Atti dell'Istituto Veneto di Scienze, Lettere ed Arti
Tomo xxxxxx (2016-2017) - Classe di scienze fisiche, matematiche e naturali

RECENT CHANGES IN TIDAL PROPAGATION IN THE VENICE LAGOON: EFFECTS OF CHANGES IN THE INLET STRUCTURES

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1. Introduzione

The Venice lagoon is the largest lagoon in the Mediterranean with an area of about 550 km^2, of which about 130 km^2 is composed of islands and the remaining 420 km^2 of open water. Situated in the northern part of the Adriatic Sea, it is connected via three inlets (Lido, Malamocco and Chioggia), and characterized by very shallow water depths (about 1m, excluding channels) and a very complex morphology.

The Upper Adriatic tidal regime is characterized by excursions of the order of 1 m and are amongst the largest in the Mediterranean. Open waters follow the oscillations of the sea, with a pattern that varies according to characteristic complex dynamics of shallow tidal systems (D'Alpaos, 1992).

The propagation of the tide in the lagoon is affected by various factors like the shape of the inlets, morphology of lagoon forms (channels, shoals, sandbars, mudflats, etc.). Proceeding from the inlets towards the lagoon interior, the signal which determines water level oscillations changes amplitude and form, via a progressive phase delay. These changes are a primary determinant of lagoon currents, since the same currents are mainly governed by the prevailing differences in water depth between one point and another in the lagoon. Small variations of the instantaneous gradients can significantly change the intensity and direction of currents inside the lagoon and can influence the position of the so-called "watershed" i.e. the bands that, in a first approximation, represent the limits of the circulation sub-basins pertaining to each of the three the inlets (D'Alpaos, 2003).

Man-made interventions in the lagoon over the centuries have significantly changed local tidal regimes. Two of the most significant alterations are the construction of breakwaters at the inlets and the overall reduction of the total surface area open to the expansion of the tides as a result of closing off the outer perimeter of fish farms at the edges of the lagoon. The effects of the excavation of major navigation channels last century have been significant, especially the Vittorio Emanuele Canal (dredged in 1920-1925), which connected the industrial area of Porto Marghera to the Giudecca Canal, which continues directly out to sea via the Lido inlet, and the so-called "Canale dei Petroli" (dredged in 1964-1968) that also connects the Porto Marghera industrial area with the sea, but via the Malamocco inlet.

Tidal dynamics have also been affected by degradation of lagoon morphology over time (in particular, reduction of the total area of salt marshes and the silting up of many tidal channels), partly due to the natural evolutionary processes typical of lagoon environments, but mostly triggered by anthropogenic actions themselves (Dorigo, 1961 Ferla et al., 2007, D'Alpaos, 2010).

The changes in lagoon hydrodynamics were recently analyzed in detail using mathematical models to reconstruct the evolution of the lagoon morphology from the

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early 1800s to the present day (D'Alpaos, 2010). Other studies have analyzed, even if only limited to more recent times, the same aspects based on records of the trend of the lagoon tide (Polli, 1952 Ferla et al., 2007).

This paper highlights some recent and significant changes to tidal propagation which can be traced to structural changes at all three inlets for installation of mobile gates (Project MoSE), designed to protect Venice and other lagoon settlements from extensive flooding. Alterations to the configuration of the connections with the lagoon consequently affect the relative alignment of tidal currents and the hydraulic resistance to currents at each inlet. The main effects are due to construction of the curvilinear sea walls just beyond each inlet on the Adriatic side (the so-called "*lunate*") and especially the narrowing of the inlets by construction of the “shoulders” of the MoSE together with shelter/refuge docks and navigation locks. In particular, the width of the Malamocco inlet has narrowed from 450m prior to the beginning of MoSE to 375m now (17% reduction). For Chioggia, the inlet width has been reduced from 485m to 360m (26% reduction).

Construction of the island in the middle of the Lido inlet has resulted in two separate openings of 400m and 415m wide, instead of a single opening that, at the narrowest point, measured 890m (8% reduction). The narrowing is evident in Fig. 1, a sequence of aerial photographs documenting the changes during construction of the flood gates that formally began May 14, 2003 with the laying of the first stone.

This paper is organized as follows: section 2 describes the array of hydrogrological data that was obtained and processed and describes methods and models used for the analyses. Section 3 shows the results of some analyses using harmonic constants, which are a component of the astronomic tide recorded by the network of tide gauges in the lagoon. Section 4 shows analyses of the tidal signal measured directly (sum of astronomical and meteorological contributions) in a selection of monitoring stations and which confirm the results obtained from the analysis of just the harmonic components. Section 5 illustrates the results from an investigation using a two-dimensional mathematical model designed to show possible consequences of changes in tidal dynamics in terms of lagoon hydrodynamics.

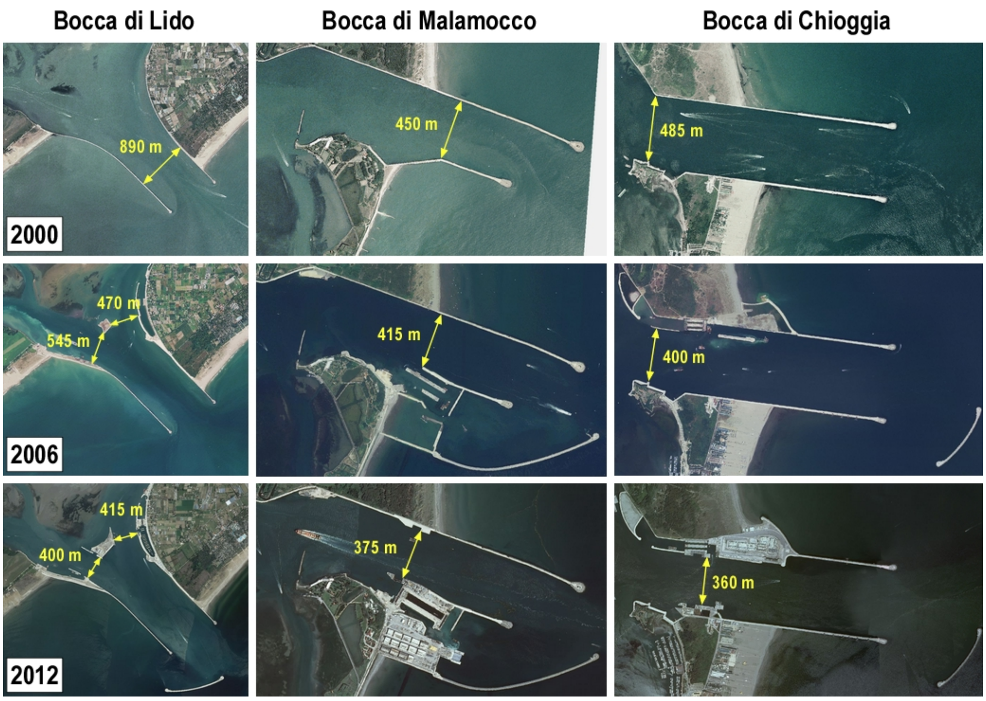

Fig. 1 – Narrowing of the inlets due to construction of Mo.S.E. (geo-referenced aerial photos from the *GeoPortale Nazionale* of the Environment Ministry http://www.pcn.minambiente.it/GN/)

2. Methods and models

Assessments set out in the following paragraphs are based mainly on analyses using the extensive tide gauge recordings for the Venice Lagoon. The first systematic tide gauge measurments began in Venice in 1871, and were carried out by the *Genio Civile* and the *Istituto Geografico Militare* (Civil Works dept. and the Military Geographical Institute). Subsequently, after reconstitution of the Water Authority (1907), another Tide Service was established with the specific task to collect tidal data in the lagoon and along the Northern Adriatic coast. Currently most of the lagoon tide gauge stations are run by the Venetian Lagoon Service of ISPRA, which has a network of 52 weather and tide stations distributed throughout the lagoon and along the coast. Additional stations are managed by the Municipality's Center for Tide Forecasting and Flood Warnings.

The tide records, subject to periodic validation procedures and controls, are available as a time series with intervals of 10 minutes and sensitivity of 1cm.

