DISCUSSIONS ON THE EXCEPTIONAL TIDE LEVEL IN THE VENICE LAGOON IN NOVEMBER 2002

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Abstract: This paper presents and discusses the observations of weather and marine parameters recorded in the Lagoon of Venice during storm surges events occurred in November 2002. These phenomena were analysed by the use of a finite element mathematical model (SHYFEM) developed by National Research Council to enable updated evaluations of the magnitude of set-up phenomena in the lagoon in relation to the particular instability due to local wind conditions.

INTRODUCTION

The Venice Lagoon is the most important in the entire Mediterranean basin for various environmental, socio-economic and historic and cultural factors. The Lagoon is 550 Km² in extension, is separated from the sea by sandy barrier islands and communicates with the sea through three inlets (Lido, Malamocco and Chioggia) through which the tidal wave enters in the lagoon.

The Lagoon is part of the north-eastern Adriatic coastal system, which also includes the inlets of the great north-eastern rivers of Italy. These coastal areas are depressed below sea level for more than 2300 Km² and exposed to risk of flooding by rivers and sea surges that strike the Northern Adriatic. This risk has increased dramatically in the past 100 years due to soil sinking in the entire area caused by natural and man-induced subsidence phenomena. On 4 November 1966 an extraordinary heavy sea storm overwhelmed coastal defences sweeping away the breakwaters at the three inlets of the lagoon. The sea storm surged into the lagoon forcing various passages along the sandy barriers and sailing upstream the mouths of Sile and Brenta rivers. A memorable high tide of 194 cm above m.s.l. was recorded in Venice. Widespread flooding occurred in the whole coastal area of the North-Western Adriatic sea caused by considerable runoff of the major rivers.

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In 2003 the *Magistrato alle Acque* (the Water Authority for safeguarding in the Lagoon of Venice) has started important works to prevent from flooding in the city of Venice and the others urban areas existing in the lagoon during exceptionally high tides. A system of 78 sluice gates will be located at the three inlets to stop the water flow from the sea during the most severe storm surge events. This will occur when forecasted tide level are above the threshold of 110 cm above local zero tidal level.
In the autumn of 2002 heavy storms struck the north – western Adriatic seashore. The water level in the lagoon was found to be different from place to place due to concurrent presence of strong and unstable local winds that blew on the lagoon surface with more or less intensity from the south-easterly (sirocco) or north- easterly (bora) quadrants. This paper presents and discusses the observations of weather and marine parameters recorded during such events through the 52 automatic and real time tide gauges stations (fig. 1). These phenomena were analysed more extensively by the use of a finite element mathematical model (SHYFEM) developed by National Research Council to enable updated evaluations of the magnitude of set-up phenomena in the lagoon in relation to the particular instability due to local wind conditions.

