APAT monitoring system in the Venice Lagoon and in the northern Adriatic Sea

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ABSTRACT The National Agency for Environmental Protection and Technical Services manages the Real Time Tidal Gauge System in the lagoon of Venice and the northern Adriatic Sea. The principal objective is the analysis of historical time series for tidal data to investigate subsidence and eustatism, storm surge events and morphological evolution in the transitional environment of the coastal areas in the north-western Adriatic regions. Results from the application of data for the analysis of storm surges are illustrated. The focus is also put on the effect of the wind set-up along the border of the lagoon of Venice caused by the local winds blowing from north-easterly (bora) or south-easterly (sirocco) quadrants. A preliminary updated analysis on the astronomical tides in the lagoon is also presented. The main differences among the hydrodynamics of the lagoon in the early 20th century and the lagoon today are high lighted, thus confirming the concern that a meaningful decay from a transitional to a marine environment is taking place. In conclusion, current measurements at the Lido inlet are presented, including recent results on the estimation of the suspended sediments transport investigated by means of acoustic doppler current profilers.

1. Introduction

The National Agency for Environmental Protection and Technical Services (APAT) has reorganised and streamlined the responsibilities previously performed by the National Environmental Agency and the National Hydrographic and Oceanographic Service. In general, APAT duties involve technical and scientific activities regarding environmental protection, water resource management, water control and water pollution.

Where APAT is concerned, the agency has also inherited the duties of the Hydrographic Office for the lagoon of Venice. These responsibilities have now been attributed to the Department for Protection of the Inner and Marine Waters of the Agency and are carried out by the Venice Lagoon Service (VLS), a unit whose head offices are in Venice at Palazzo X Savi formerly the Venetian Hydrographic Office.

Its responsibilities include:

- systematic observation of water levels and parameters influencing meteo-marine phenomena in the lagoon and along the northern Adriatic coast;
- management of the Real Time Tidal Gauge System of the lagoon of Venice (RTLV);
- daily tidal forecasting service and forecasting and warning for exceptionally high tides (flooding or *acque alte*) for the benefit of all institutions associated with safeguarding the lagoon, civil defence as well as coastal risk and hydrological risks at the larger river mouths of north-eastern

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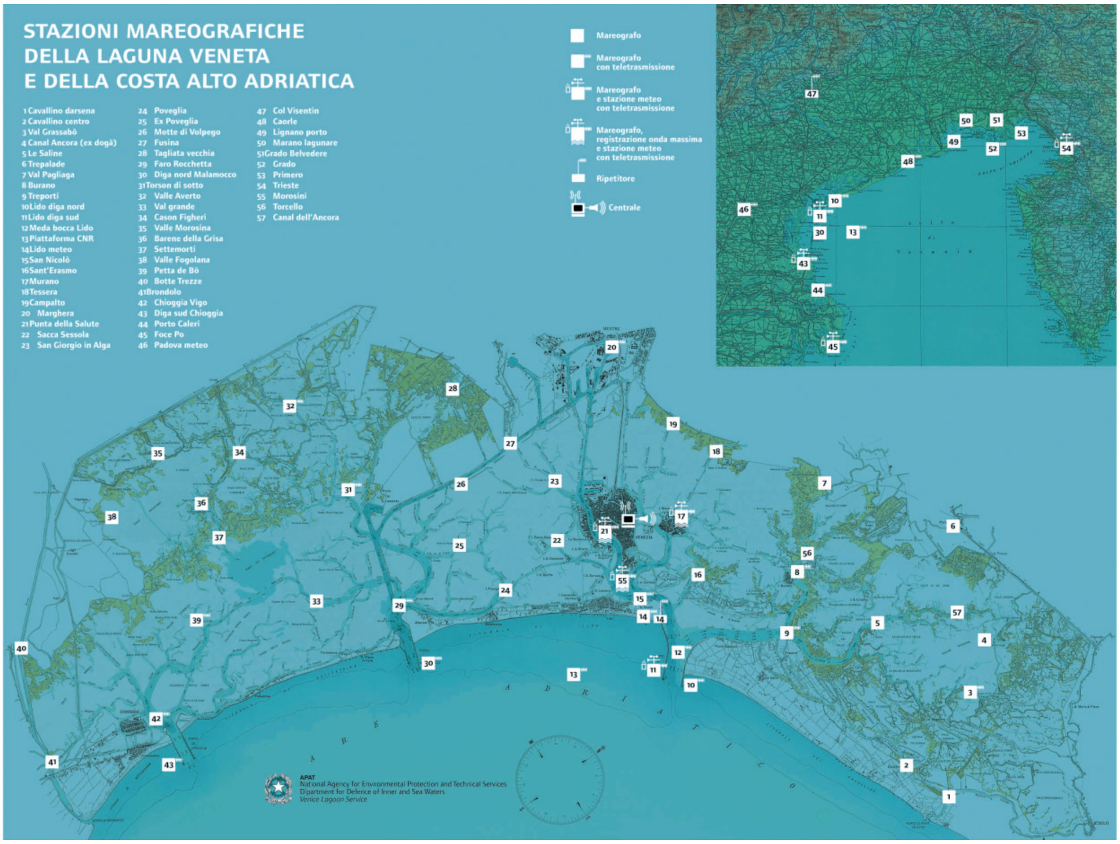

Fig. 1 - Tidal gauge system of the lagoon of Venice.

Italy, lagoon navigation and general population;
- elaboration, validation and dissemination of data, especially analyses regarding observations from extreme tide events;
- analysis of historical time series for tide data, also in relation to subsidence and eustatism in the northern Adriatic region;
- measurement of current parameters at the inlets in relation to lagoon-sea exchanges under different tide conditions.

The APAT sea level and meteorological parameter network in the Venice lagoon and in the northern Adriatic Sea is presented. Results on the application of the data to the analysis of storm surges and astronomical tides inside the lagoon are illustrated. The final part is related to current measurements at the Lido inlet including recent results on the estimation of the rate of solid suspended transport investigated by means of the acoustic doppler current profilers (ADCP).

2. The Real Time Tidal Gauge System of the lagoon of Venice

The VLS manages a network of 52 tide gauge stations equipped for the systematic measurement of the water level and other related parameters, such as wind direction, wind speed,

Fig. 2 - Venice Punta della Salute tide gauge station.

atmospheric pressure, precipitation, and wave-height in the lagoon of Venice and in the north-western Adriatic coastline (Fig. 1). The greater part of the 52 tide gauge stations have been operating for several decades; therefore, today VLS manages time series of tide data lasting more than 120 years.

Correct functioning of this system is fundamental for the warning and prediction of exceptional or atypical tides (storm surges) and for the management of the lagoon hydraulic system.

The RTLV is a fundamental part of the weather and marine monitoring systems of the Italian seas, controlled by the APAT, and includes the National Tide Gauge Network and National Sea Waves Measuring Network . In addition, the VLS has the capability of exchanging data measured in real time between the networks of the Environmental Operating Centres of the north eastern regions of Italy (Ferla, 2005).

3. Tide gauge station located at the "Punta della Salute"and the Daily Tide Bulletin

Regular tidal observations started in Venice in 1872. They are among the oldest and most reliable in Italy and in the Mediterranean in general. In the 1960s, the Hydrographic Office of the *Magistrato alle Acque* established a correlation between the tide levels, levels recorded in Venice in the early decades and the levels recorded at Punta della Salute tide gauge instituted in 1923 (Fig. 2).

