Hydrodynamic modeling in the channel network of Venice

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Summary. — A combined framework of hydrodynamic models is presented that describes the water dynamics in the channel network of the city of Venice. The application of these hydrodynamic models is part of a larger project carried out by UNESCO that has the aim of describing the water quality of the channels in Venice. An existing 2-dimensional finite element model simulates the hydrodynamic features in the Venice Lagoon. The simulated data is then used as the boundary condition for the 1-dimensional hydrodynamic model of the inner channels of Venice. Inside the channel system the water elevation and the current velocities are computed. The simulated variables are calibrated and compared with data from field measurements that UNESCO has carried out during the years 1990-92 and during 1998. It was possible to use a constant friction parameter for all the channels in the network. Simulated water elevation shows an excellent agreement with the measured data, and also current velocities are generally reproduced quite faithfully. Some low-energy channels show major errors in the reproduction of the velocity speed. It is believed that changing bathymetry (silting-up of the channels) could be a cause of this phenomenon. The hydrodynamic data will eventually be used in the second part of the project where the water quality of the channel network will be investigated. For this purpose the hydrodynamic parameters simulated will be used by the water quality model as a boundary and initial condition in order to simulate the biological and chemical variables and to describe the ecological dynamics.

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1. – Introduction

The uniqueness of Venice and its peculiar appearance are certainly due to its relationship with water. Its complicated channel network is as important for the life of the city as the streets, being even today the principal way of communication for people, goods and public services: the major channels, the Grand Canal and the Canal of Giudecca, allow the transit of public boats and every kind of boat, but also the inner

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channels, smaller and shallower, can be traveled by "gondole" and small boats for private transport.

The pollution and the silting-up are two pressing problems regarding the channels: actually in Venice the channels are collectors of pollutants, the most important source of which are the sewage waters. The load of particulate matter coming from human waste emphasizes the natural tendency of the channels to accumulate sediments and to decrease their depth, with remarkable damage to navigation.

To start solving these problems the Municipality of Venice has scheduled and started a series of dredging works in the channels, after a long period where no dredging had been done between the 1960s and 1994. Moreover, some research projects have started, that deal with the circulation and the water quality in the channel network. One of them is the project "Inner channels of Venice", coordinated by UNESCO's UVO-ROSTE Office in Venice and financed by the Italian Ministry for Scientific Research. The main research subjects in the project include the quality of water and sediments, the health of the inner channels and water quality modeling. The first two topics are performed through field measurements and laboratory analysis. The authors are directly involved in the modeling activity, that constitute the topic of this article.

The various research projects, showing a growing interest towards the ecological problems of the channels, stress the necessity of a better understanding of the hydrodynamic behavior of the channel network.

In sect. **2** of this paper a general description of the channel network of Venice is given: some old studies about the circulation in the inner channels are reviewed together with a more recent and more complete investigation on the hydrodynamics of the channel system. Two datasets are described, that collect useful data for the calibration of hydrodynamic models.

The modeling of the network channel of Venice is discussed in sect. **3**. A previous model of the inner channels is mentioned and the new coupled model of the complex system "Venice Lagoon-channels of Venice", set up by the authors, is described in details. This system is made out of a 2-dimensional model of the Venice Lagoon and a 1-dimensional model of the channel network.

The results are shown and commented in sect. **4**. The circulation in the inner channels of Venice has been reproduced through a set of simulations. A sensitivity analysis has been carried out to understand the influence of neap and spring tide, and the effect of bora and sirocco winds on the water levels and current velocities in the network channel. The coupled model has been calibrated with the available data described in sect. **2**. Finally a preliminary calibration of salinity has been carried out.

In the last section some concluding remarks and a future outlook are presented.

2. – The channel network of Venice

The island of Venice is situated in the middle of the Venice Lagoon. The lagoon communicates with the Northern Adriatic Sea through three inlets (Lido, Malamocco and Chioggia), as can be seen in fig. 1. It receives some fresh water input mainly by eight rivers, flowing in from the main land at the boundary of the lagoon.