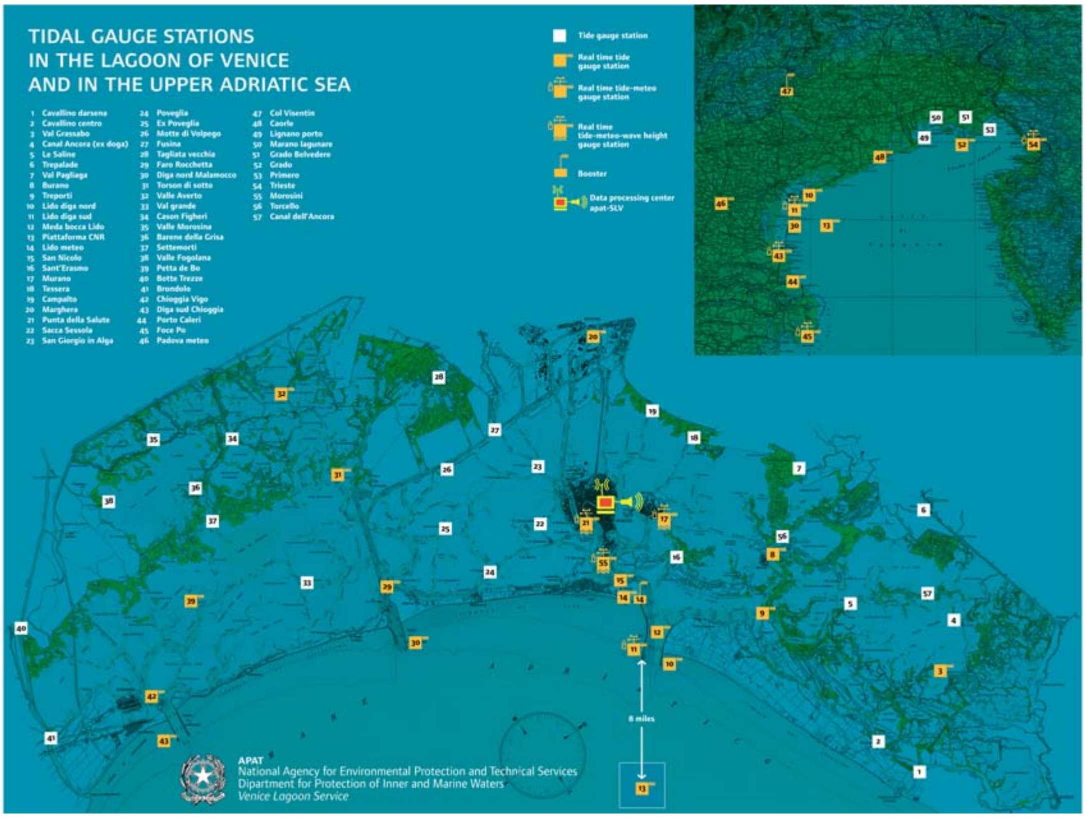

Fig. 1 – Tidal gauge stations in the lagoon of Venice.

DATA ANALYSIS

The latter half of November 2002 was characterised by the persistence of meteorological conditions that favoured the occurrence of exceptionally high tide levels along the Northern Adriatic coasts. Figure 2 shows the isobaric field at 12:00 p.m. UTC on 15th November 2002. The Mediterranean basin was dominated by the presence of a vast depression area centred on the Gulf of Biscaglia whose effects persisted for several weeks

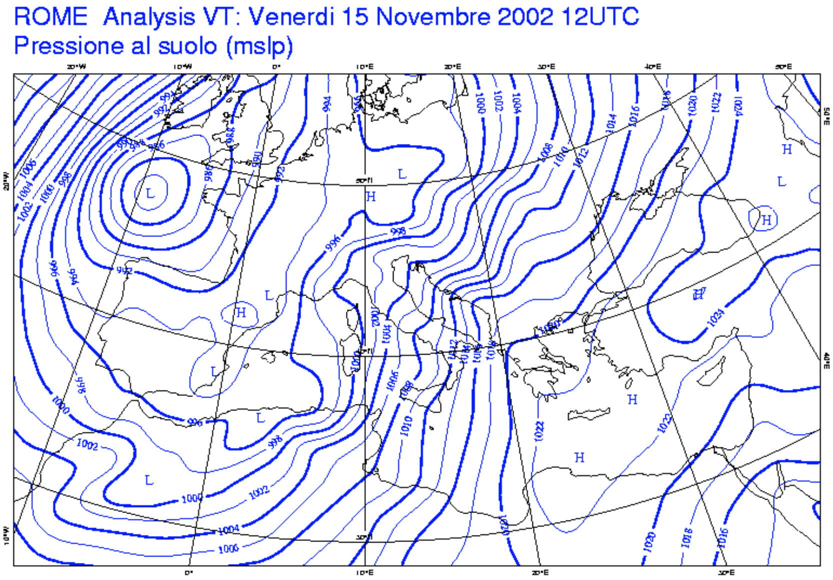

Fig. 2 – Mean sea level pressure on 15 November 2002 at 12.00 UTC

The situation in the Adriatic Basin was characterised by a marked degree of atmospheric pressure oriented from the south to the north with south-easterly winds gusting across the surface of the sea which caused large wave swells and increased sea level much higher than normal high tide in the northern part of the basin.

Fig. 3– North-Adriatic Sea. Recorded peak sea-level on 16 November 2002.

The maximum tide level reached on the morning of 16 November at the tide gauges located along the coast and at the inlets of the Venetian Lagoon exceeded the level 110 cm above the local tidal reference for many hours (fig.3). This value is traditionally adopted to distinguish those particular high tide events that are extensive enough to create a crisis conditions at the mouths of Northern Italy's major rivers as well as the whole lagoon system, which also includes the extensive surrounding territory below sea level, whose water control depend on the efficiency of al large number of water scooping plants.

