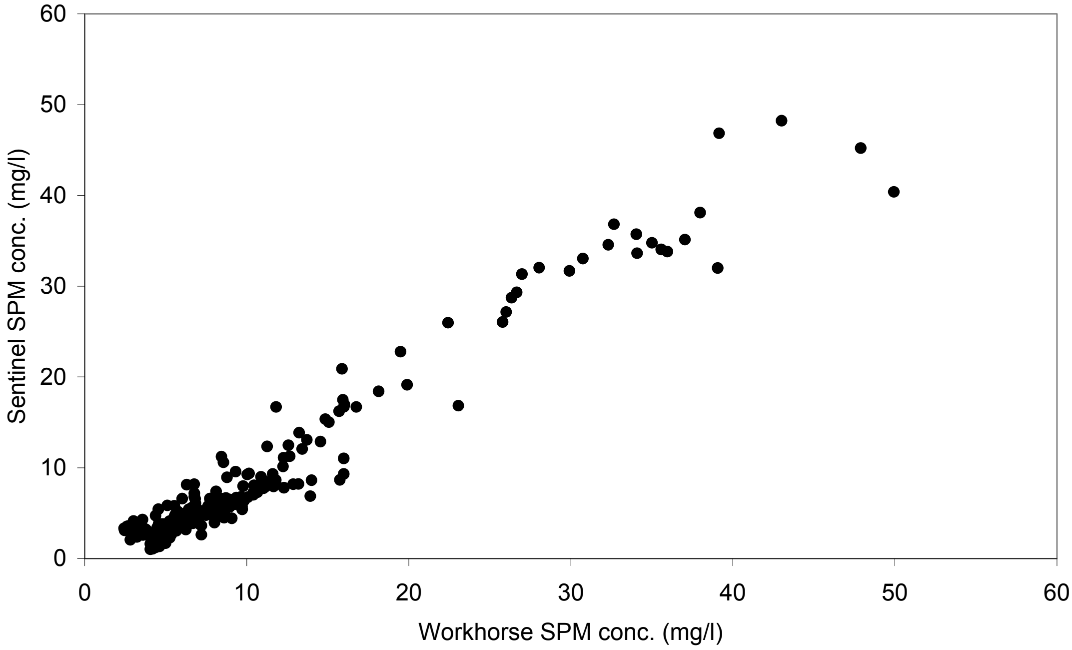

Fig. 5. Calibration of the bottom-mounted ADCP (Sentinel). SPM concentration estimates obtained from the current meter and corresponding indirect estimates provided in the period Jul 2004 – Jan 2005 by the boat-mounted ADCP (Workhorse).

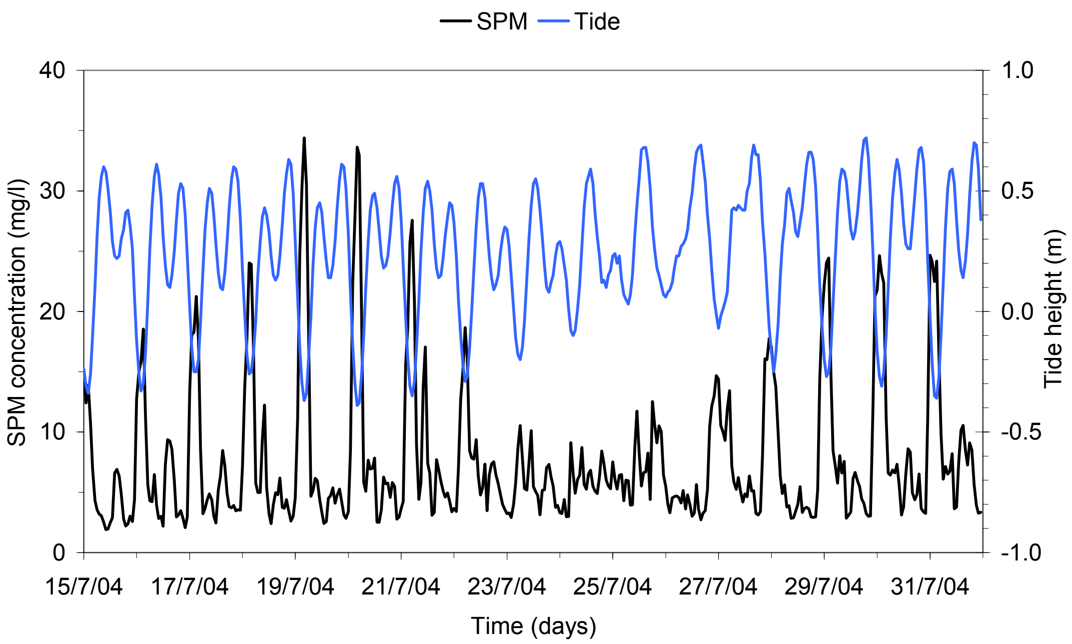

Fig. 6. Extract of the time series of average SPM concentration along the vertical profile in the mid-channel and tide height at the Lido inlet.