The result was to put together a continuous string of data that dates back to 1872. The reference benchmark, called *"Zero Mareografico di Punta della Salute"* (ZMPS) corresponds to

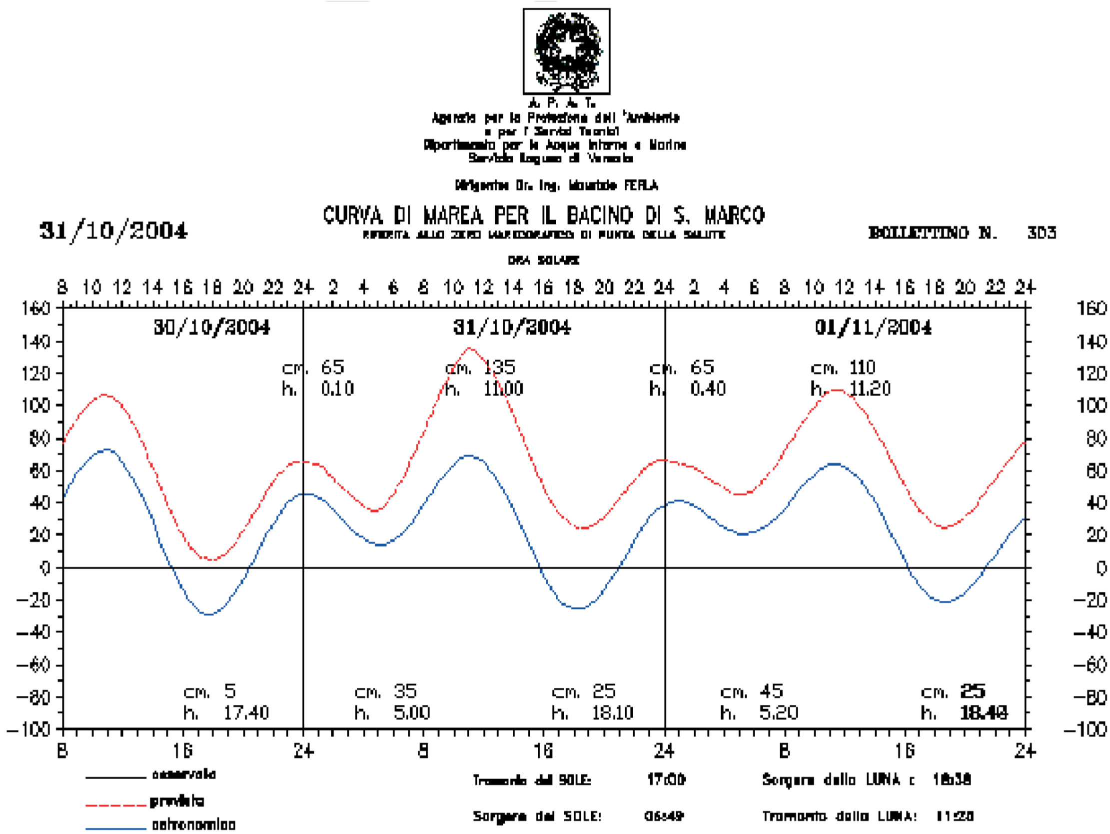

Fig. 3 - Example of the Daily Tide Bulletin at Punta della Salute Tide gauge station.

this day to the mean sea level recorded in 1897. The tide levels across the lagoon are measured with respect to this benchmark. Therefore, if we can legitimately assume this reference to be integral with the soil level of Venice, the average sea level calculated today at Punta della Salute gives us an accurate indication of how far Venice has subsided, with respect to the sea, in just over a century. Such sinking is due to the combined effect of phenomena of eustasy and subsidence. The most recent estimates give us an average level of subsidence of about 24 cm (Bonato *et al*., 2001a).

The production and publication of the Daily Tide Bulletin (DTB) is one of the main activities of the VLS (Fig. 3). The DTB gives details of both the measured water level and the predicted level at the fundamental tide gauge at Punta della Salute, located in the historic centre of the city. The DTB is published every day at 10:00 a.m. and reports:

- the tide observed from midnight of the day before until 10:00 on the date of publication (black line);
- the tide expected from 10:00 a.m. of the date of publication until midnight of the following day (red line);
- the astronomic tide (blue line).

The DTB is sent to the Water Authority, the Ministry for the Environment, the Prefecture

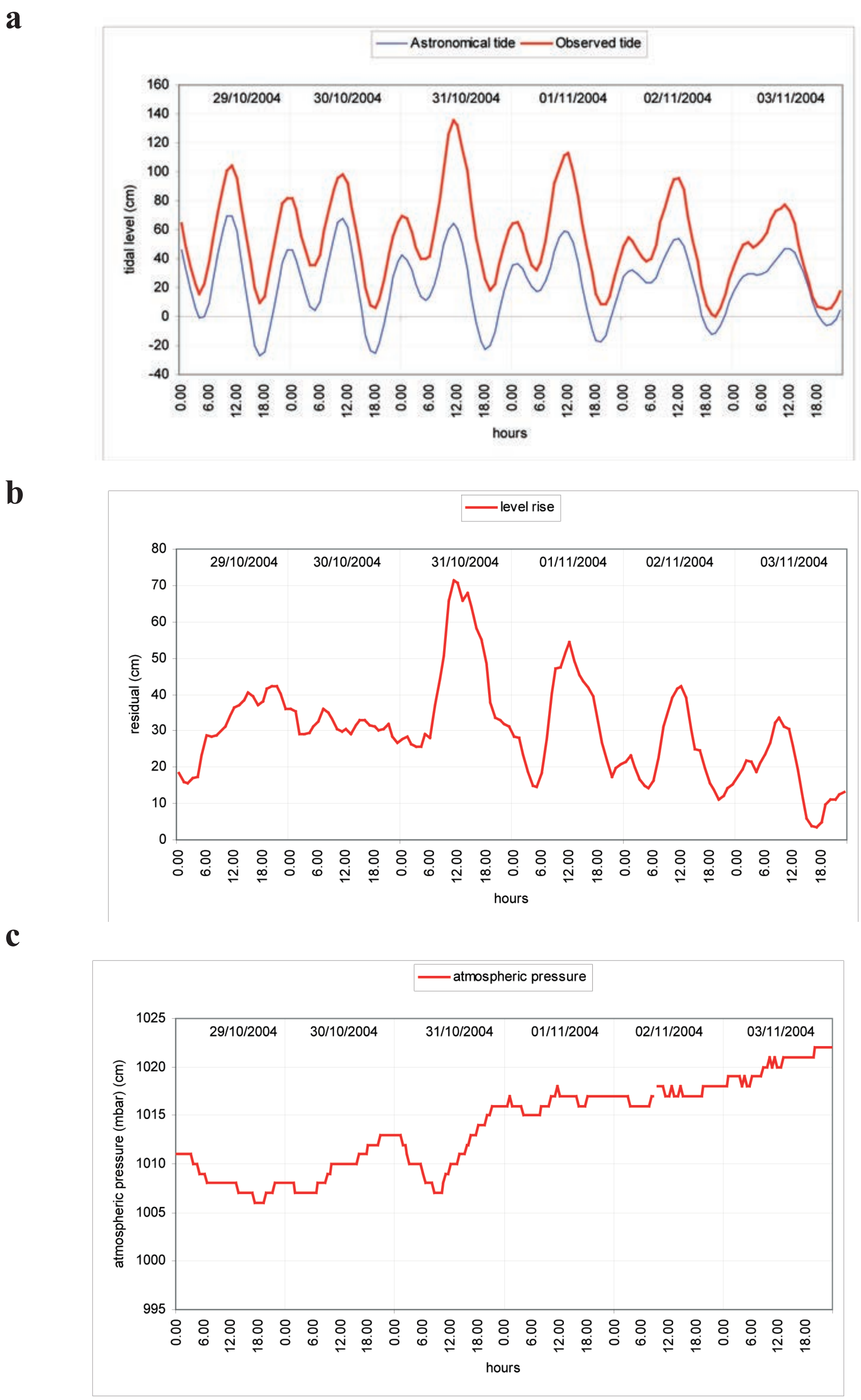

Fig. 4 - Storm surge event of October 31, 2004: a) recorded and predicted astronomic tide at Punta della Salute gauge station; b) recorded sea level rise at Punta della Salute gauge station; c) atmospheric pressure at Lido S. Nicolò meteorological station.