The city of Venice is constituted by over a hundred small islands, delimited by almost 160 channels that communicate with the lagoon. The backbone of this

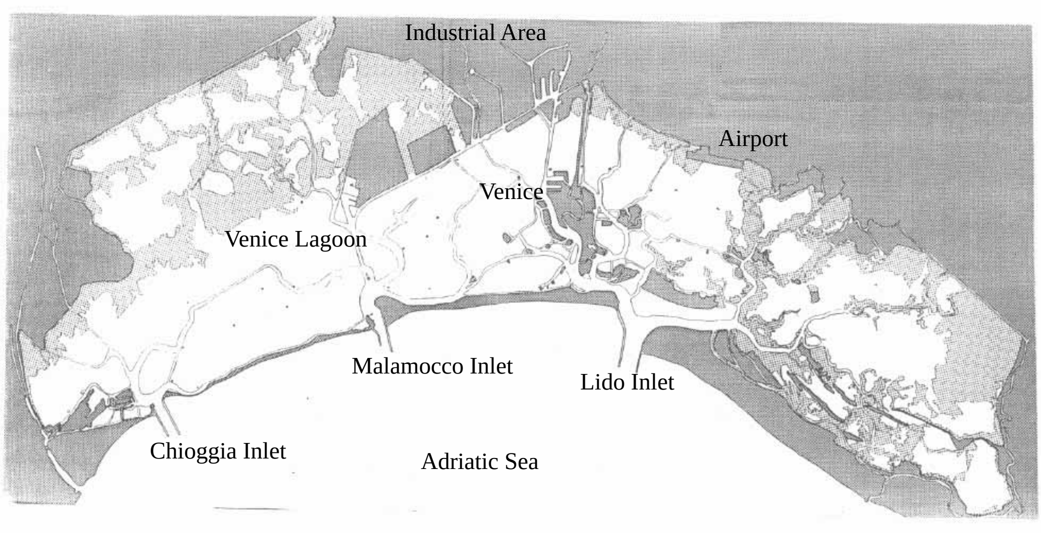


Fig. 1. – Map of the Venice Lagoon.

complicated network of channels is the Grand Canal, the main channel that crosses the city of Venice from North to South shaping out a big "S". From there the other channels spread out in all directions until reaching the lagoon, which is the limit of the city of Venice.

2˙1. *Phenomenology.* – In the current century, the whole circulation in the inner channel of Venice has rarely been investigated: among the few studies, mention has to be made of the one by Paluello [1], who produced a map of the current direction in many channels in the case of entering tide, and the one by Dorigo [2] that provided a quantitative investigation of the velocity in 40 channels.

Both of them show that the circulation in the inner channels of Venice is mainly driven by the tidal force: the tidal wave propagates from the Adriatic Sea through the three inlets into the Venice Lagoon and reaches the boundary of the city. Because of the geographical position of the city (see fig. 1) the tidal signal arrives first along the meridional limit of the city, *i.e.*, at Saint Mark's Square, and later at the northern part. The time lag of the tidal wave along the various points of the boundary (around Venice), in which the inner channels communicate with the lagoon, creates a level gradient that forces the circulation in the channels.

The northern Adriatic Sea is subject to two main wind systems: *bora*, from the North-East, and *sirocco*, from the South-East, both of which can reach high speeds (up to 20 m/s). In case of such strong winds, Paluello assessed that the meteorological conditions are also important in determining the flow direction.

These two studies, with some others, have been reviewed by Carrera [3], who was also responsible for a series of field measurements carried out during the period 1990-92. Unlike the old studies, restricted in time and space and limited to the case of spring tide, in which the exchanges with the Adriatic Sea are maximum, this study covers 55% of the inner channels of Venice and considers both spring tides and neap tides for each channel.

In accordance with the older studies, Carrera observed that, in the case of spring tide, during the influx phase, in which the water coming from the Adriatic Sea enters the lagoon, the general direction of circulation is from East toward West and from South to North. During the ebb phase the water flows, in general, in the opposite direction. There are some exceptions to this behavior, especially in the eastern zone of the city (Sestiere di Castello). Carrera characterized the hydrodynamic vivacity of the inner channels subdividing them on the basis of their maximum velocity, in *lively* ($20 < v < 100$ cm/s), *medium* ($10 < v < 20$ cm/s), *slow* ($1 < v < 10$ cm/s) and *stagnant* ($v < 1$ cm/s), separately for the entering and the leaving tidal phases. The study highlighted a percentage of stagnant channel of 12% with entering tide and of 9% with leaving tide.