on the evolution of the tidal signal with a main modulation corresponding to the semi-diurnal excursion. A further modulation, related to the spring-neap tide cycle, is superimposed on the main trend determining changes at the scale of a week. Peak concentrations occur during the ebb tide phase in spring conditions, when the water level in the lagoon decreases below the mean sea level, and the effects of tidal currents on the sediments of the shallows are more intense. These changes are amplified in the periods when the contrast between the seawater and lagoon waters is more marked, as in the summer when microalgae blooming determines markedly higher SPM concentrations in waters of the marginal areas of the lagoon. In normal conditions, the temporal variability of the suspended particle transport through the Lido inlet seems to be mainly regulated by the change of the tidal regime and our preliminary results suggest a predominance of the seaward transport.
By examining the time series in detail, several peaks of SPM concentration can be found in correspondence to particular sea-weather conditions. The peaks generally follow by a few hours the surges of wind speed and are particularly evident when a threshold of about 15 m/s is exceeded. An example of these peaks is represented in Figure 7, which refers to an event occurred on January 19th 2005 during one of the periodical field survey (the same of Figure 4). In the diagram, wind speed and significant wave height, obtained from the records of instruments hosted onto the oceanographic platform "Acqua alta" (CNR-ISMAR, Venice, Latitude: 45°18.133' N, Longitude: 12°30.083' E), are superimposed for comparison. The significant wave height at the Lido inlet, obtained using the VENICE model, a waves propagation spectral model with a 50 m spatial step grid (Cavaleri and Malanotte Rizzoli, 1981), starting from the platform data, is also reported.

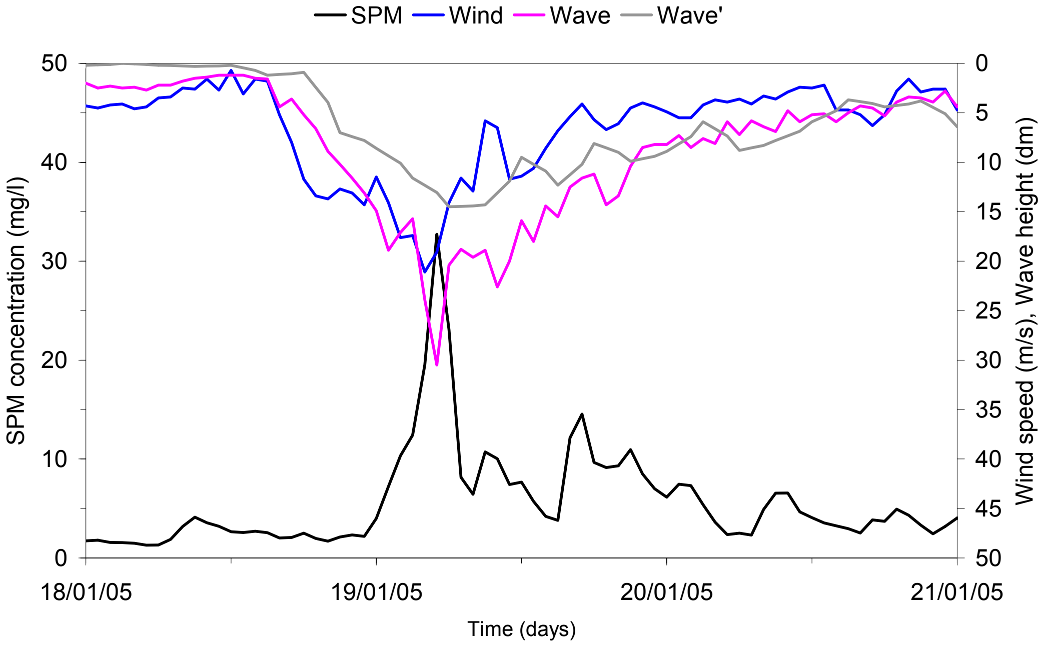

Fig. 7. Time series of average SPM concentration along the vertical profile in the mid-channel of the Lido inlet. Wind speed and significant wave height offshore (Wave) and at the Lido inlet (Wave') are superimposed.

The event is the fourth in terms of wind speed magnitude during the period June 2004 - February 2005. The results show a good correspondence between the trend of the concentrations, obtained from the conversion of backscattering data, and the sea-weather conditions. The concentration peak that occurs exactly at the beginning of the ebb phase is influenced by the relatively intense wind field and delays of only a few hours the peak of wind intensity at the offshore platform. The materials transported come therefore from inside the lagoon and mainly represent a seaward transport. The subsequent peak at about 15 mg/l, occurred in the second half of the same day, corresponds to the flood phase and is essentially material coming from resuspension on the littorals entering the lagoon.

CONCLUSIONS

The preliminary analysis of time series of SPM concentration obtained by the calibration of field instruments shows as the average concentration at the Lido inlet is very low, of the order of 10 mg/l, and is strongly modulated by the tide, showing a net dependence on semidiurnal and neap-spring tidal cycles. Peaks of the suspended particulate matter concentration associated to moderate and extreme sea-weather conditions are clearly identifiable in time series obtained from the bed-mounted instruments and show a good correspondence with the trend of wind speed and significant wave height.

SPM distributions obtained from data set acquired along transects perpendicular to the flow revealed the occurrence of marked inhomogeneities in the pattern of transport which are induced by the interaction of hydrodynamics with the morphology of the channel bed. The way these inhomogeneities affect the suspended load estimated values, obtained by the bottom-mounted ADCP SPM concentration time series, is a key issue and is the focus of an ongoing research project which also considers the characteristics of bedload transport.

The investigation on the techniques for the conversion of acoustic backscattering provided by commercial ADCPs is very promising and has a potential for the long-term monitoring of the suspended load through the inlets of the Venice Lagoon. The advantages of acoustics over conventional techniques also permit to obtain suspended particle concentration profiles with a spatial and temporal resolution sufficient to investigate in detail the effects of waves and turbulence on sediment transport processes in large tidal channels, even in difficult and highly dynamic environments such as the inlets of the Venetian Lagoon.

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