Along with CNR-ISMAR and the Venice Municipality, ISPRA also provides tide forecasts for a selection of stations, both in the short term using models that project a few days forwards, as well as long term annual tide tables. These latter predictions relate purely to the astronomical tide, i.e. the tidal oscillation component that is determined by lunar-solar attraction, without considering the other components that are linked to weather factors, sea level variations in the Adriatic and changes in long-term global mean sea level.

In this study we considered hydrographic data for the period 1994-2015 from 21 stations in the lagoon and at the inlets. The stations that had the most complete set of validated data were selected, especially for the last decade, which is of particular interest for the present investigation. Data was also used from the Oceanographic Platform “High Water”, located in the Adriatic about 15km offshore, collected by the Tide office of Venice Municipality (Fig. 2).

The astronomical tide was calculated using POLIFEMO software (Tomasin, 2005) developed at ISMAR-CNR. The programme processes measured sea levels to determine the harmonic constants that make up the astronomical tide. This is expressed as follows:

$$y(t) = A_0 + \sum_{n=1}^{N} A_n \cos\left(\sigma_n t - \kappa_n\right)$$

where $y(t)$ is water level at time t, A_n, σ_n, κ_n are, respectively, amplitude, angular velocity and phase delay of the singular component, A_0 is average sea level. In the calculation, angular velocities σ_n, that depend on the periods of celestial mechanics, are assumed to be known constants. The amplitude and phase of each component are determined by the programme via historic tide level data and by selecting the best approximation between observations and the theoretical function via the least squares method (Cordella e al., 2010).

Specifically for the Adriatic and the Venice Lagoon, eight harmonic components are sufficient to calculate the astronomical component of the tide level with centimetre precision. The various components, four with diurnal periodicity and four semi-diurnal, are characterised with a symbol connected to their astronomic origin: M2, S2, N2, K2, K1, O1, P1, S1 (ISPRA, 2016).

The phase delay κ_n that, generally, represents the delay in tidal peak with respect to the moon, or the reference astral period, on the meridian of the location under consideration, can be calculated using different conventions. This study used phase delays calculated according to a reference zero fixed for the year 1900, which are then corrected and aligned with the specific year under consideration. An important characteristic of the POLIFEMO code that relates to this is the ability to take into account long term variations in harmonic constant, associated with the periodicity of the celestial mechanics (Cordella et al., 2010).

Hydrodynamic simulations were carried out using the 2DEF model, developed by researchers at ICEA dept. of Padua University (D’Alpaos and Defina, 1993, D’Alpaos and Defina, 1995, Defina, 2000). This modelling tool is the product of over forty years' experience studying lagoon hydrodynamics that continues today and is updated with results of further investigations by the same research group into eco-morphodynamic processes that characterise the Venice Lagoon (e.g. Carniello et al. 2005, 2011, 2012, 2014).

The model is based on a uni-bidimensional numerical scheme of finite elements that resolves differential equations for the current *moto* in open, shallow waters, formulated in order to be applied in area which are only partially submerged or that are submerged only during evolution of the phenomenon under investigation (Defina et al, 1994; D’Alpaos and Defina, 1995; Defina, 2000).

In this study the hydrodynamic model was used to simulate tidal propagation in the Lagoon, considering two different configurations of the three inlets: prior to the structural changes for the Mo.S.E. Project (2003 scenario) and after completion of the modifications (2012 scenario).

3. Variations in height and delay of the astronomic tide

In calm atmospheric conditions, when circulation is influenced only by the tide, the Venice Lagoon can be considered to be composed of three sub basins that, from the hydrodynamic viewpoint, are almost independent. Each sub-basin is connected to the sea via one of the three inlets (Lido, Malamocco and Chioggia) and is separated from the adjacent basin by an area in which there are almost no currents that is identified as a "*partiacque*" (watershed) strip. Oscillation of the Adriatic tide propagates from each inlet towards the edges of each sub-basin, changing according to the dynamics of the currents in the canals and across the lagoon shallows. In particluar, in the inner open waters, the amplitude signal varies (normally a reduction) and there is a phase delay with respect to the tide signal in the open sea (D'Alpaos, 1992).

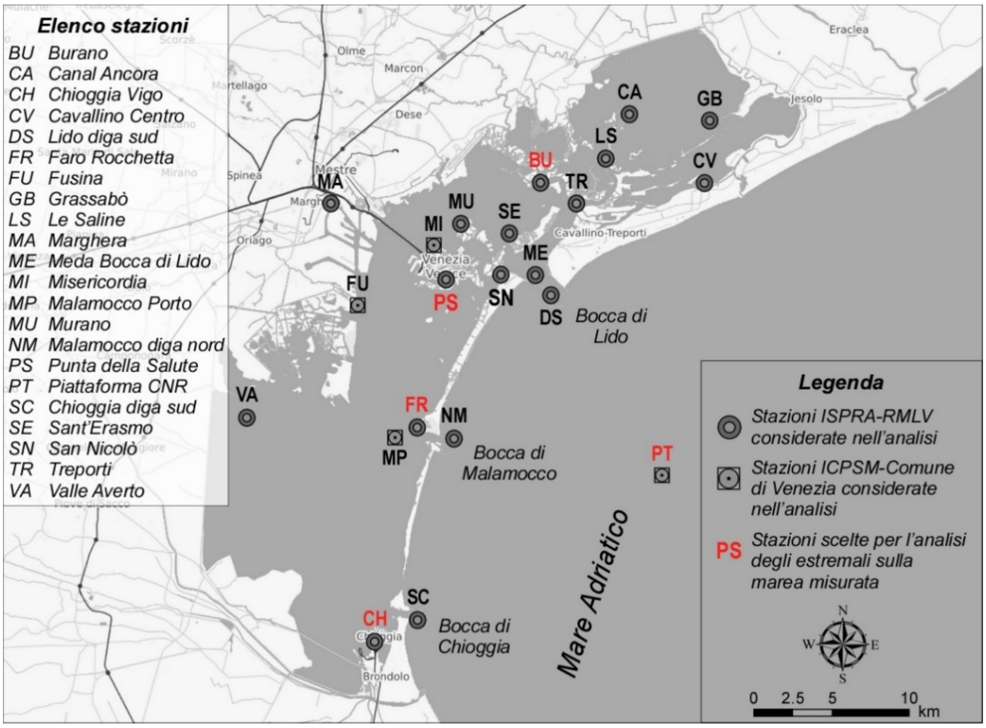

Fig. 2 – Map of the networks of monitoring stations run by ISPRA and Municipality Tide Office used for this study.

Analyses of the astronomic tide provide an evaluation of the reference conditions, not influenced by the effects of meteorological perturbations. These can very significantly modify both oscillations in water level in the Adriatic as well as the levels and currents in the lagoon to the point where, in particular wind conditions, subdivision of the three basins can change substantially (Carniello et al. 2011, D'Alpaos, 2010). However atmospheric perturbations produce effects that are limited in time and that do not significantly modify the average characteristics of lagoon hydrodynamics on the scale of a year, that are essentially governed by astronomical forcing.

To evaluate variations in amplitude and phase delay of tides over the years at the various stations in the lagoon it is therefore appropriate to consider the astronomical tide (Ferla et al, 2007, Polli, 1952, Tomasin, 1974).

For this purpose, 21 stations in the lagoon have been considered (Fig. 2). These include some stations of the ISPRA Venice Lagoon Service Network, for which readings for the period 1994-2015 are almost complete and the data has been subjected to validation procedures and published (ISPRA 2012). Distribution of these stations covers a large area of the northern lagoon, north of the city. Not many available stations are situated in the central and southern lagoon. Unfortunately of these stations, there was not enough validated data to carry out the analyses, especially for recent years which are the main interest of this study.

To further expand the data set, but above all, for testing purposes, three stations of the Municipal network were considered (Malamocco, Misericordia and Fusina, Fig. 2) that also have continuous recordings, although limited to recent years.

In addition, a series of measurements from the CNR-ISMAR "High Water" Platform was included, acquired via the Municipal Tide Office which also keeps instruments on the platform, covering the whole study period.

For each year and for each station, using the POLIFEMO software, the amplitudes and phase delays of the seven main components of the astronomical tide (M2, S2, N2, K2 and K1 of semidiurnal periodicity, O1, P1 of diurnal periodicity) were determined. The effect of the eighth diurnal component S1has been omitted which, in practical terms, has a very small influence on the height of the tide and for which changes from year to year are minimal.