2·2. *Available data.* – For the purpose of calibrating a hydrodynamic model of the inner channel of Venice, two types of data are available:

– the data collected by Carrera during 1990-92 [4, 3], mentioned in the previous paragraph and indicated here as the *UNESCO database*: it contains measurements of velocity and sea surface elevation in 68 channels out of 165. These data regard the lunar phases of spring tide and neap tide; they result from repeated measurements realized in five instants during each field measurements: two measurements corresponding to the maximum of elevation, one measurement at the minimum and two for the maximum values of velocity, that occur half-way between the extrema of elevation;

– a new set of data collected during the year 1998, in the framework of the UNESCO project “Inner channel of Venice”: the measurement campaigns regard the *Sestiere di Castello* in the east zone of the city. Five stations have been monitored: the first, external to the channel network, is considered representative of the lagoon environment; the others are situated in four inner channels. During 1998 nine field measurements have been realized, five with spring tide and four with neap tide; all field measurements had the duration of one tidal cycle, except for one that was extended to two tidal cycles, to cover one complete day.

The singularity of the 1998 data set consists in the fact that the hydrodynamic measurements are simultaneous to a series of measurements of ecological parameters (temperature, salinity, pH, dissolved oxygen, nitrogen and phosphorus compounds and others) and biological indicators (virological parameters and pathogenic bacteria). Actually the project “Inner channel of Venice” during 1998 focuses on the sanitary conditions of the channels of Venice and aims at the realization of a hydrodynamic and water quality model for the channel network.

3. – Hydrodynamic modeling

The modeling of the hydrodynamic behavior in the inner channels of Venice is strictly connected to the geometrical shape of the network: because of the small width and depth of the channels, in comparison with their length (length/depth $\simeq 10$), the motion of water can be considered 1-dimensional to a good approximation. On the other hand, the circulation in the inner channels depends strongly on the motion of the surrounding lagoon that presents a different geometry: with its low average depth ($\simeq$ 1 m) and the alternation of large shallow zones with deep, narrow channels, the Venice

Lagoon can be accurately described only by a 2-dimensional model. Moreover, the circulation of the whole system Venice Lagoon-Inner channels of Venice strongly feels the influence of the Adriatic Sea, that therefore has to be modeled adequately.

In this section two different models for the channel network will be described: the first has been realized by De Marchi in the period 1993-96 [5, 6], the second is the topic of this article and has been developed by the authors during 1998.

3·1. *Link-node model of the channel network.* – During his Master's Thesis, De Marchi [5] implemented in the channel network of Venice the 1-dimensional link-node model realized by Orlob [7]. In this model the total water volume is discretized by a network of irregular polygons (nodes), characterized by depth, slope of sides, surface area and volume. The nodes are connected to each other through channels (links), representing the water exchange between nodes; the links are defined by length, width, hydraulic radius, friction and slope of sides.

De Marchi embedded the model for the inner channels in a simplified model for the surrounding lagoon (see fig. 2). The tide was simulated with an oscillating sea surface elevation imposed as forcing in only one grid point, representing the exchanges with the Adriatic Sea. The effect of wind was not included in the model.

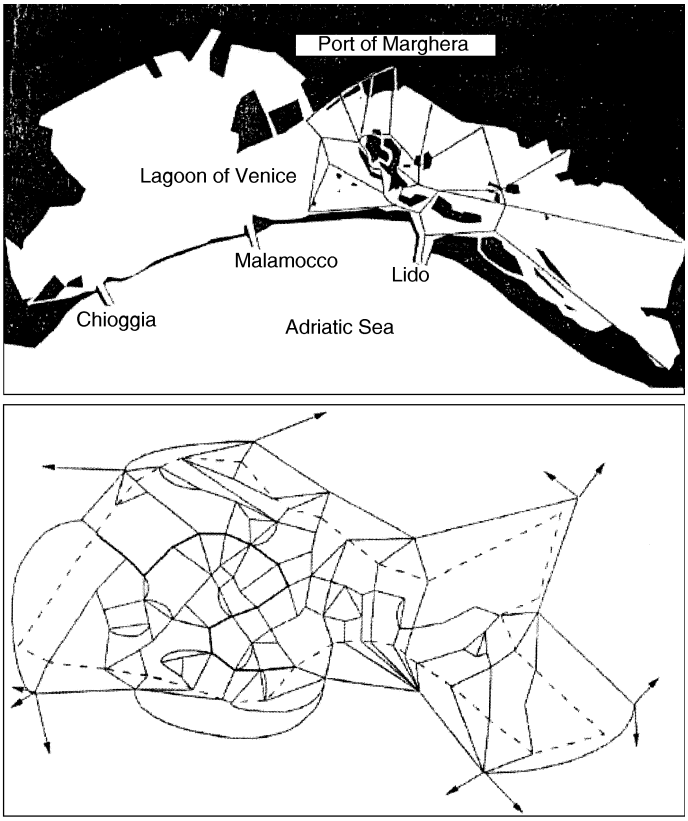


Fig. 2. – Grid of the link-node model realized by De Marchi: the simplified discretization of the Venice Lagoon through a network of channels (top) and the grid of the inner channels of Venice (bottom). (Adapted from [6].)