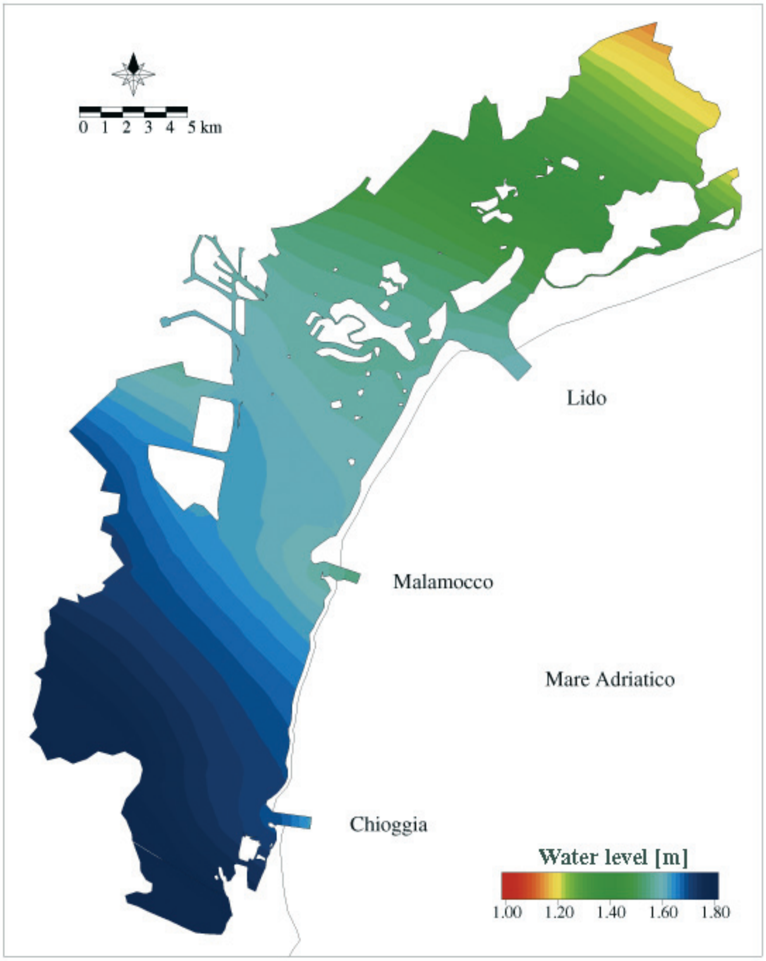

Fig. 5 - High tide of the December 8, 1992: local effect of north-east (bora).

Offices, the Municipality of Venice, Steersmen of the Port, Police, the City Fire Department, and other bodies; it is also published through information broadcasting units and an Internet Web Site (www.apatvenezia.it). A telephone messaging service is posted in the main city points of transit (St. Mark's Square, the Rialto Bridge and Piazzale Roma).

4. Analysis of the data relating to storm surge events

It is well known that the occurrence of storm surge events in the northern Adriatic Sea is due to the passage of deep fields of low pressure moving from south of the Alpine crescent and the consequent persistence of south easterly winds blowing across the Adriatic Sea (scirocco). The primary effect is that the mass of water is squeezed toward the northern Adriatic coast and

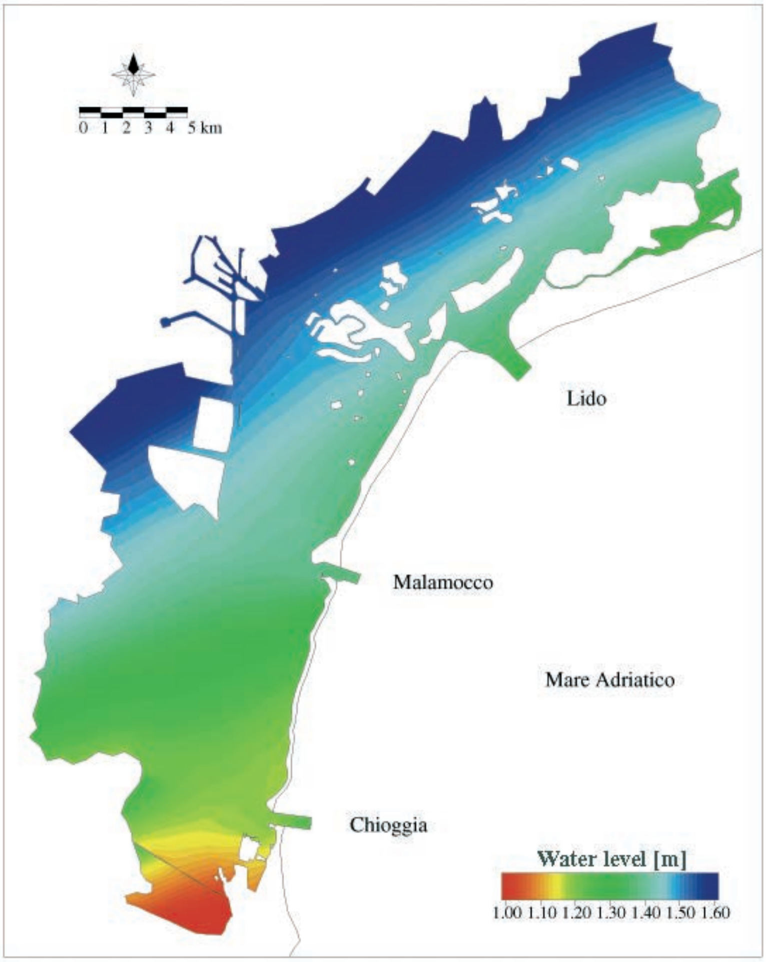

Fig. 6 - High tide of November 6, 2000: local effect of south-east (sirocco).

therefore into the Venice lagoon. Indeed, local minimum in atmospheric pressure causes the level to rise, attracting water from the areas where the pressure is high and it pushes down the sea. This is followed by a seiche, a long wave with a period of about 22 hours in oscillation along the Adriatic in a south-east/north-west direction (Tomasin, 2005).

As far as this occurrence is concerned, it determines a superiore increase of tide levels with respect to the highest astronomical levels which sometimes causes persistent and remarkable flooding of the lagoon's populated areas and the straightening of the sea storms breaking over the coastal defences. A comparison between the tide levels observed in Venice during the storm surge event of October 31, 2004 and the relative astronomic tide levels is shown in Fig. 4a. On the other hand, Fig. 4b shows the residual estimated deductions of the astronomical tide levels observed. Such a residual represents the so called meteorological forcings and the effect of the seiche estimated for the days after which has determined repeated flooding during the following days in

Table 1 - Worst cases of exceptionally high tides recorded at Punta della Salute tide gauge.

Date Above	ZMPS	Date Above	ZMPS
4 November 1966	194 cm	6 November 2000	144 cm
22 December 1979	166 cm	8 December 1992	142 cm
1 February 1986	158 cm	17 February 1979	140 cm
15 January 1867	153 cm	5 November 1967	138 cm
12 November 1951	151 cm	26 November 1969	138 cm
16 April 1936	147 cm	22 December 1981	138 cm
16 November 2002	147 cm	25 February 1879	137 cm
15 October 1960	145 cm	31 October 2004	137 cm
3 November 1968	144 cm		

conjunction with the astronomical high tide. On the other side, the atmospheric pressure registered at the Lido meteorological station of the RTLV can be seen in Fig. 4c. The combined observation of Fig. 4b and Fig. 4c show a net correlation between the maximum surge and the maximum negative atmospheric pressure rate.