During the evening of 16 November the tide level exceeded again the value of 110 cm. (132 cm at Caorle, 125/129 cm at the lagoon inlets, 125 cm at Porto Caleri). This limit was exceeded again in the early morning of 18 November and in the late morning of 22 November. In the former case the maximum peaks values taken along the coastline were between 125 and 130 cm. In the latter they were between 114 and 120 cm. It's worth remembering that the year 2002 is widely regarded as the most critical in more than a century of observation. There were 12 cases of exceptionally high tide levels in the Northern Adriatic, compared with the annual average of 5-6 cases normally concentrated in the fall and early winter.

The evolution of meteorological situation favoured a more complex circulation of local winds with special effects on the Venetian lagoon due to their variability between south-easterly (sirocco) and north-easterly (bora) directions.

Figure 4 shows the wind data measured at the tide-gauge stations located along the coastline (Grado, Lido and Chioggia inlets, Po Delta) and at the oceanographic platform of CNR located in open sea, 8 miles outside of the lagoon.

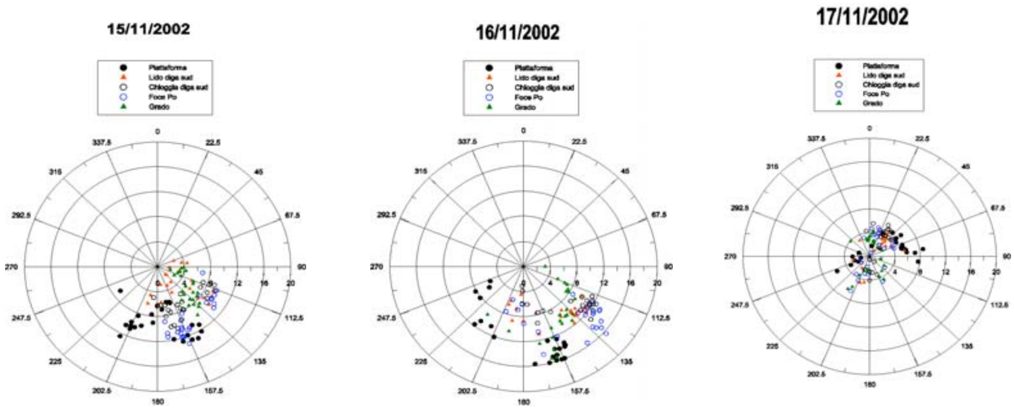

Fig. 4 – Polar diagrams of the wind data measured along the Northern Adriatic Coast and out of the Venetian lagoon on 15, 16 and 17 November 2002.

In general the wind data collected at the platform presents an average difference of 30° in a clockwise direction with respect to the measurements taken at the other meteorological stations. At same time the wind intensity at the platform is general stronger by 3 m/s with respect to the measurements along the coastline.

All data taken between 2:00 p.m. on 15 November and 2:00 p.m. on 16 November showed that south-easterly winds were prevailing (sirocco), setting up perpendicularly to the sandy barrier islands and piling up sea water at the inlets of Lido and Malamocco. The highest speed levels are recorded along the southern coastline of the lagoon (Po Estuary), while the lowest values are recorded at the Lido inlet. On 16 November, the wind speed on the platform exceeded 15 m/s at about 1:45 p.m. at the same time as the maximum rise of the tide. The intensification of the wind is found along the entire coast with 13 m/s at the inlets and 16 m/s at the Po Estuary. Between 4:00 p.m. on 16 November and 3:00 am on 17 November, the strength of the wind diminished and turned toward the south west quadrant, except for Grado station, located on the north-east coast of the lagoon. In this station peak value of wind-intensity was recorded at

5:15 p.m. (16 m/s) from south-easterly quadrants. Winds continued blowing with a moderate intensity along the coast, fluctuating from 3-4 m/s. A further peak of 8 m/s was recorded on the platform at 9:00 p.m.

Figure 5 shows the wind data collected throughout the day on the 18 and on the 19 November . A general shift in the direction from the north-easterly direction (bora) to a south-easterly direction (sirocco) was recorded between 9:00 am and 11:30 am on 18 November, starting from the northern tide gauge stations (Grado). Wind intensity increased to maximum values of 11 m/s at the lagoon inlets and 13 m/s at the south (Po Estuary) and the north (Grado). After 9:00 p.m. on 18th, there was a general overall attenuation of the intensity and a rotation toward the south-west, which was maintained throughout the entire day of 19 November.