Once calibrated with the data of the UNESCO database (first set of data described above), the model of De Marchi, even while reproducing the general circulation in the channel network quite faithfully, however showed some limits:

- the poor representation of the Venice Lagoon, that plays a crucial role in determining the features of the channel circulation;
- the possibility to include only one point of tidal forcing;
- the missing inclusion of the wind, that makes the model unsuitable for the simulation of extreme events, such as storm surge or high-water situations, important for the city;
- the restrictions on the duration of the simulations: the model can simulate only one tidal cycle. This results particularly inadequate in the case of a neap tide, that lasts more than 12 hours.

3˙2. *Coupled model Venice Lagoon-Inner channels of Venice.* – To cope with the deficiency of the above-mentioned model, a new framework of models has been set up. Because of the different dynamical properties of the lagoon and the channel network of the city of Venice, two different type of models have been used for its description. For the lagoon an existing two-dimensional finite-element shallow-water model has been used, whereas for the channel network the 1-dimensional link-node model DYNHYD has been adopted.

3˙2.1. The SHYFEM model of the Venice Lagoon. The hydrodynamic behavior of the Venice Lagoon has been simulated by the 2-dimensional finite-element model SHYFEM, developed at ISDGM-CNR in Venice [8, 9]. The advantage of such a model consists in the possibility to vary the dimension and shape of the elements to adequately represent complicated bathymetry regions, as the Venice Lagoon, without need of a large number of nodes. The SHYFEM model grid (see fig. 3) is made up of 4237 nodes and 7666 triangular elements: the grid spacing varies from 40 m in the channels, to about 1 km for the zones with nearly constant depth.

The model uses a semi-implicit time discretization to accomplish the time integration. The finite-element method in space uses staggered finite elements to avoid numerical damping. Details are given in [8].

The equations are the well-known vertically integrated shallow-water equations in their formulation with levels and transports:

$$\frac{\partial U}{\partial t} + gH\frac{\partial \zeta}{\partial x} + RU + X = 0\,, \tag{1}$$

$$\frac{\partial V}{\partial t} + gH\frac{\partial \zeta}{\partial y} + RV + Y = 0\,, \tag{2}$$

$$\frac{\partial \zeta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0\,, \tag{3}$$