Table 1 charts the most severe cases of exceptionally high water level recorded over more than 120 years of tidal observations.

The level at the tide gauge Punta della Salute is not, in itself, enough to represent the conditions of the lagoon basin during occurrences of storm surge.

Other critical factors ensue, for example, from the winds that are localised in the upper Adriatic. Tidal observations have shown that the forcing action of the wind along the lagoon surface gives rise to considerable pressure on the water against the southern or northern boundaries of the lagoon, depending on the wind direction, either north-easterly (bora) or south-easterly (sirocco). The maximum levels of the tide will be significantly different compared with

Table 2- Astronomical tide spread delay referred to the lido inlet. Astronomical tide height 1912 - 2002 (M2+S2).

	gauge station	DELAY (min)	HEIGHT (cm)
coast	PORTO PIAVE V	1	36
Lido inlet	LIDO DS	0	37
Northern lagoon	CAVALLINO C	227	16
	PAGLIAGA	140	30
	S. NICOLO’	53	34
	PUNTA SALUTE	66	35
	MARGHERA	83	39
Malamocco inlet	MALAMOCCO DN	17	38
Central lagoon	TORSON DI SOTTO	82	33
	FARO ROCCHETTA	24	34
Southern lagoon	MILLECAMPI	174	26
	CHIOGGIA SAN FELICE	33	35
	BOTTE TREZZE	88	33

Table 3 - Astronomical tide spread delay referred to the lido inlet. Astronomical tide height 2002 (M2+S2).

	Gauge station	DELAY (min)	HEIGHT (cm)
coast	CAVALLINO D	20	34
Lido inlet	LIDO DN	5	38
	LIDO DS	0	38
Northern lagoon	CAVALLINO C	199	24
	GRASSABO'	171	30
	LE SALINE	126	30
	PAGLIAGA	122	33
	BURANO	83	34
	TREPORTI	74	33
	MEDA	12	37
	S. NICOLO'	33	38
	MURANO	70	38
	TESSERA	87	38
	CAMPALTO	77	38
	PUNTA SALUTE	51	39
	SACCA SESSOLA	52	40
	SAN GIORGIO IN ALGA	55	40
	MARGHERA	56	40
	FUSINA	56	40
Malamocco inlet	MALAMOCCO DN	5	38
Central lagoon	MOTTE DI VOLPEGO	52	40
	TORSON DI SOTTO	57	38
	EX POVEGLIA	48	39
	POVEGLIA	46	40
	TAGLIATA VECCHIA	84	40
	VALLE AVERTO	96	39
	FARO ROCCHETTA	30	37
	VALGRANDE	68	37
	VAL FIGHERI	105	38
Chioggia inlet	CHIOGGIA DS	5	37
Southern lagoon	SETTEMORTI	86	37
	PETTA DE BO'	86	37
	BRONDOLO	52	38
	CHIOGGIA VIGO	29	37
	BOTTE TREZZE	65	38
	VAL FOGOLANA	98	38

the levels recorded in Venice in the larger inhabited centres, such as Chioggia in the southern section of the lagoon or Burano in the northern portion (Fig. 5 and 6).

In such a weather conditions the data analysis has shed light on the fact that sea-level differences between the various parts of the lagoon and especially between the lagoon and the sea (or vice versa) can determine asymmetrical hydrodynamic conditions at the inlets. Such phenomena were observed during the exceptionally high tide that occurred with the December 8, 1992 event, when the local wind was blowing from north east; in only a few hours the tide entered from the Lido inlet and, simultaneously, exited from the Chioggia inlet (Ferla *et al*., 1999). The opposite effect occurred during the high tide of November 6, 2000 when the local wind was

Table 4- Differences between tide delay and tide height in the Venice lagoon (1900 – 2002).

	Gauge station	DELAY (min)	HEIGHT (cm)
Lido inlet	LIDO DS	-	1
Northern lagoon	CAVALLINO C	-27	8
	PAGLIAGA	-18	3
	S. NICOLO’	-20	4
	PUNTA SALUTE	-16	4
	MARGHERA	-27	1
Malamocco inlet	MALAMOCCO DN	-11	0
Central lagoon	TORSON DI SOTTO	-25	6
	FARO ROCCHETTA	6	4
Southern lagoon	MILLECAMPI	-88	11
	CHIOGGIA SAN FELICE	-5	2
	BOTTE TREZZE	-23	5

blowing from south-east (Bonato *et al*., 2001b).

These singularities were also revealed by means of a finite element hydrodynamic model developed by the Consiglio Nazionale delle Ricerche, Istituto di Scienze Marine di Venezia (CNR-ISMAR), and calibrated with data collected by RTLV (Melaku Canu *et al*., 2002).

All this brought about the instruments for further investigation of the dynamics of the sea and lagoon exchanges by means of the direct measurements of current speed and discharge through the three inlets.

5. The spread of the astronomical tide in the Venice lagoon

The first studies of the features of the tide spread in the Venice lagoon took place in the early decades of the 20th century, under Giovanni Magrini, first Managing Director of the Ufficio Idrografico del Magistrato alle Acque di Venezia (Magrini, 1908; Rusconi and Ventrice, 2001).

The analysis of the spread of the astronomical tide in the Venice lagoon was carried out in the 1950s (Polli, 1952).

In general, the estimation of the astronomical tide, caused by the gravitational field of the Sun-Earth-Moon system, is based on a harmonic analysis. Just 7 sinusoidal components are usually sufficient to obtain a good estimate of the astronomical tide in the Venice lagoon.

The British Admiralty method was used to determine harmonic constants in the 1952 analysis (Doodson and Warburg, 1941). The least square method, applied to the Fourier analysis, was used to estimate the harmonic constants of each component in 2002 (Tomasin, 1974).

Silvio Polli determined the harmonic constants and the tide delay in spreading across the lagoon compared to the Lido inlet of 13 gauge stations inside the lagoon that had been working for different periods in the first half of the 20th century. As a result he could draw the same-level lines of astronomical tide inside the lagoon, adding up the two main semi-diurnal components of each station (M_2 and S_2). Despite the few stations available, he was able to depict the situation of the first half of the 20th century (Figs. 7a and 8a). It is necessary to stress that data taken into consideration refer to different years between 1912 and 1940, therefore all observations refer,

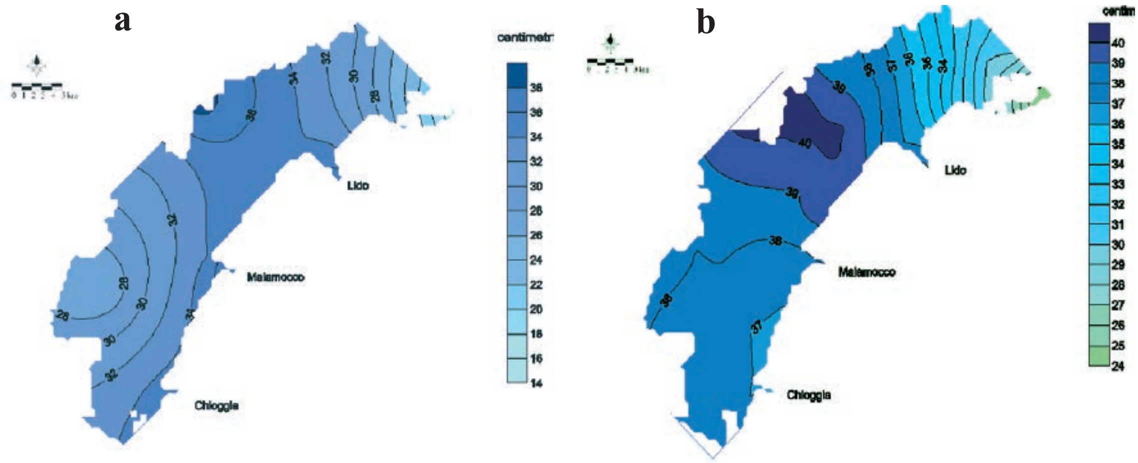

Fig. 7 - Comparison between astronomical tide height (M2+S2) at the begining of the 20th century (a) and in 2002 (b).

generically, to all the 50 years taken all together (Table 2).