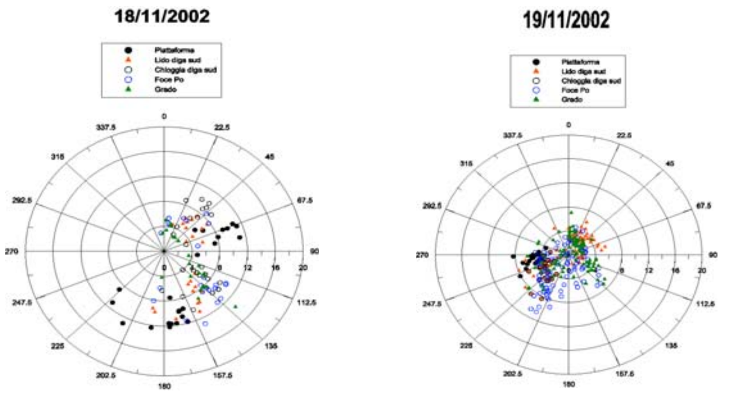

Fig. 5 – Polar diagrams of the wind data measured along the Northern Adriatic Coast and out of the Venetian lagoon on 18 e 19 November 2002.

THE TIDE IN THE LAGOON

The first diagram reported in figure 6 shows the progress of tidal levels recorded in Venice at the historic tide gauge station of *Punta della Sal*ute during the said period. The graph shows that the threshold of 110 cm was exceeded on 5 separate occasions and the maximum peak of 147 was recorded at 9:40 am on 16 November delayed by just over an hour of astronomic maximum (64 cm at 8:30 am).

The second diagram describes the progress of calculated surge by taking the difference between the recorded tide level and the astronomic tide level. The maximum surge of 105 cm was recorded at 2:30 p.m., five and half hours after the astronomic maximum. On 18 November, a new maximum tide level occurred (123 cm at 10:25). The maximum surge of 82 cm was recorded at 1:45 with a four and half after the astronomic maximum (70 cm at 9:10 am).

Finally, the surge recorded at *Punta della Salute* during the period from 15 to 23 November shows an irregularly fluctuating progression that is not always in agreement with the variations of meteorological parameters (atmospheric pressure, wind speed and wind direction).

This is partly due to the variations of slope of the lagoon surface due to local winds as well as to the free oscillations of the Adriatic Sea subsequent to the primary surge of 16 November; the main component of these oscillations is oriented in a south-east/north-west direction with a period of fluctuation of about 22 hours.

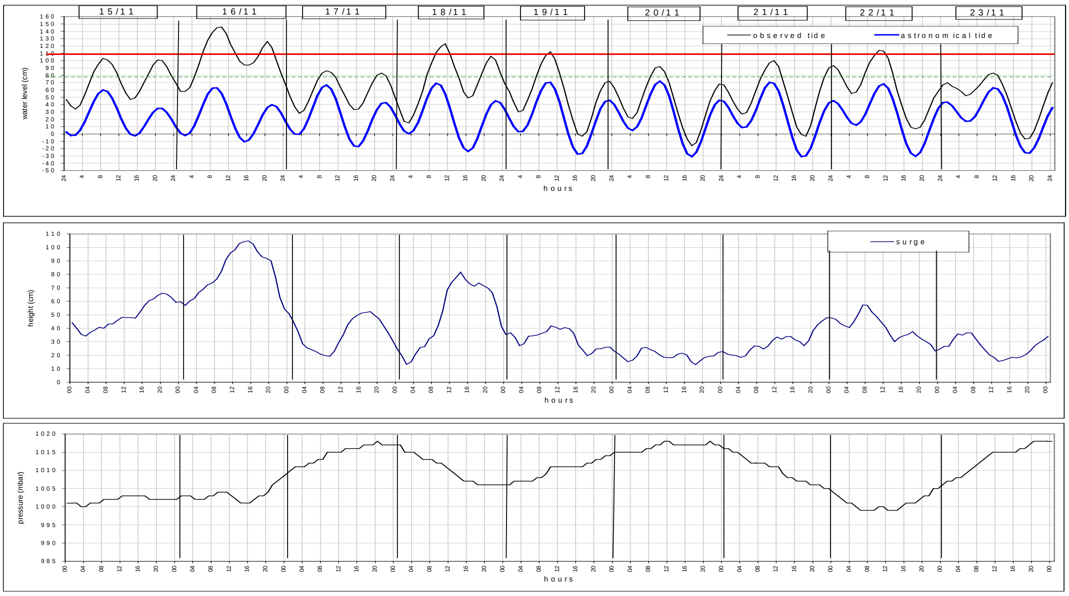

Fig. 6 – Tidal level, surge height and atmospheric pressure in Venice between 15-23 November 2002.