Calculation of the "annual averages" for amplitude and phase delay at each station was obtained by a process analogous to that used in previous investigations (Ferla et al., 2007, Polli, 1952). The overall spread was obtained by summing the amplitudes of the individual components. Unlike the other studies mentioned, in this case the sum included all 7 astronomical components and not only the most important M2 and S2.

The phase delays, in line with criteria followed by other studies cited, were calculated singly in degrees for each of the 7 components. On the basis of the known angular velocity of each component, the degrees were then converted to minutes and turned into delays according to the time difference compared to the corresponding values for the offshore station (CNR-ISMAR Platform). Finally, the overall delay for the generic station in a given year was obtained by calculating the weighted average of the delays of each component relative to the amplitude of each of them.

The results obtained for amplitude and phase delay are reported in Tab. 1 and 2, and graphically represented in Figs. 3 and 4.

Considering amplitude, the curves of Fig. 3 highlight a trend that, despite year to year variations, seems quite clear. It shows that for the period 1994-2004 the amplitude remained stable or slightly increased but in the years after 2004 amplitude has gradually fallen in almost all the stations. Only the outer stations of the lagoon deviate from this trend – the offshore platform and the three stations located on the jetties at the inlets (South wall at Lido, Malamocco North wall and South wall at Chioggia), where even after 2004 the amplitudes do not vary appreciably.

The data shown in Tab. 1 show that, on average, the amplitude variations in the decade 2004-2014 are of the order of 5 to 7%. This result was obtained by comparing the average of the three years 2003-2005 with that of 2013-2015.

Even the delays with respect to the sea show a trend that differs markedly if we consider the period prior to 2004 and the next. It is shown that after 2004 the phase delay tends to increase generally (Fig. 4). As in the case of the amplitudes, this trend appears in all the lagoon stations but does not at the three stations located outside the inlets. On average, the phase delay increases by amounts varying from 5 to 15 minutes, but there are some stations for which the delay is more than 20 minutes (Tab. 2).

These variations cannot be ignored since they affect the majority of the stations in the lagoon, but not to those at sea, indicating that changes in the last decade have influenced the propagation of the tide from the sea towards the interior.

These variations seem to be attributable to the narrowing of the cross-sections of the inlets due to construction of the Mo.S.E. supporting structures (Fig. 1) that began in 2003. While construction of the barrier system is not yet complete, the so-called fixed structures that have changed the configuration of the inlets and seem to affect the tidal currents were already substantially built in 2011. These works include curvilinear sea walls (the so-called "lunate") beyond the inlets, raising the lagoon floor, adding the supporting “shoulders” for the mobile gates, the navigation locks, the refuge ports (Fig. 2). The narrowing of the inlets and the modification of their geometric configuration has caused increased hydraulic resistance to the tidal currents passing through and, consequently, a modification of the tidal signal which results in a reduction in its amplitude, and an increase of the phase delay (Matticchio, 2004 Umgiesser, 2004).

As mentioned above, the tide gauge stations included in this study are not distributed evenly across the lagoon so it is not possible, based on the available data, to differentiate with sufficient precision between the effects reported in different parts of the lagoon. The results nonetheless suggest that the largest changes, both in terms of amplitude and phase delays, have occurred in the Malamocco Basin. This is evident when examining variations at the ISPRA Faro Rocchetta (FR) station, located at the Malamocco inlet, for which the observed variations are the highest. In this case, the reliability of the result obtained is implicitly confirmed by comparison with the Malamocco Port station (MP), managed by the Municipality Tide Office. Although the municipality's station has data only for a limited period, which limits the comparison of results for the two stations, situated a short distance from each other, readings match closely.

Somma delle semi-ampiezze delle componenti astronomiche in alcune stazioni della Laguna di Venezia dal 1994 al 2015																						
Anno	**BU**	**CH**	**CN**	**CV**	**DS**	**FR**	**FU**	**GB**	**LS**	**MA**	**ME**	**MI**	**MP**	**MU**	**NM**	**PS**	**PT**	**SC**	**SE**	**SN**	**TR**	**VA**
1994	66.7	73.3		47.9	75.1	75.8		59.0	58.9	77.8	74.9				*76.1*	76.3	*74.2*	*74.6*		74.9	66.8	
1995	67.3	73.4		48.3	74.7	74.4	*73.7*	58.9		74.0	73.7			76.9	*76.9*	76.3	*74.5*	*74.0*		74.8	67.5	74.6
1996	65.4	73.2		48.8	74.1	75.0	*78.3*	59.4		78.8	73.2			74.3	*75.8*	76.6	*74.0*	*73.9*	72.6	73.9	66.8	75.1
1997	67.5	73.9		49.5	76.2	76.3	*79.2*	59.2		80.4	76.7			78.5	*77.8*	78.1	*75.9*	*76.1*		75.4	67.6	75.8
1998	67.4	73.1		48.4	74.6	75.4		57.9		77.7	73.8				*76.4*	76.6	*75.1*	*74.5*		75.5	66.9	
1999	67.6	72.5		48.1	74.7	75.7	*78.0*	58.2	58.9	77.6	73.8			74.8	*76.5*	76.2	*74.7*	*74.7*	73.0	75.2	67.1	74.4
2000	65.7	71.5		47.5	74.8		*76.3*	57.7	58.4	75.5	71.9			73.4	74.1	74.9	*72.1*	73.0	71.9	72.9		73.3
2001	68.7	73.9		50.7	77.1	74.8	79.1	60.7	61.5	78.0				75.8	*77.6*	77.4	*75.4*	75.2	74.3	75.5	67.5	75.5
2002	67.2	73.3		51.3	75.7	74.9	77.9	60.7	60.7	77.6				74.9	75.2	77.3	*74.3*	73.9	72.9			75.3
2003		73.9		52.5	76.2	75.0	78.7	60.0	60.7	78.7		*75.4*		75.6	76.1	78.0	*74.7*	74.3	73.5	75.4	67.1	75.6
2004	68.5	74.3	61.5	53.5	76.9	76.8	79.4	61.0	61.5	78.9	74.5	*75.1*		75.2	76.1	77.7	*75.2*	74.9	73.2	75.1		76.8
2005	65.4	71.7	58.3	50.8	75.2	73.5	77.2	57.4	58.9	77.5	73.2	*72.0*	*74.2*	72.0	75.1	75.9	*73.9*	73.4	72.3	73.3		74.3
2006	64.9	71.5		48.8	75.3	73.0	77.6	57.2	58.4	77.0		*72.3*	*74.0*	71.0	*75.0*	76.0	*73.8*	72.4	72.4	73.2		73.6
2007	64.7	71.7	58.5	49.2	76.2	73.6	77.8	57.1	58.3	77.5	74.0	*72.3*	*74.4*	71.5	74.3	75.2	*74.6*	74.5	72.0	73.5	62.1	73.4
2008	63.1	70.6	57.1	48.4	75.2	72.2	75.5	56.5	56.8	75.6	73.3	*70.2*	*72.4*	68.4	75.1	73.4	*73.8*	74.0	69.9	71.1	60.3	71.5
2009	64.1	71.3	58.9	51.2	77.4	72.0	75.7	57.9	58.0	75.7	73.7	*70.5*	*72.3*	70.4	75.3	73.2	*74.7*	74.4	69.8	71.6	61.4	71.9
2010	62.8	69.5	57.0	50.2	74.9	69.5		57.0	56.8	73.3	72.4	*68.9*	*69.7*	68.6	74.7	71.1	*73.6*	73.2	67.3	69.5	60.0	70.9
2011	63.6	70.7	56.8	48.3	75.5	70.7		55.9	56.5	75.0		*70.7*	*71.0*	69.8	76.2	72.6	*74.7*	74.4	69.7	71.1	60.5	72.1
2012	62.3	69.4	56.3	47.9	73.0	69.6		56.6	56.0	73.9	73.3	*69.7*	*70.0*	68.7	74.5	71.7	*73.4*	73.1	68.0	69.4	58.9	70.7
2013	62.4	69.2	56.9	48.4	73.5	69.2		57.2	56.2	73.3	73.2	*69.3*	*69.8*	68.5	75.0	71.2	*73.5*	73.4	67.7	70.9	59.4	70.9
2014	62.4	69.6	56.5	48.1	74.3	68.7		55.8	56.0	73.1	73.2	*69.0*	*70.4*	68.2	74.4	71.5	*73.1*	73.0	67.3	69.5	59.2	69.6
2015	62.7	71.0	56.5	48.6	75.3	70.4		56.7	56.4	75.2	74.3		*71.0*	70.1	75.9	72.8	*74.8*	74.1	69.1	71.2	58.8	71.3
Codice stazione: BU: Burano, CH: Chioggia Vigo, CN: Canal Ancora, CV: Cavallino Centro, DS: Diga sud Lido, FR: Faro Rocchetta, FU: Fusina, GB: Grassabò LS: Le Saline, MA: Marghera, ME: Meda bocca di Lido, MI: Misericordia, MP: Malamocco Porto, MU: Murano, NM: Diga nord Malamocco, PS: Punta della Salute PT: Piattaforma CNR, SC: Diga sud Chioggia, SE: Sant'Erasmo, SN: San Nicolò, TR: Treporti, VA: Valle Averto.																						
Note: tutti i dati sono stati messi a disposizione da ISPRA - Servizio Laguna di Venezia ad eccezione di quelli evidenziati in blu, forniti da ICPSM - Comune di Venezia																						