Polli used a few months-long series in his calculation for each station, and showed that along the boundary of the northern part of the lagoon the tide delay ranged from between 3h47' at the Cavallino tide gauge and 1h23' at the Marghera tide gauge. In the city of Venice the tide arrived at the Punta della Salute tide gauge 1h06' after passing the Lido inlet. In the central part of the lagoon, the maximum level was registered at the Torson tide gauge, 1h22' after the Lido inlet. Spread-delay of the Malamocco inlet, proposed in the work of Polli, appears doubtful; a negligible delay in tide-spreading between the three inlets (Lido, Malamocco, Chioggia) seems more appropriate. In the southern part of the lagoon (Chioggia inlet) the maximum delay (~3h) was referred to Millecampi, close to the salt marshes areas.

The height of the tide was significantly lower in the northern part of the lagoon, where the dumping action was able to cut down the tide; the reduction of tide level reaches at 57% at the Cavallino tide gauge and 19% at the Pagliaga tide gauge. Near the historical centre, the reduction was not so noticeable: Punta Salute had just a 5% reduction in comparison with the Lido inlet while the Marghera tide gauge had a tide level slightly higher than the Lido inlet.

In the central part of the lagoon, the Torson tide gauge was 5 cm lower than at the Malamocco inlet which recorded the same level as the Lido inlet. In the southern part of the lagoon, the recorded tide at the Millecampi station was 68% lower than at the Chioggia inlet.

Using the continuous tide data collected in 2002, a new analysis has been reproduced for 37 tide tide gauges by APAT. The results of this study show that the tide delay along the boundary of the northern lagoon ranges between 3h19' at the Cavallino tide gauge, 2h02' at the Pagliaga tide gauge and 0h56' at the Marghera tide gauge, while the tide height ranges between 24 cm at the Cavallino tide gauge and 40 cm at the Marghera tide gauge. At the Punta della Salute tide gauge the maximum tide level is recorded at 51 minutes and it is slightly higher than at the Lido inlet. In the central part of the lagoon, the maximum delay is registered in the Val Figheri tide gauge (1h45'). In this part of the lagoon, the astronomical tide is higher than at the Malamocco inlet. The southern part of the lagoon reaches the maximum delay at the Val Fogolana station

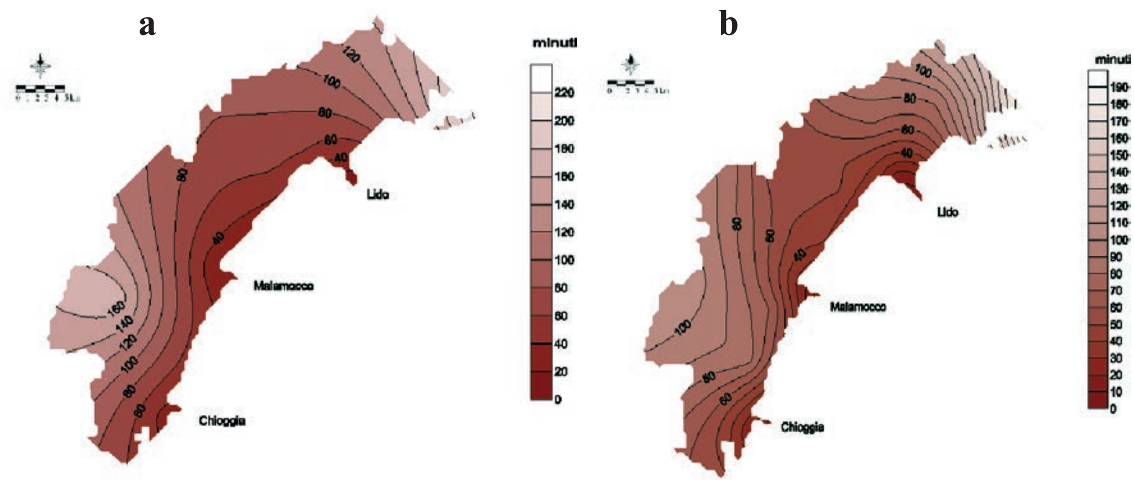

Fig. 8 - Comparison between astronomical tide delay at the begining of the 20th century (a) and in 2002 (b).

(1h38’). Tide heights are comparable with those of its inlet. (Table 3)

During the last century a number of relevant high impact-actions were carried out in the Venice lagoon: the Chioggia inlet reinforcement, finished during the 1930s, closure of the fish farms by the 1940s, the Petroli canal excavation. A comparative analysis of tide features between the first half the 20th century and 2002 represents one of the most important subjects for the study of the lagoon environment. A general tendency towards the reduction of a tide delay is recognized at all the gauge stations; tide height diminishing power is still a characteristic in the only northern part of the lagoon.

In 2002, tide levels in the southern part of the lagoon are comparable to those of the inlet; in the early 20th century they were significantly lower than at the Chioggia inlet. Elevating effects of 1-2 cm in comparison with the inlets are seen to be in the part of the lagoon between Petroli canal and San Nicolò canal. Tide heights are on average 4 centimetres greater in the whole of the Venice lagoon. In 2002, astronomical tide arrived 20 minutes earlier than in the first half of 1900. A comparison between the two different periods is shown in Table 4. A graphical comparison between the tide height and tide delay are also plotted in Figs. 7 and 8.

6. Currents and suspended sediment measurements at the Lido inlet

Current measurements in the lagoon channels and at the inlets have always been of crucial importance for the study of hydrodynamics and morphologies in the Venice lagoon.

Since its institution, the Hydrographic Office has regularly measured the current parameters at the inlets and along the internal channels in order to investigate the capacity to transport suspended sediments in relation to the maintenance of the beds for navigation requirements (Magrini, 1908).

In the following decades, the Hydrographic Office continued its investigations to update knowledge on the distribution of water fluxes between the shallower lagoon basins and the