Water level was also investigated by means data collected at the 33 tide gauge stations located in the lagoon. Data analysis show a difference in level between the northern part and the southern part of approximately 35 cm in correspondence to the phase of greatest intensity of the south-easterly winds (sirocco) at 3:30 p.m. on 16 November. The situation is reversed after only two days due to the wind rotation which is found from the north –eastern quadrant (bora) at reduced intensity. In this case, the southern lagoon shows higher levels with differences between the north and south on the order of 45 cm. Furthermore, during the period of north-easterly wind, the internal tide level in the southern part of the lagoon is generally higher than the sea, generating an outward flow at the inlet of Chioggia. At the same time, in the northern part of the lagoon, the internal tide level is lower than the sea, causing an inward flow from the inlet of the Lido (Rusconi et al., 2000; Gacic et al., 2005).
When south-easterly winds blow, the situation reverses, generating outward flow at the inlets of the Lido and inward flow from the inlet of Chioggia (Melaku Canu et al., 2002).

MODEL APPLICATION

To better quantify the storm surge phenomenon inside the Venice lagoon a shallow water hydrodynamic model has been applied to simulate the storm event. The model has been developed for the Venice lagoon (Umgiesser et al., 1993, 2004) and has been successfully applied in various other occasions (Umgiesser, 1997, 2000, Zecchetto et al.,1997, Solidoro et al., 2004). It solves the shallow water equations on a finite element grid using a semi-implicit formulation especially suited for the complicated topography of the Venice lagoon.
The period modelled is from the 15th to the 23rd November 2002. Available wind and water levels at the inlets have been prescribed. Water levels have been compared with stations inside the lagoon. Agreement with measured values is generally very good, as

can also be seen from Tab 1. The *rms* error for the whole stations during the total period is 3.1 cm.

Table 1. Measured and simulated peak values at Punta della Salute tide gauge station between 15-23 November 2002

Event	Measured Peak Value		Simulated Peak Value	
	Hours	Height, cm	Hours	Height, cm
16 November	9.40	147	10.00	148
	20.00	126	19.50	126
18 November	10.25	123	10.30	120
22 November	10.30	114	10.20	117

Further investigations have shown the entity of the water level difference inside the lagoon. During the 16th of November, the model simulates a water level difference of about 25 cm, which underestimates the measured difference by about 10 cm. On the other hand, two days later a water level difference of 45 cm is well reproduced between the southern and the northern lagoon. In Fig. 7 the water level differences can be seen. During the first event the scirocco winds pile up the water in the north eastern corner of the lagoon. On the other side, during the bora event 2 days later water levels are minimum in the northern lagoon.