Table 1 – Variation in tidal amplitude between 1994 and 2015

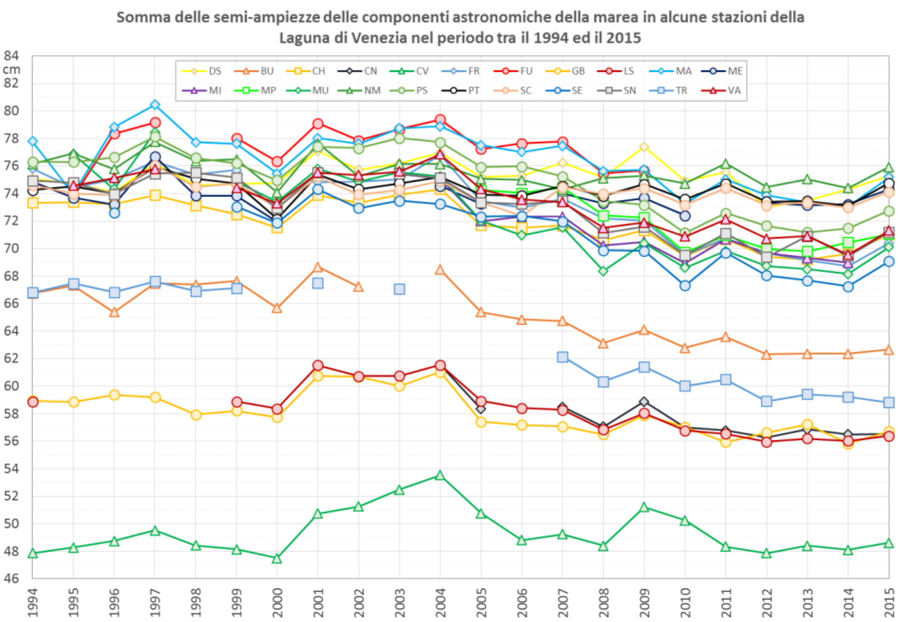

Fig. 3 – Variation in tidal amplitude between 1994 and 2015.

Ritardo di propagazione delle componenti astronomiche in alcune stazioni della Laguna di Venezia rispetto a Piattaforma CNR																						
Anno	BU	CH	CN	CV	DS	FR	FU	GB	LS	MA	ME	MI	MP	MU	NM	PS	PT	SC	SE	SN	TR	VA
1994	78.3	21.1		185.1	0.2	15.0		165.8	103.9	72.5	7.1				*10.8*	44.6	*0.0*	*2.4*		29.2	50.4	
1995	74.9	22.4		187.5	1.3	25.9	*40.7*	160.4		66.2	12.8			55.1	*2.9*	48.4	*0.0*	*3.9*		30.2	50.4	92.4
1996	81.3	21.4		193.5	-0.2	20.9	*60.6*	164.0		66.0	14.2			65.2	*4.2*	49.6	*0.0*	*-0.9*	46.4	32.7	51.8	97.3
1997	84.7	24.1		189.8	-1.7	20.0	*43.4*	174.2		56.1	5.2			58.4	*-1.2*	45.4	*0.0*	*-2.0*		28.0	47.4	98.5
1998	85.4	24.9		189.1	3.0	20.0		167.5		62.1	13.1				*8.1*	53.8	*0.0*	*3.1*		29.7	52.4	
1999	86.1	26.3		196.6	4.7	19.0	*56.8*	167.2	124.5	63.2	10.3			67.3	*4.2*	51.3	*0.0*	*0.0*	47.0	28.7	54.3	94.7
2000	80.9	21.1		191.3	-4.0		*53.0*	160.5	115.0	57.7	5.3			62.9	-9.9	43.4	*0.0*	-5.4	41.7	26.7		86.5
2001	88.2	27.1		195.2	3.5	12.0	60.4	162.0	122.1	62.4				71.2	*5.4*	51.1	*0.0*	2.9	49.6	36.1	58.6	94.7
2002	78.3	26.5		185.4	-2.9	24.9	58.2	163.0	118.8	58.8				67.1	0.9	50.1	*0.0*	0.6	48.1			89.9
2003		19.9		173.8	-9.9	20.7	48.7	154.5	112.4	52.8		*59.2*		69.5	-6.1	41.8	*0.0*	-7.0	39.2	26.4	50.6	84.4
2004	76.9	27.3	145.8	183.5	-3.7	22.1	51.8	159.1	120.8	69.1	1.4	*64.8*		73.5	-1.5	46.9	*0.0*	1.2	52.5	28.2		84.3
2005	84.1	32.5	154.1	183.4	4.4	28.5	53.5	160.8	114.7	66.2	7.3	*65.6*	*31.9*	72.5	-0.4	51.0	*0.0*	4.9	47.7	30.3		84.7
2006	88.0	32.0		187.9	-0.8	28.3	60.1	161.2	123.1	56.9		*68.8*	*36.5*	71.1	*-0.5*	47.5	*0.0*	4.2	47.1	29.0		91.0
2007	93.7	36.9	153.6	193.7	5.2	35.3	65.4	172.1	126.1	74.0	16.1	*74.4*	*41.5*	83.6	5.7	56.5	*0.0*	6.3	40.6	36.4	70.0	101.3
2008	94.8	37.6	155.3	194.5	6.2	37.0	67.4	169.8	133.1	73.5	13.7	*75.6*	*44.3*	84.3	2.4	56.3	*0.0*	5.9	56.7	33.2	72.7	108.1
2009	91.6	38.0	151.7	193.3	4.9	38.6	74.7	163.8	132.6	72.0	11.6	*76.3*	*48.6*	81.2	2.5	57.1	*0.0*	6.3	57.2	39.0	74.0	100.5
2010	90.7	37.9	161.0	195.2	0.3	41.8		162.7	134.2	72.1	10.9	*76.5*	*54.5*	80.4	-3.3	57.1	*0.0*	2.8	62.3	37.2	73.0	99.4
2011	94.7	38.7	162.1	208.2	7.1	45.2		173.4	135.7	78.5		*79.0*	*55.4*	85.7	5.3	60.6	*0.0*	7.9	61.8	38.7	69.9	109.6
2012	90.3	38.9	163.9	208.3	11.9	46.1		172.7	136.4	78.2	12.1	*77.6*	*53.5*	86.6	13.0	58.9	*0.0*	16.2	58.3	44.4	75.9	112.0
2013	95.1	36.9	159.0	202.5	8.8	44.1		170.2	134.5	76.9	10.1	*77.8*	*51.1*	83.9	5.3	60.3	*0.0*	5.6	58.7	45.4	79.5	112.0
2014	90.4	32.5	161.1	201.1	-0.6	38.7		164.6	132.3	75.0	6.4	*73.8*	*44.1*	78.3	1.0	56.2	*0.0*	2.1	56.8	40.7	74.8	108.4
2015	90.3	34.1	160.8	202.8	2.6	41.2		174.9	135.0	76.4	10.5		*48.4*	84.8	0.7	58.7	*0.0*	2.1	58.3	43.4	78.4	109.1
Codice stazione: BU: Burano, CH: Chioggia Vigo, CN: Canal Ancora, CV: Cavallino Centro, DS: Diga sud Lido, FR: Faro Rocchetta, FU: Fusina, GB: Grassabò LS: Le Saline, MA: Marghera, ME: Meda bocca di Lido, MI: Misericordia, MP: Malamocco Porto, MU: Murano, NM: Diga nord Malamocco, PS: Punta della Salute PT: Piattaforma CNR, SC: Diga sud Chioggia, SE: Sant'Erasmo, SN: San Nicolò, TR: Treporti, VA: Valle Averto.																						
Note: tutti i dati sono stati messi a disposizione da ISPRA - Servizio Laguna di Venezia ad eccezione di quelli evidenziati in blu, forniti da ICPSM - Comune di Venezia																						

Table 2 – Variation in tide propagation between 1994 and 2015.