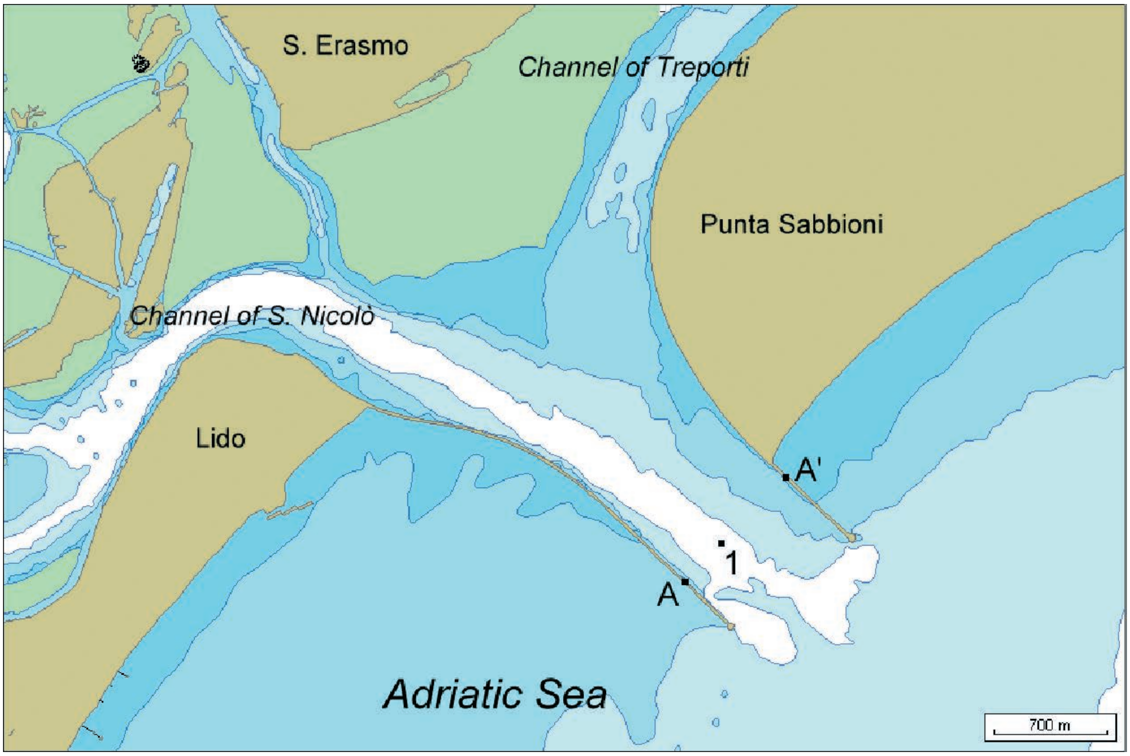

Fig. 9 - Lagoon of Venice Lido inlet: schematic map of the study area. A-A' identifies the investigated section; (1) indicates the position of the bottom-mounted current meter 2001 (latitude: 45° 25.350' N, longitude: 12° 25.593' E).

discharge along the internal channels which developed near the inlets. They have found, for example, that the all water fluxes that flow to the Lido inlet divide during the spring tide – approximately 60% goes towards the San Nicolò channel, 6% towards the San Erasmo channel and 34% towards the Tre Porti channel.

Taking into consideration some measurements carried out in the 1930s and others in the 1960s some comparisons were then made concerning the Lido inlet. These comparisons revealed that the quantity of water exchanged between the lagoon and the sea through that inlet remained almost constant.

The average speed registered during the inflow and outflow phases of the tide, diminished by almost 14% because of the increase of the cross-section of the inlet which had increased by 18% in the same period. The highest speed registered in 1930 had, in time, determined the increase of the beds, thus establishing a suitable balance for the inflow and the outflow (Dorigo, 1966).

In 2001, the APAT and the CNR - ISMAR, carried out a survey to test its ship-borne Acoustic Doppler Current Profiler (ADCP). Several repeated series of transects, to measure the fluxes towards the Lido inlet, were carried out during a complete tidal cycle in different sea-weather conditions. These surveys revealed a detailed high level in the velocity field along the cross-section and more precise measurements of the water flux superior in comparison with measurements carried out by means of electromagnetic or mechanical pointed speed recorders.

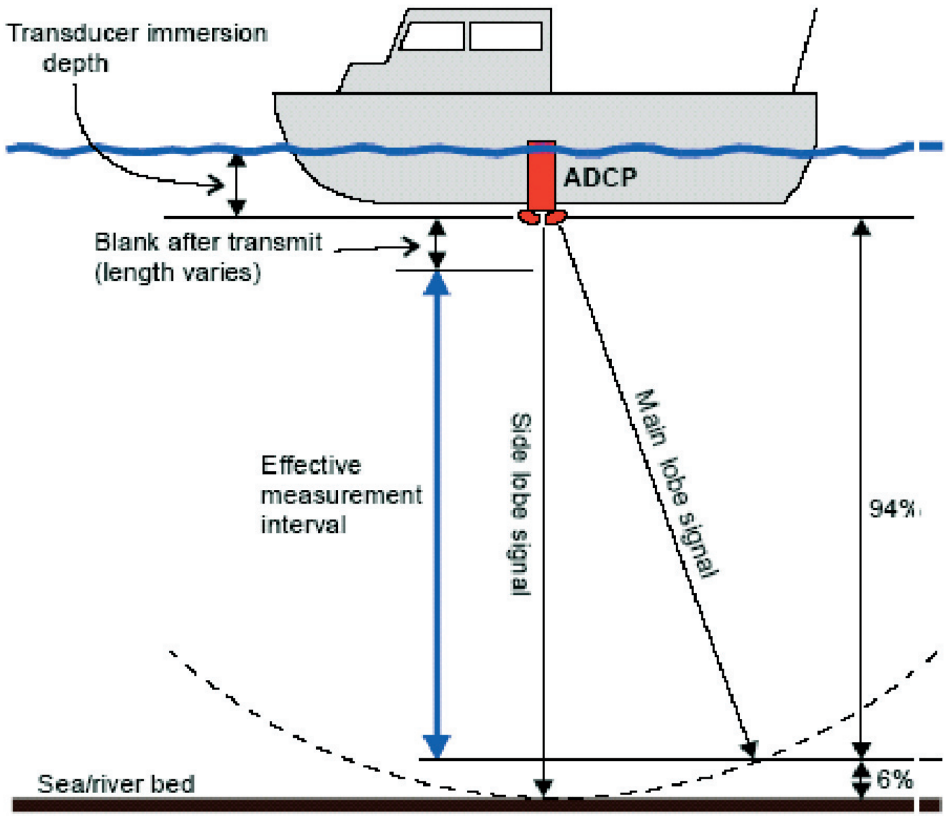

Fig. 10 - Limits of ADCP measurement interval.

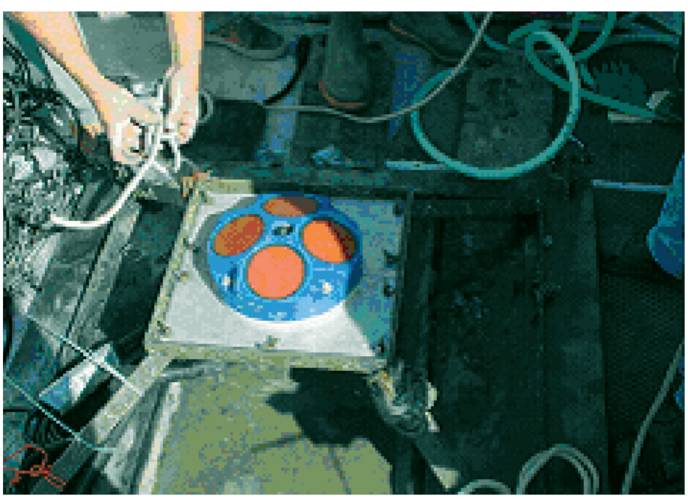

Fig. 11 - Bottom-mounted ADCP (middle of the inlet channel .

Fig. 12 - Boat-mounted ADCP.