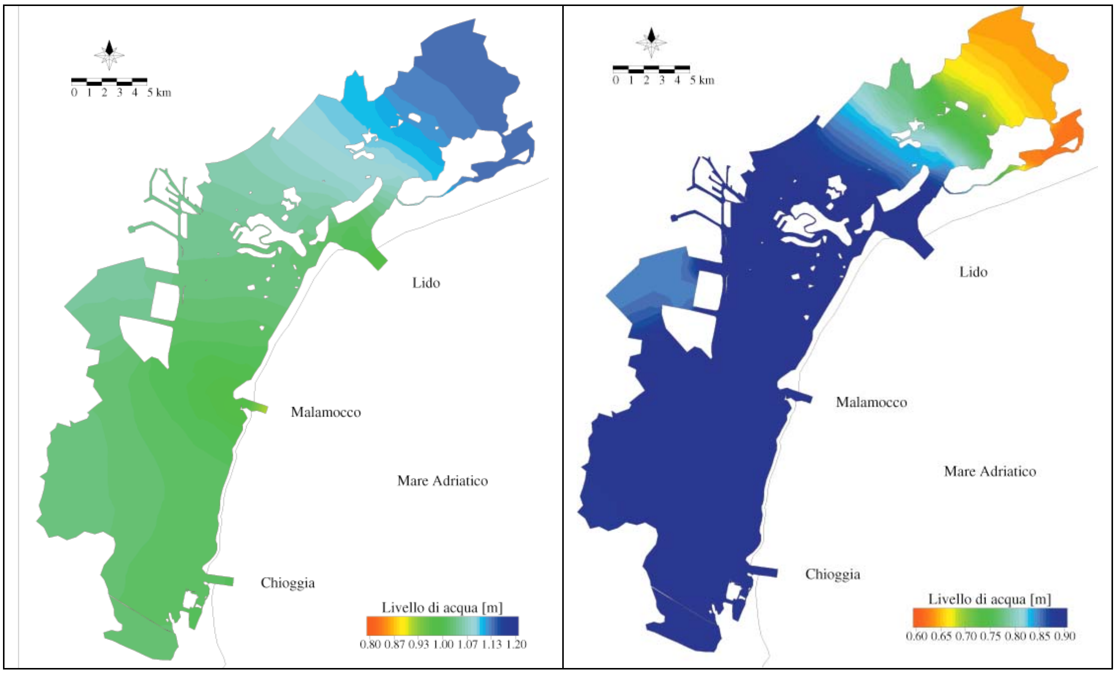

Fig. 7 – Water levels inside the Venice lagoon simulated with the SHYFEM model. Results are shown during 16 Nov. 13:10 (left) and 18 Nov. 8:10 (right). Clearly visible the set-up and set-down in the northern lagoon.

Discharges have been computed through the inlets, both in conditions with wind and without. This allows for a quantification of effect that the wind has on the exchanges between the lagoon and the Adriatic Sea.
In Fig. 8 results are shown for the southernmost inlet which is Chioggia. During days

15 and 16, where south and south-easterly winds were prevailing, discharges were higher due to the local wind action. This trend persists for the whole two days until the 17th, where winds change to bora (north-easterly winds). Now water is pushed southwards and is exiting the lagoon mostly through the Chioggia inlet. In the figure this phenomenon can be seen as an increase of the negative discharge through the inlet. During the strongest winds of scirocco an increase of nearly 1000 m^3/s can has been found through this inlet.

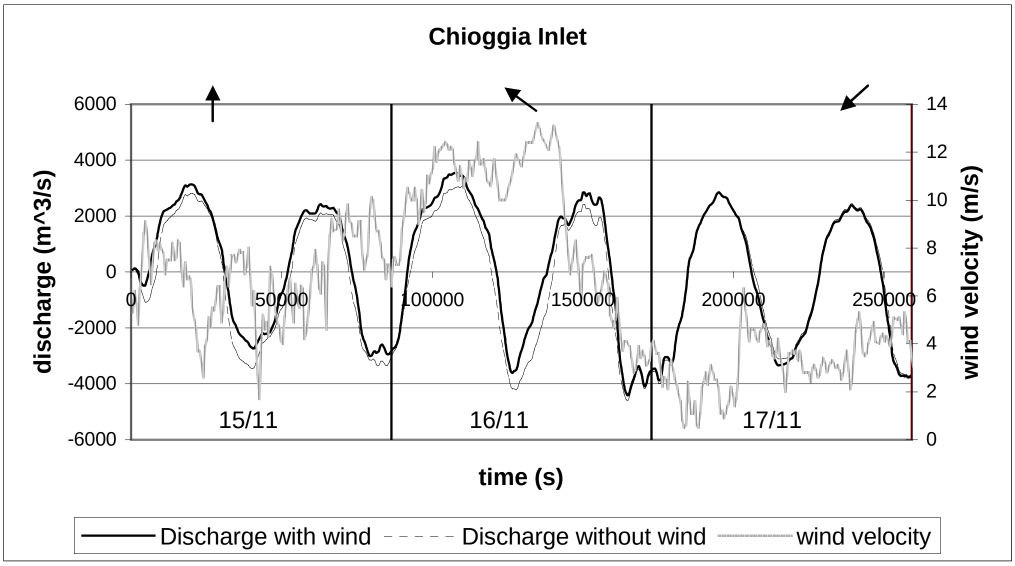

Fig. 8 – Discharges through the Chioggia inlet, both with and without the local wind action. During scirocco winds the ingoing discharge is sensibly higher than without wind.