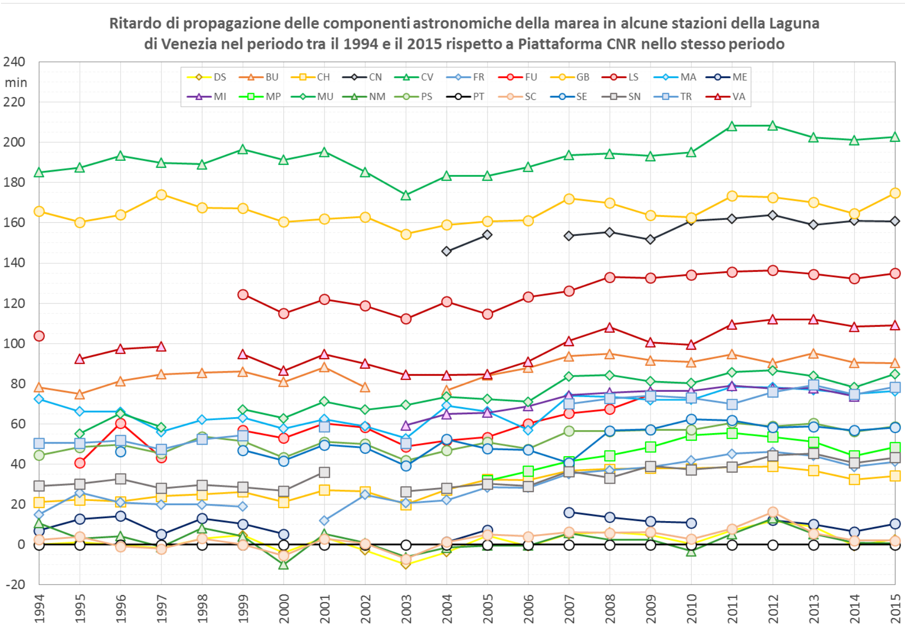

Fig. 4 – Variation in tide propagation between 1994 and 2015

4. Variations in tidal amplitude and delay of the real tide

The above considerations have indirectly yielded estimates of variations in amplitude and delay in tidal phase, opportunistically combining the values that define the individual harmonic components that constitute the astronomical tide. It was therefore considered worth completing the above evaluations via direct calculation of the amplitude and the phase delay based on analysis of the complete tidal signal, in which the peaks and troughs of the oscillations have been identified (the so-called "extremes") . On the one hand, this is to verify results obtained indirectly, and on the other to obtain variations in amplitudes and phase delay that are quantitatively congruent with the tidal readings in the lagoon.

The first calculation, for each year and for each station, was the evolution of the astronomical tide on the basis of the harmonic components was produced by the POLIFEMO software and used in the previous section. The signal was calculated by selecting all the maxima and the minima, and the average tidal oscillation amplitude was calculated as the difference between the average maximum and the average of the minimum for each year. The phase delay with respect to the CNR Platform was calculated by identifying, for each extreme (maximum or minimum) of the particular station, the corresponding extreme registered at the Platform, and calculating the delay from the latter in minutes. For each station, the amplitude (A_{med}) and the phase delay (R_{med}) were ultimately obtained using the following formulas:

$$A_{med} = \frac{1}{N_{max}} \sum_{i=1}^{N_{max}} H_i^{max} - \frac{1}{N_{min}} \sum_{j=1}^{N_{min}} H_j^{min}$$

$$R_{med} = \frac{1}{N_{max} + N_{min}} \left(\sum_{i=1}^{N_{max}} \left(T_i^{max} - T_{i\_PT}^{max}\right) + \sum_{j=1}^{N_{min}} \left(T_i^{min} - T_{i\_PT}^{min}\right) \right)$$

in which N_{max} and N_{min} represent the number of positive peaks (tide maxima) and negatives (tide minima), H^{max} and H^{min} indicate the value of water level corresponding to each tide maxima and minima, while (T^{max}-$T^{max}{}_P$) and (T^{min}–$T^{min}{}_P$) are the delay with which each extreme is reached at the particular station under consideration with respect to the corresponding extreme at the CNR platform.

The second calculation involved directly analysing measurements, i.e. without reconstructing just the astronomical component of the tide but considering the complete signal (combination of astronomic and meteorological factors) as registered at the various stations.

Specifically, the data measured at 10 minute intervals (or extrapolated to fit that frequency in the few cases where the sampling intervals were higher) have been recalculated by applying a moving average filter of 5 measurements, in order to regularize trends that, as stated already, are measured with a sensitivity of 1cm. Identification of the extremes from measured data was carried out for each station, taking all astronomical maxima and minima and identifying, for each, the nearest measured maximum or minimum within 2 hours. Once the extremal was identified, the amplitude and phase delay were calculated using the same formulas used for astronomical tides.

The graphs in Fig. 5 and 6 show the results obtained by analysis of the extremes considering both the astronomical component alone (solid lines) and the measured tide level including the meteorological contribution (dotted lines) for the tide gauge stations at Chioggia Vigo, Faro Rocchetta, Punta della Salute, Burano, selected to obtain a good spread around the lagoon basin.

From the graphs it is clear how variations in the amplitude and phase delay are totally in line with results obtained on the basis of the harmonic constants alone, described in the previous section. Comparing the amplitudes of the 2003-2005 period with measurements for the period 2013-2015 at four stations, it can be seen that the tidal amplitude decreases by about 3-4 cm. The largest reductions are at the Faro Rocchetta station and Burano. Slightly lower reductions are found for Punta della Salute and Chioggia. As for the phase delay with respect to the sea, the results indicate that this is increased by about 20 minutes at Faro Rocchetta, and a little over 10 minutes for the other stations. This confirms that the most significant effects of interventions at the inlets concerned the Malamocco basin, above all.

Agreement between the results obtained by analyzing the individual harmonic components (section 3), and those derived using the peak highs and lows (astronomical range and the full tide signal - section 4), as well as confirming the validity of the results, also confirms the reliability of the initial approach which, above all, is much less costly to carry out.