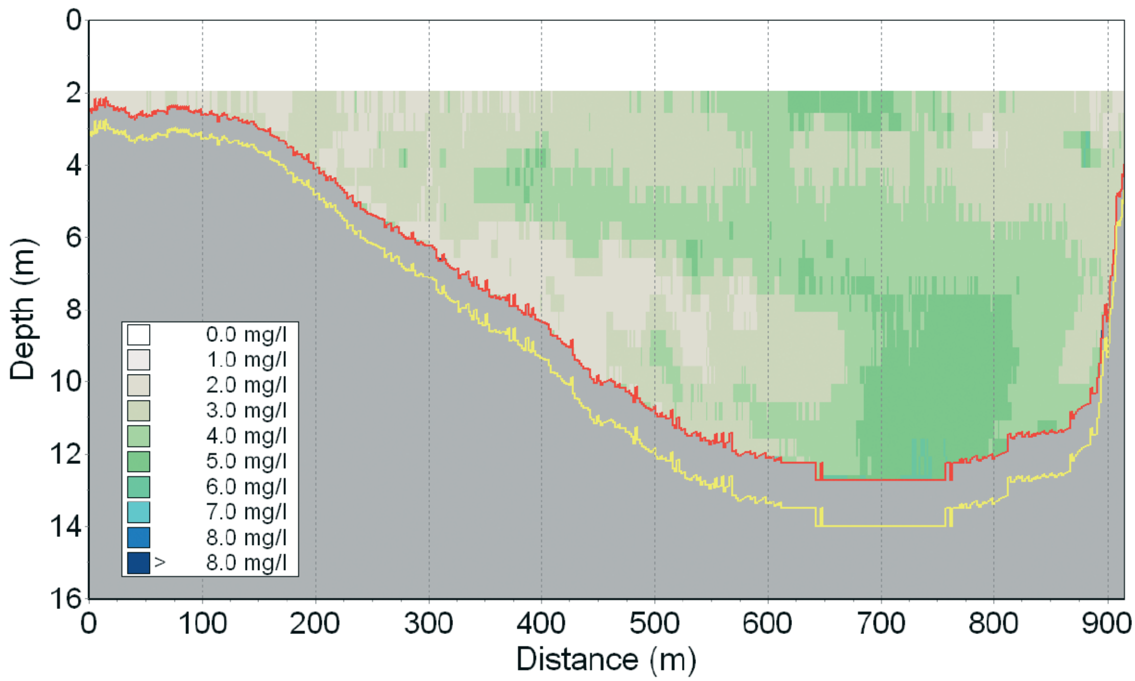

Fig. 13 - Distribution of SPM concentrations across the A-A' section in the early flood phase. Transect acquired on January 17, 2005 at 13.57 UT.

In recent years, water-flux monitoring through the three inlets has had even more importance due to the foreseen realisation of flood gates and therefore greater importance in understanding how long to close off the lagoon basins to protect Venice from flooding by storm surges.

In 2001, in conjunction with APAT's investigations, a working committee made up of the Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS), CNR- ISMAR and CO.RI.LA (Consorzio per la gestione del Centro di Coordinamento delle Attività di Ricerca inerenti il Sistema Lagunare di Venezia) began a series of continued measurements of speed of tidal currents along a fixed vertical using a strategically placed ADCP on the bottom of each of the inlets in order to pinpoint a correlation between a size index which can be measured continuously and the discharge measured through transects carried out periodically at the three inlets by means of a ship-borne profiler. These analyses allowed the construction of rating curves through a simple linear regression of each inlet which correlated the average speed calculated along the vertical of each fixed profiler with the fluxes estimated at the inlets by the ship-borne profiler.

This allowed us to have a first, continuous time-series of data on the water fluxes at the three inlets from February 2002 to December 2003. This data set has shown that current speed can reach up to 1.5 m/s with a corresponding discharge of about 10,000 m^3/s The analysis of these data showed that 90% of the water flux exchanged between the lagoon and the sea is caused by the forcing tide whilst the non-forcing tide, analysed on a time-scale of 20-40 days, showed that the variation in the flux at the Lido inlet is not in time with that of Chioggia, largely due to the

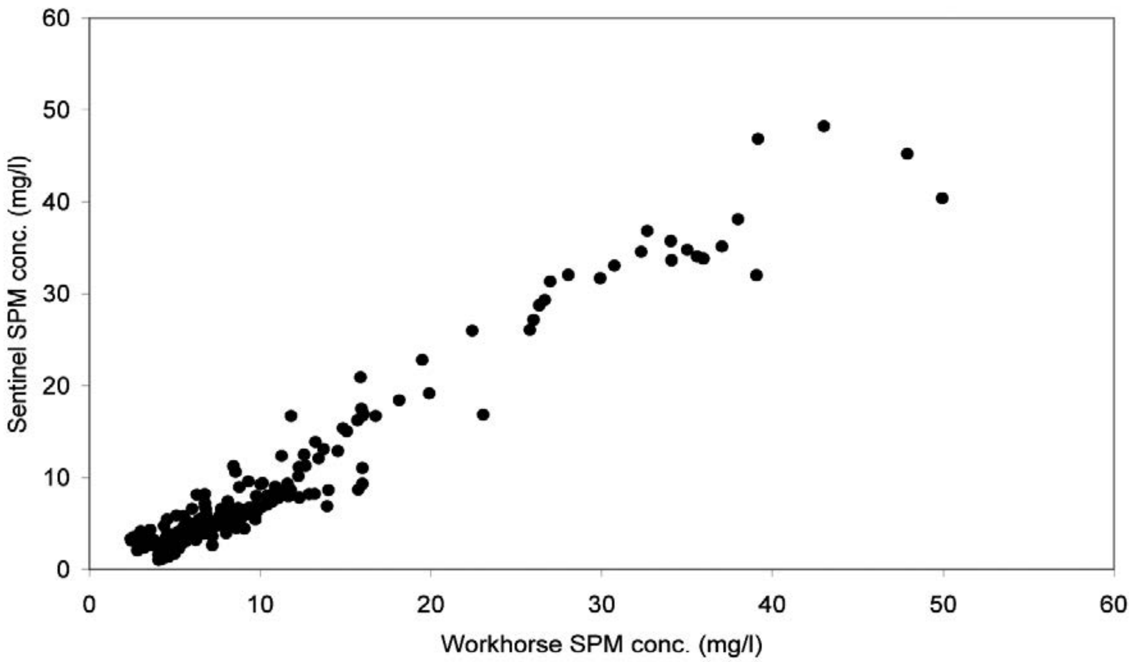

Fig. 14 - Calibration of the bottom-mounted ADCP (y-axis) with indirect concentration estimates provided by the boat-mounted ADCP (x-axis).

effect of the wind from the north-east (bora).

The net flow associated to non-forcing tides reveals an average flow of approximately 88 m^3/s with amplitude oscillations equal to approximately 500 m^3/s (Gacic *et al*., 2002, 2005; Cosoli *et al*., 2004).

Another significant aspect in the study of the morphologic transformation in the Venice lagoon concerns the understanding of the transport of solids associated with tidal currents.

Systematic measurements of concentration of suspended solids along the San Nicolò channel were carried out by the Hydrographic Office for more than a decade between 1924 and 1937 and the relative data were published in the Annals.

The quantification of the sediment exchanges through the inlets of the Venice lagoon is fundamental to interventions aimed at protecting the lagoon environment against erosion processes. A CNR – ISMAR and APAT research project has been investigating (since 2002) the hydrodynamics and suspended sediment transport in the cross-section at the Lido inlet. The transport mechanisms are studied with a ship-borne and bottom mounted ADCP (Zaggia *et al*., 2004; Costa *et al*., 2005). A large series of direct measurements 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