Finally a simulation has been carried out that tries to mimic a possible closure of the mobile barriers that are planned for the high water defense in the Venice lagoon. For the closing procedures the guidelines in Eprim et al. (2003) have been followed. The high water events are classified in two big classes, where class 2 is made of events that have a return time of more than 10 years. Class 1 is further divided using rain and wind data. After the classification has taken place the level at which the barriers are to be closed. The safeguarding level has been set to 110 cm, which means that the water level should never exceed 110 cm at the Punta Salute tide gauge, close to the city center. For the storm under investigation this meant that the gates had to be closed once the water level reached 80 cm at Punta Salute.

In Fig. 9 the water level trend can bee seen. Two situations have been simulated, one with the real measured wind and one without the local action of the wind. For this purpose the wind is switched off once the mobile gates are closed. In the case the wind continues blowing the water levels stabilizes at the level of closure which is 70 cm.

This level is about 10 cm lower than the one in the central lagoon, since the closure of the gates is started once Punta Salute reaches a level of 80 cm. However, if the wind action is switched off, then the water inside the lagoon is redistributed due to the existing pressure gradient. Therefore, the water that was accumulated in the northern part of the lagoon flows southward and fills the southern basin. This can be nicely seen in figure 9, where the full line shows how the water level increases until it reaches a level of about 80 cm, some 7 cm higher than in the former case.

During the period of bora, Chioggia reaches much higher water levels than the rest of the lagoon (not shown). It is therefore important to guarantee a closing level that will also safeguard the city of Chioggia. As shown before, water level differences in the lagoon of up to 45 cm can be reached, and therefore a choice of when to close the barriers is not always simple.

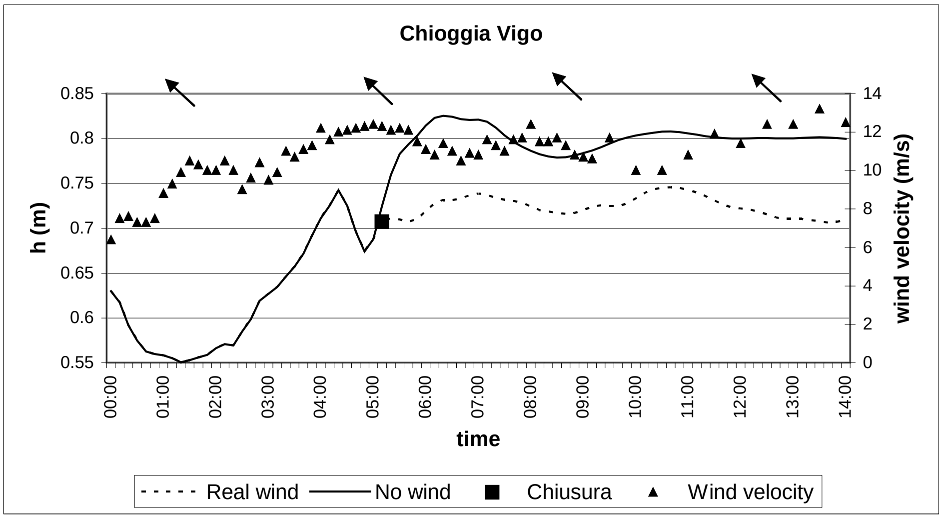

Fig. 9 – Water levels in Chioggia (southern lagoon) during the simulation of the closures of the mobile barriers. Clearly visible are the water level difference between the simulation with and without wind. In the first case the water levels in the southern lagoon are sensibly lower.

CONCLUSIONS

This study of the exceptional high water event in November 2002 with sirocco and bora winds has permitted an estimate of the set-up occuring inside the lagoon of Venice. With a sirocco of 15 m/s an increase of water level of 15 cm could be found in the northern lagoon, about 5 cm for the city of Venice and a decrease of 5 cm at the city of Chioggia, in the southern lagoon.

During the bora event of 10 m/s the north experiences a set-down of 16 cm, whereas Chioggia shows a set-up of 5 cm. During stronger bora events (20-25 m/s) the set-up in the southern lagoon is of the order of 20 cm, which induces a strong asymmetrical behaviour for the exchanges through the inlets.

The numerical simulations that have been carried out to test the closing strategies of the planned mobile barriers have evidenced that, in the case the wind stops blowing during sirocco, the southern lagoon experiences a water level increase of around 10 cm. This increase does not yet take into account other contributions as the river discharge, the rain and the water leaking between the single barrier elements.

What is needed is therefore a better forecast capability of meteorological conditions and limited area models that should be able to describe the small scale dynamics of the wind pattern over a relative small area such as the Venice lagoon.

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