	Ampiezza dell'oscillazione di marea (cm)										**Ritardo rispetto al mare (minuti)**							
	marea astronomica					*marea reale*					*marea astronomica*				*marea reale*			
Anno	**PT**	**FR**	**BU**	**CH**	**PS**	**PT**	**FR**	**BU**	**CH**	**PS**	**FR**	**BU**	**CH**	**PS**	**FR**	**BU**	**CH**	**PS**
1994	56.2	56.9	50.5	55.7	58.7	55.4	57.6	52.1	56.3	60.5	18.8	75.4	20.7	40.6	25.9	78.1	25.4	43.2
1995	56.0	56.6	50.8	55.6	58.8	55.6	57.2	52.3	57.0	60.9	24.4	74.6	21.4	43.4	28.7	78.3	24.9	46.8
1996	56.3	56.6	49.8	55.8	59.0	55.6	58.7	52.4	57.4	61.2	23.3	79.5	21.1	45.7	27.0	77.6	24.3	48.5
1997	56.6	56.8	51.3	56.1	59.2	56.1	58.4	53.7	58.0	61.5	21.5	77.4	19.4	40.5	25.0	77.4	23.3	44.3
1998	56.2	56.5	51.6	55.5	58.9	56.5	58.1	53.5	56.5	60.8	21.2	81.1	22.6	48.9	27.7	84.8	27.7	49.5
1999	56.6	56.9	51.7	55.7	59.0	56.6	58.4	54.5	57.4	61.2	24.3	81.6	24.1	46.8	29.8	84.6	28.1	52.4
2000	55.8		50.9	55.5	58.7	56.2		53.6	57.0	61.0		77.5	20.7	39.7		80.9	26.3	46.1
2001	57.0	56.1	52.4	56.1	59.6	57.5	57.0	55.0	57.7	61.7	14.9	83.3	25.4	45.5	29.8	86.8	29.5	51.6
2002	56.1	56.5	51.0	55.6	59.1	56.4	57.5	53.8	56.9	61.0	26.8	73.7	25.4	46.3	30.8	75.2	28.6	51.2
2003	56.3	56.2		56.0	59.4	56.6	58.0		57.7	61.5	22.9		17.5	37.5	28.5		23.5	43.1
2004	56.5	57.6	51.7	55.9	59.3	57.5	59.6	54.9	58.1	61.7	27.7	73.6	27.6	43.1	32.8	73.6	30.7	48.9
2005	56.2	55.5	49.8	54.9	58.0	57.0	57.7	53.1	57.1	60.8	31.2	81.4	30.4	49.5	34.4	83.7	33.2	49.7
2006	56.2	54.9	49.3	54.4	58.2	56.3	56.8	52.0	55.5	60.0	30.2	84.6	31.1	44.6	34.7	86.9	33.8	51.2
2007	56.3	55.4	48.9	54.4	57.6	56.7	56.9	51.8	55.9	59.7	37.4	90.6	36.4	54.1	40.0	94.4	39.6	56.5
2008	55.8	54.3	47.6	53.4	56.0	56.7	56.4	50.9	55.3	58.5	39.8	94.4	38.1	55.6	40.6	97.2	40.2	58.5
2009	56.0	53.7	48.1	53.6	55.4	56.9	56.1	51.4	55.8	58.0	42.2	91.3	38.8	55.3	42.0	91.2	39.9	58.7
2010	56.1	52.6	47.7	53.0	54.7	56.6	55.0	50.7	55.1	57.3	45.6	89.1	38.9	55.2	44.5	89.0	40.1	58.4
2011	56.5	53.0	48.0	53.3	55.3	56.9	55.3	51.0	55.2	57.6	48.2	92.2	39.0	57.7	47.9	93.0	41.5	61.9
2012	55.6	52.0	46.8	52.6	54.6	56.3	54.6	50.3	54.9	57.2	48.7	86.9	38.8	55.9	47.9	88.4	40.6	60.0
2013	55.7	51.8	47.2	52.5	54.6	56.6	54.4	50.4	54.6	57.2	46.1	90.4	35.4	55.9	46.7	93.2	38.1	60.6
2014	55.5	51.4	46.9	52.6	54.5	56.4	53.5	49.8	54.3	56.8	41.7	87.2	32.2	53.7	42.1	89.4	36.0	57.7
2015	56.6	52.3	47.2	53.7	55.6	57.1	54.7	50.4	55.3	57.8	44.6	85.6	33.2	55.2	44.4	88.3	36.5	59.2
media 94-04	*56.3*	*56.7*	*51.2*	*55.8*	*59.1*	*56.4*	*58.0*	*53.6*	*57.3*	*61.2*	*22.6*	*77.8*	*22.4*	*43.5*	*28.6*	*79.7*	*26.6*	*47.8*
media 05-15	*56.1*	*53.4*	*48.0*	*53.5*	*55.9*	*56.7*	*55.6*	*51.1*	*55.4*	*58.3*	*41.4*	*88.5*	*35.7*	*53.9*	*42.3*	*90.4*	*38.1*	*57.5*
differenza	***-0.3***	***-3.3***	***-3.2***	***-2.3***	***-3.2***	***0.3***	***-2.4***	***-2.5***	***-1.9***	***-2.9***	***18.9***	***10.8***	***13.3***	***10.4***	***13.7***	***10.7***	***11.6***	***9.7***

Table 3 – Variation in amplitude and phase delay obtained by analysing the extremes relative to a single astronomic component and the complete tidal signal (also containing the meteriological contribution) in some of the stations in Fig. 2.

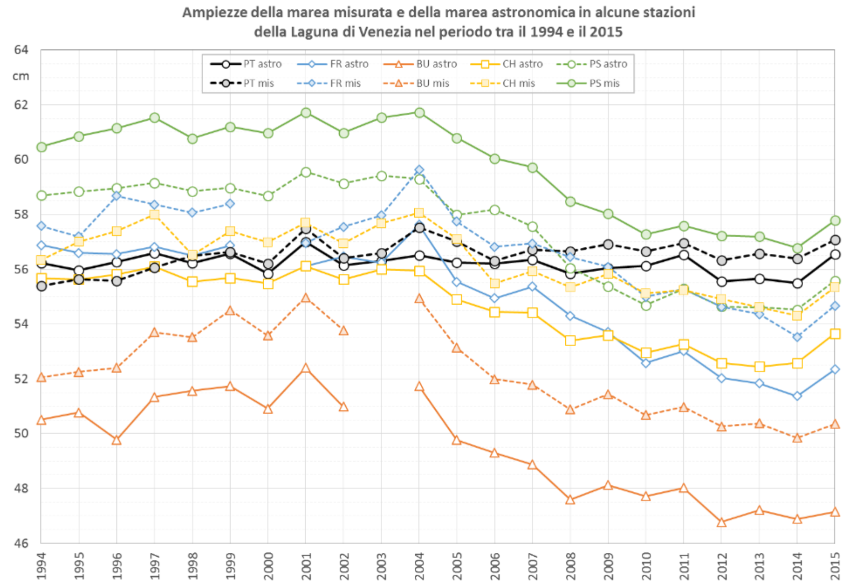

Fig. 5 – Variation in tidal amplitude using the extremes relative to a single astronomic component (continous line) and the complete tidal signal including the meteorological contribution (dotted line) in some stations of Fig. 2.

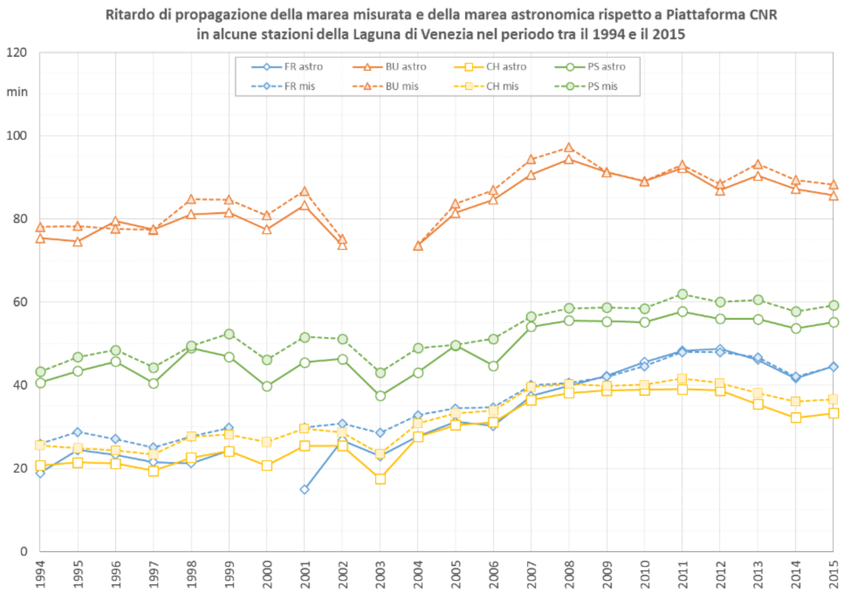

Fig. 6 – Variation in the tide propagation delay obtained by analysing the extremes relative to a single astronomic component (continous line) and the complete tidal signal including the meteorological contribution (dotted line) in some of the 4 stations of Fig. 2.

5. Effects on lagoon circulation

To complete the study, modelling simulations were carried out to analyse the effects of changes in the inlet configuration on overall lagoon hydrodynamics, using the one-dimensional hydrodynamic model of the Venice lagoon developed by the ICEA Department of Padua University, described in section. 2.

The model considered two different lagoon configurations: the 2003 version with the inlets as they were before the start of the Mo.S.E. works (Fig. 7a); the 2012 situation when the inlet changes had been completed. The calculation grid for the second configuration is not shown for brevity but it differs from the "pre-construction" configuration in shape and dimensions. Bathymetry at the inlets was taken from the design specifications and the aerial surveys in Fig. 1. The internal lagoon bathymetric levels were from the most recent comprehensive survey of the lagoon available (Carniello et al. 2011 - Fig. 7b).