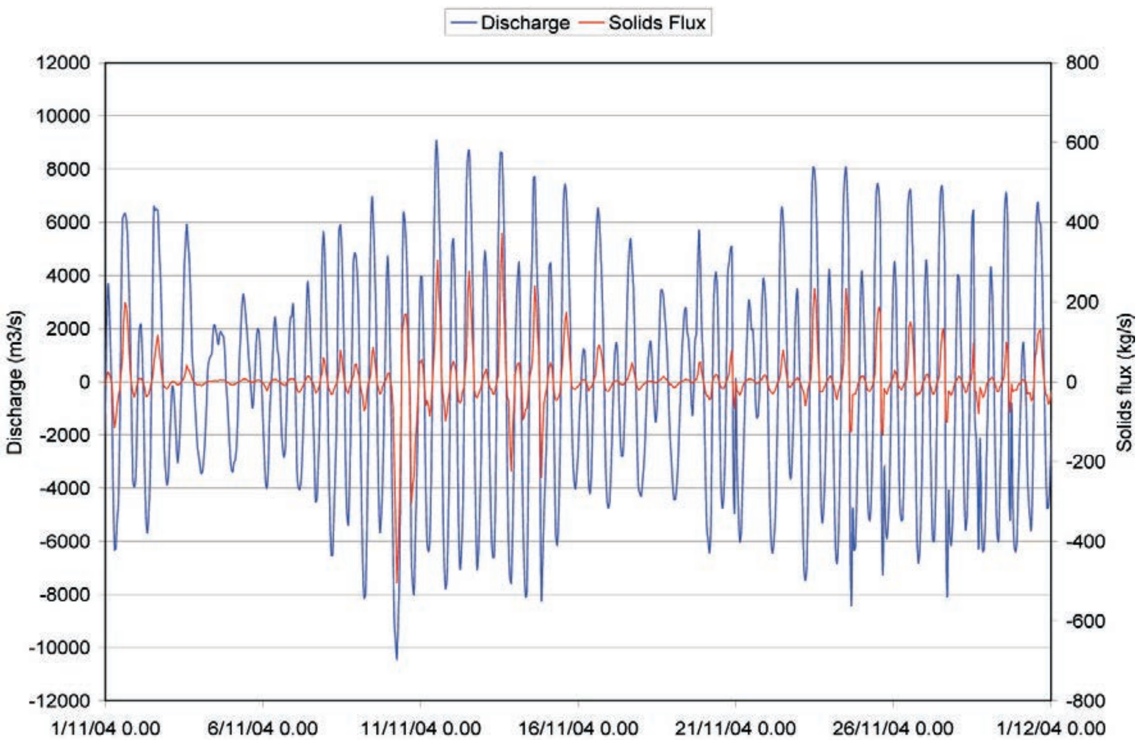

Fig. 15 - Evaluating discharge and SPM flux gained by bottom-mounted ADCP data.

resolution both in terms of time, which permits the highlighting of 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.

The investigated area of Lido inlet, shown in Fig. 9, includes the section where the bed-mounted ADCP has been monitoring the flow since, 2001 when framework of the research program started and has been coordinated by CORLA, as mentioned before.

Two types of monitoring carried out between July 2004 and April 2005:

- seasonal surveys over approx. 48 hours, finalized to investigate the variations caused by the tide;
- survey of a particular metereological event.

The equipment used during the monitoring includes an ADCP (600 kHz Workhorse Rio Grande - River Direct Reading ADCP), 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, 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 filtering 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. This conversion is carried out after 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 the water.

Near-bed concentrations and data in the near-surface zone, called blanking zone, cannot be measured reliably by the ADCP due to the corruption of the backscatter data by side lobe echoes and the blank-after-transmit requirement (Fig. 10). In order to overcome these problems, a profiling silt meter can be used to measure the near-bed concentration gradient; so the form of the concentration profile can be put into the Sediview software which will calculate an estimate of the flow of the solids. Naturally, the estimates must be treated with caution (Land and Jones, 2001).

The profiler has been installed on board a small (Fig. 12), flat-bottomed boat that moves along the cross-section at low speeds (less than 1 m/s). This installation has enabled researchers to achieve the vertical profile of the tide current with constant scanning over time. The current speed values are given by the instrument for "cells" whose height is set between 0.50, 1.00 and 2.00 m, depending on the water depths across the section. At the shallow water ends of the section the heights of the cells are set to values of 5.00, 10.00 and 25.00 cm. The width of the cells depends on the speed of the boat and, in this case, resulted in a few tens of centimeters. Fig. 13 represents an example of distribution of the SPM concentration corresponding to one specific situation.

This spatial inhomogeneity of the SPM distribution is the effect of the interaction between bottom morphology and hydrodynamics. Scraping at the bottom with high velocity fields is, in fact, more intense in the shallower part of the channel section and the observed effect is visible even in the absence of waves (Zaggia *et al*., 2005).

The bottom-mounted profiler was calibrated, using the concentrations derived by the boat-mounted ADCP, in order to obtain a continuous SPM concentration (Fig. 14).

The next step was a solid flow temporal series in the cross-section (Fig. 15). On this point the SPM concentration temporal series was multiplied by the discharge.

The trend of suspended particle matter shows a strong dependency 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 over 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 sea water and the lagoon waters are more marked, as in the summer when microalgae growth 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. The preliminary analysis of the time series of SPM concentration obtained by the calibration of field instruments shows that the average concentration at the Lido inlet is very low, about 10 mg/l, and is strongly modulated by the tide, showing a net dependence on semidiurnal and neap-spring tidal cycles.The advantages of acoustics over conventional techniques also permit the acquisition of 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 dynamical environments such as the inlets of the Venetian lagoon.

Based on information, currently available, the value of the sediment transport estimate during the period July 2004 - April 2005 in the cross-section at the Lido inlet is about 240,000 ton, corresponding to approximately 150,000 m^3. This value is in accordance with the mathematic model estimate, 300,000 m^3 per year across the three inlets of the Venice Lagoon (D'Alpaos, 2003).

7. Conclusion

The monitoring of the Venice lagoon and the northern Adriatic Sea carried out by APAT represents a fundamental point of reference for understanding and governing the effects caused by natural and anthropic processes that influence the evolution of one of the most important and extensive transition environments in Italy.

The RTLV is important for the daily tidal analysis in Venice and becomes even more important when storm surge events occur. In addition, monitoring the tides of the whole of the lagoon area allows us to study the hydro-dynamic effects produced by the action of strong local winds which can blow from the lagoon coinciding with the arrival of exceptional tides. Significant differences in level occur between the internal part of the lagoon, between the inside of the lagoon and the sea when the bora or sirocco blow over the lagoon surface with a persistent intensity of over 30 - 40 knots. Due to this monitoring, it has been shown that, when the bora is concerned, some phases are generated and last several hours, when the flow enters through the Lido inlet and leaves through the Chioggia inlet. On the other hand, the opposite situation is recorded when the sirocco blows intensely on the lagoon surface.

Another important contribution is obtained through the elaboration of the historic series data gathered by the various lagoon oceanographic stations. The calculation of the astronomic tide highlights significant modifications of the delay with which the tide propagates from the inlet to the more peripheral areas. For example, in the northern lagoon, such delays are shorter today compared to those calculated in the early decades of the 20^{th} century by a span of ten minutes. The amplitude of the tide, however, appears to have increased, especially in the central part of the lagoon where the most incisive morphological transformations of the lagoon basin have been recorded above all, due to human intervention.

It is precisely in the ambit of experimental investigations of morphological transformations of the lagoon basin that APAT, in collaboration with CNR-ISMAR, promoted a new phase of experimental surveys in 2002 for the transport of solid material in suspension. The combined use of two measuring instruments with Doppler effect (ADCP), one of which was fixed to the sea-bed at the Lido inlet and the other transported on a vessel along the section of the inlet, allowed us to collect and calibrate a great quantity of data of back-scattering acoustics of complete tide cycles. The data collected through seasonal measurements during some heavy seas allowed us to carry out new calculations for the transport of solid material in suspension. The analysis of the data collected between 2004 and 2005 has highlighted a negative balance with a loss of about 240,000 ton of suspended solids, corresponding to about 150,000 m^3 of very fine material (silt) which reaches the sea through the Lido inlet. This activity continues today through a wide-ranging research project which involves not only APAT and CNR.ISMAR, but also OGS of Trieste, Southampton Oceanographic Centre (SOC), CO.RI.LA and the Municipality of Venice. During the three-year project the measurements of suspended solids at the Lido inlet will be improved by a new survey and measurements of solids transported due to the action of drag on the sea-bed according to SOC methodology (instrumentation of the AQUILA type).

APAT is committed, therefore, to maintain up-to-date information and create a wealth of research data through the application and straightening of the survey network. A commitment which is no less significant is to implement a forecast system of sea and tide conditions in the northern Adriatic Sea in conjunction with the development of experimental activities necessary for integration of monitoring systems, orienting them towards the understanding of the morphological processes of the lagoon and the surrounding coastal environment.

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