The ability of the model to reproduce the hydrodynamic behaviour of the lagoon had already been widely tested in other applications (eg Carniello et al. 2005, 2011); it was further verified by simulating two real events (in 2003 and 2012) with two different configurations and comparing the results with tidal data from the ISPRA network. The results (not shown for brevity) displayed excellent correlation between field measurements and model calculations, confirming the accuracy of the model when simulating tidal propagation in the Venice Lagoon system.

Subsequently, additional simulations were carried out with both configurations (2003 and 2012) with the same sea and tide boundary conditions (an astronomical Spring tide lasting a few days).

Results obtained from the two scenarios was found to be in line with the results obtained in the previous analyses. In fact, the model indicates that the configuration change at the inlets due to the fixed structures of Mo.S.E. Caused a greater attenuation of tidal amplitude in the lagoon and increased the phase delays. Data provided by the model in the entire computational domain has revealed that these changes are not evenly distributed in the lagoon, but are mainly concentrated in the central basin, an extension of the Malamocco inlet, and in the North Lagoon, via the Treporti canal.

The model highlights how the variation of the configuration of the inlets, especially the narrowing of the cross-section, causes current velocity through the inlets to increase. This is especially noticeable at the Malamocco inlet (Fig. 8) which has the fastest current velocity of the three.

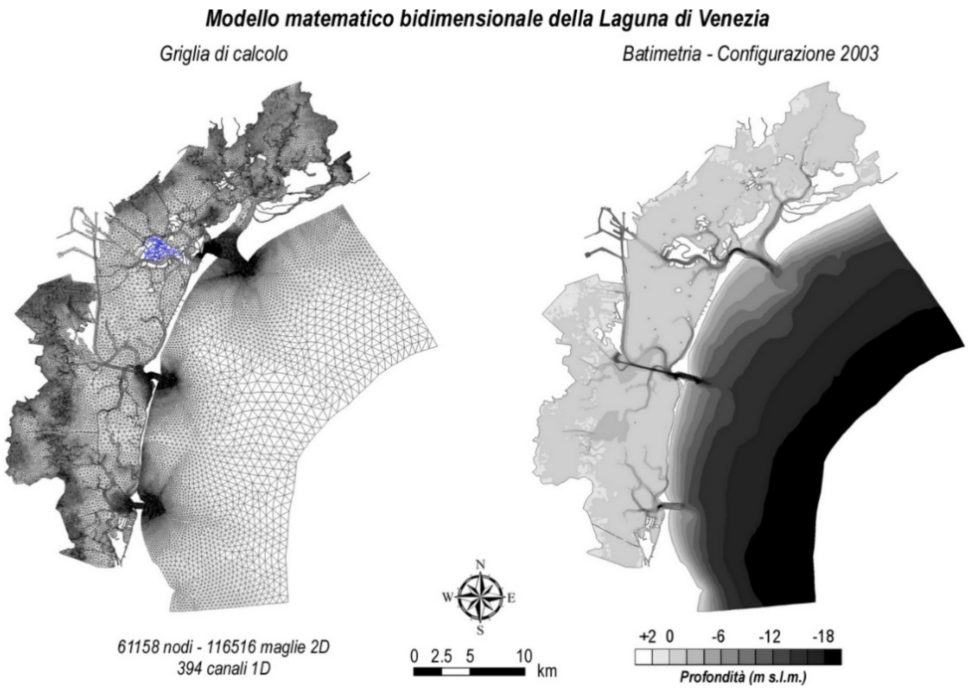

Fig. 7 –Calculation grid and bathymetric scheme of the bidimentional model of the Venice Lagoon.

Subsequently, additional simulations were carried out with both configurations (2003 and 2012) with the same tide boundary conditions at sea (an astronomical Spring tide lasting a few days).

Results obtained from the two scenarios was found to be in line with the results obtained in the previous analyses. In fact, the model indicates that the configuration change at the inlets due to the fixed structures of Mo.S.E. caused a greater attenuation of tidal amplitude in the lagoon and increased the phase delays. Data provided by the model in the entire computational domain has revealed that these changes are not evenly distributed in the lagoon, but are mainly concentrated in the central basin, an extension of the Malamocco inlet, and in the northern Lagoon, via the Treporti canal.

The model highlights how the variation in the geometrical configuration of the inlets, especially the narrowing of the cross-section, causes current velocity through the inlets to increase. This is especially noticeable at the Malamocco inlet (Fig. 8) which has the fastest current velocity of the three.

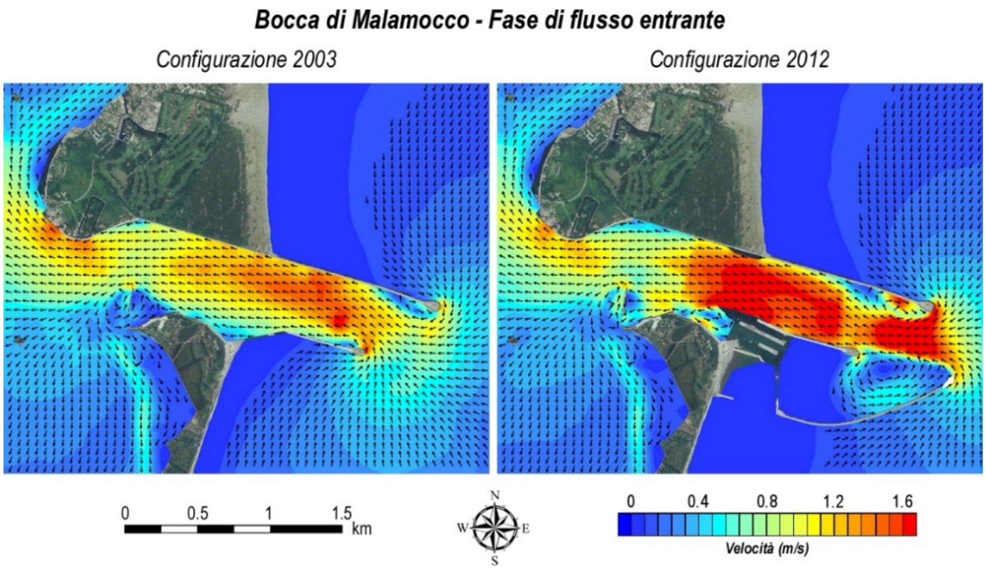

Fig. 8 – Comparison between velocity fields with the incoming tide calculated with the 2D model, considering two configurations: 2003 e 2012.

Localised increases in current velocity explain the observed changes in oscillations of the tide in the lagoon, because higher velocities correspond to greater dissipative action. These translate into greater hydraulic resistance that the tide must overcome at the inlet, followed by dampening of the tidal oscillation within the lagoon basin (Matticchio, 2004 Umgiesser, 2004).

The model was particularly useful for analysing displacements in the "watershed" areas which separate the influences of the sub-basins of the lagoon corresponding to each inlet. The "watershed" lines were identified by analysing the velocity fields in both phases of the tide, incoming and outgoing, and delineating the sub-basins pertaining to each mouth on the basis of the distribution of current lines. Not being a perfectly symmetrical process, the lines of the two tidal phases (ebb and flow) are not coincident and instead show the "watershed strips".

Model findings were especially useful for showing how the watersheds have moved since the changes to the inlet configurations (green lines in Fig. 9) with respect to the previously (black lines in Fig. 9). In particular the Malamocco basin has contracted, due to a shift of both the northern and southern limits towards the central part of the lagoon (Fig. 9).

Fig. 9 shows in particular that the strip separating the basins dominated by the Lido and Malamocco has moved towards the central lagoon. The amplitude of this strip is also noticeably reduced.

Vice versa the position of the strip separating the Chioggia and Malamocco basins does not seem to be significantly altered

This result further confirms how modifications at the inlets have caused the biggest changes at Malamocco. The model simulation shows that narrowing of the inlets has caused an expansion of the Lido sub-basin, at the expense of the area of Malamocco.

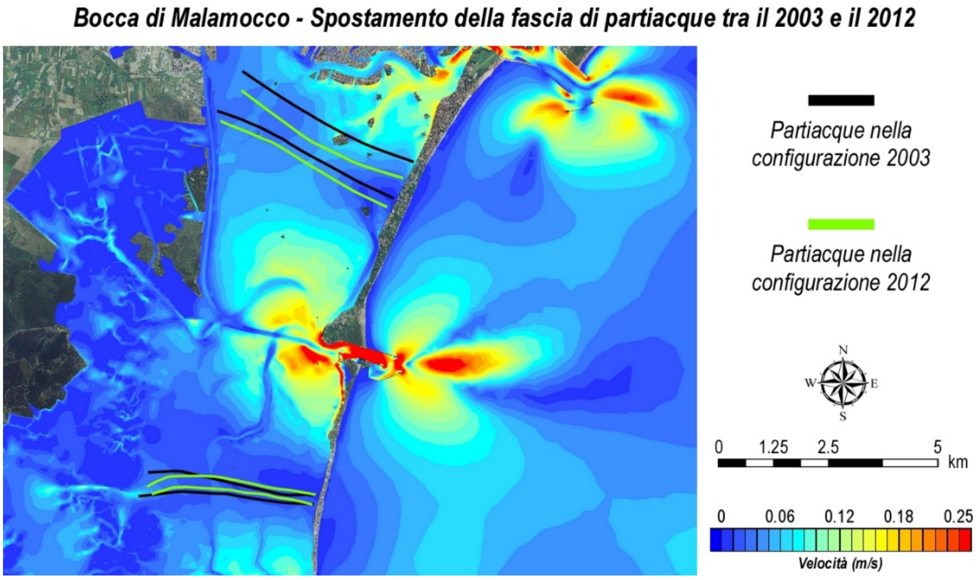

Fig. 9 – Displacement of the “watershed strips” marking the Malamocco sub-basin, obtained using the hydrodynamic model. The black lines show the “watershed strips” determined by the previous configuration, pre Mo.S.E. structural works (2003) and the green lines mark the “watershed strip” determined using the post-interventions configuration (2012).

The position of the watershed has a crucial role in hydrodynamics of the inner lagoon because it determines the position of the open waters where tidal currents are weaker and therefore more vulnerable in terms of issues connected with residence times and low exchange of water. Variation in amplitude of these strips, in turn, signal significant changes to the regime of localised currents and particularly hydrodynamic dispersion phenomena associated with secondary (or “residual”) currents that are superimposed on the periodic alternations of the tide.

The "watershed" shift can have considerable effects on hydrodynamics that also need to be carefully considered inside the lagoon including flows in the inner canals of Venice where the intensity and direction of these flows, at different stages of the tide, are determined by small gradients in water level. Even slight changes in both tidal phase and amplitude, but especially phase delays, can lead to significant changes in current velocity in the canals and, at times, even cause a change in current direction in certain canals at various stages of the tide.

This has been clearly highlighted by modelling simulations, which show that in some canals of the historic centre very significant variations in velocity and, in some cases, even current direction occurs.

Empirical evidence for these changes in canal flow in Venice is limited to reported observations of many Venetians, not least the gondoliers, locals and others interested in the most famous waterway in the world. Direct observations, using current meters, also confirm this as shown in Fig. 10, concerning the intersection of the Grand Canal and the Rio di Cannaregio. In contrast to what was reported in the past (Dorigo, 1966), more recent measurements reveal that with the incoming tide, waters flow into the Rio di Cannaregio from both directions of the Grand Canal – Rialto and from the Railway Station. Similarly, when the tide is going out, flow from the Rio di Cannaregio splits into two directions, towards Rialto and towards the station. As a result, the velocity of the current in the Cannaregio canal is much faster than currents in the Grand Canal, considering the much larger width of the latter.

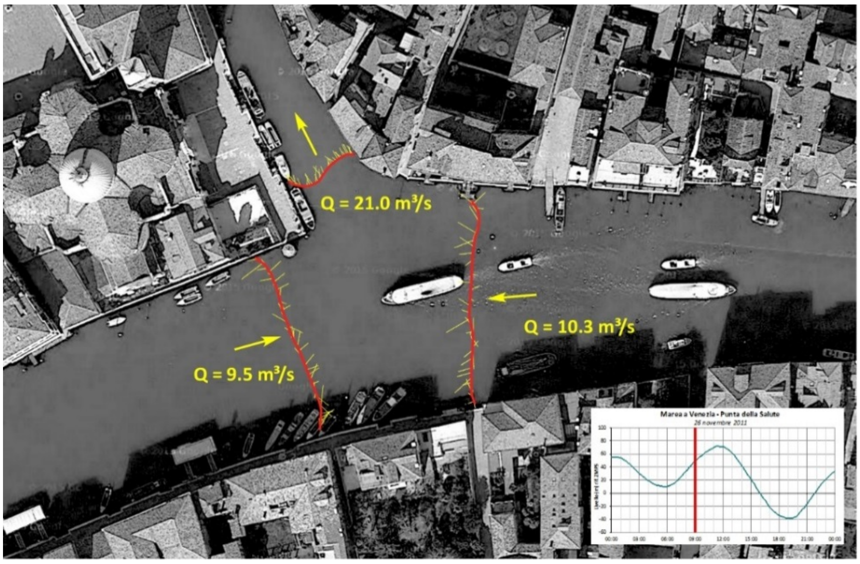

Fig. 10 – Current measurements at the intersection of the C. Grande – C. Cannaregio carried out on 26/11/2011 during the incoming tide (between 8.57am and 9.06am). In the three sections, measurements are not simultaneous therefore the continuity is not rigorously respected (data supplied by ing. P. Peretti).

6. Conclusions

The analysis of tide gauge records collected from various stations around the lagoon and beyond the inlets in the Adriatic sea over many years revealed changes beginning around years 2003-2004, in particular a reduction in amplitude of the tide, and an increase in phase delays.

Since these changes were found at all stations in the lagoon, but not at the stations at sea (“High Water” Platform and in the inlets themselves), the logical conclusion is that the cause of these changes in tidal regime is to be found inside the lagoon. The results of this study suggest that these changes correlate with geometric changes made at the three inlets as part of the structural interventions for the mobile floodgates system Mo.SE, which resulted in considerable narrowing of the inlet cross-sections.

According to the data, variations are not homogeneous throughout the lagoon basin but vary from zone to zone. The changes are greatest in the central and northern lagoon sub-basins, suggesting that the inlets that most affected are Malamocco and Lido-Treporti.

Numerical modeling confirmed this and identified some variations in the position of the areas of influence of each inlet sub-basin (so-called "watershed"). In particular, the

Lido inlet seems to have expanded its area of influence, and reduced the sub-basin dependent on Malamocco. This implies changes to the way the three inlets supply the lagoon, in terms of both tidal current paths, which show a strengthening of the currents in the vicinity of the Lido inlet compared to those in the central part of the lagoon, dependent on Malamocco inlet.

Although indirectly, these changes can probably explain the increase in current velocity observed in some of the inner canals of Venice, since the flows through the channels are essentially related to instantaneous water level differences between the Grand Canal and the open waters surrounding the city. This phenomenon, evident to anyone who navigates the canals of the city, risks getting overlooked, not only in terms of the impact on navigation, but also possible accelerated damage to old buildings in direct contact with water. In addition, changes in hydrodynamic regime linked to changes in the propagation of the tide could lead to non-negligible consequences for the main parameters of lagoon circulation, such as residence times and water quality, especially in the more remote parts on the periphery of the northern lagoon.

These indications, based on analyses of tide data, strongly indicate the need for further work to deepen and refine the study of lagoon currents. In particular, the necessity to examine using direct measurements at the inlets, the degree of the variations in the flows between the sea and lagoon as a result of the structural narrowing produced by the MoSE system.

In parallel, investigations of the currents in the inner canals of Venice are needed, via direct measurements and model simulations, to compare with measurments and studies predating the interventions at the inlets (Dorigo, 1966, Carrera, 1999, Coraci et al., 2007).

Acknowledgements

We are grateful toISPRA – Venice Lagoon Service and the Municipal Tide Office of Venice for providing the hydrography data used in this study.

The calculations were made possible by a contribution from We are here Venice (wahv), wearehereveniceorg, a non-profit association dedicated to the production and dissemination of critical information for decisions affecting the future of Venice.

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