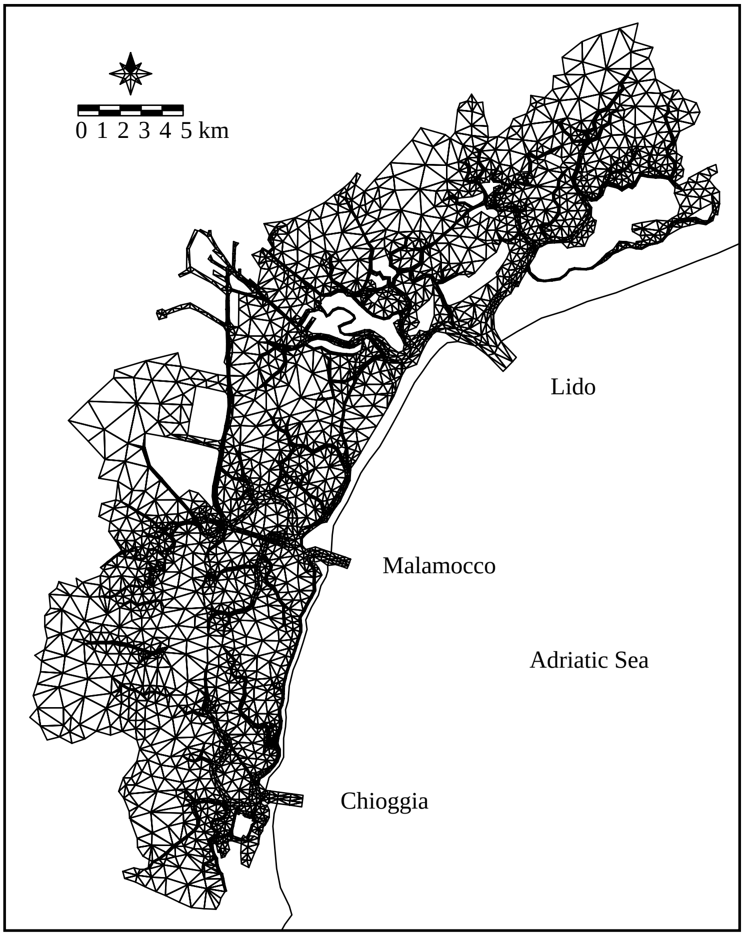


Fig. 3. – Finite-element grid of the Venice Lagoon.

where ζ is the water level, u, v the velocities in x and y directions, U, V the vertical integrated velocities (total or barotropic transports):

$$U = \int_{-h}^{\zeta} u \, \mathrm{d}z \,, \qquad V = \int_{-h}^{\zeta} v \, \mathrm{d}z \,,$$

g the gravitational acceleration, $H = h + \zeta$ the total water depth, h the undisturbed water depth, t the time and R the friction coefficient. The terms X, Y contain all other terms like the wind stress or the nonlinear terms that need not be treated implicitly in the time discretization.

At open boundaries the water levels are prescribed. At closed boundaries the normal velocity component is set to zero whereas the tangential velocity is a free parameter. This corresponds to a full slip condition.

The SHYFEM model has already been calibrated using the level data measured by fourteen tide gauges located at the inlets and inside the lagoon. The parameter to be varied is the bottom friction (Chezy coefficient). The calibrated model reproduces the tidal oscillations faithfully in most parts of the lagoon.

3.2.2. The DYNHYD model of the channel network of Venice. The circulation in the channel network of Venice has been reproduced by the 1-dimensional link-node model DYNHYD [10], realized at the US EPA office in Athens, Georgia. DYNHYD is the hydrodynamic module of the water quality model WASP, that is constituted by a set of compatible and interfaced sub-models. The hydrodynamic part solves the 1-dimensional equations that describe the water movement in a shallow basin, where the horizontal scale of motion is much larger than the vertical scale and where it ensures the conservation of momentum and mass.

The momentum equation is

$$\frac{\partial u}{\partial t} = -u\frac{\partial u}{\partial x} + a_{\mathrm{g},\lambda} + a_{\mathrm{f}} + a_{\mathrm{w},\lambda}, \tag{4}$$

where u is the water velocity along the channel axis, x is the distance along the channel axis, $a_{\mathrm{g},\lambda}$, $a_{\mathrm{w},\lambda}$ are the gravitational acceleration and the wind acceleration along the channel axis λ, a_{f} is the frictional acceleration:

$$a_{\mathrm{g},\lambda} = -g\sin\alpha \simeq -g\frac{\partial\zeta}{\partial x}, \tag{5}$$

$$a_{\mathrm{f}} = -\frac{gn^2}{r^{4/3}}|u|u, \tag{6}$$

$$a_{\mathrm{w},\lambda} = \frac{C_{\mathrm{d}}}{r}\frac{\varrho_{\mathrm{a}}}{\varrho_{\mathrm{w}}}W^2\cos\psi, \tag{7}$$

where $g = 9.81\ \mathrm{m/s^2}$ is the gravitational acceleration, α is the surface slope, ζ is the surface elevation, r is the hydraulic radius of the channel, n is the Manning coefficient, C_{d} is the drag coefficient, ϱ_{a} and ϱ_{w} are the density of air and water, W is the wind velocity at 10 m height, relative to the water surface and ψ the angle between the wind direction and the channel axis.

The continuity equation is

$$\frac{\partial A}{\partial t} = -\frac{\partial Q}{\partial x}, \tag{8}$$

where A is the cross-sectional area of the channel, Q is the flow in $\mathrm{m^3/s}$.

At each time step, the model solves the momentum equation in the links, calculating the water velocity, and the continuity equation in the nodes, computing the sea surface elevation.

The boundary conditions at the open boundaries representing the sea are imposed giving the sea surface elevation. The effect of the wind is taken into account, using the wind speed and direction at 10 meters, variable in time and constant in space.

The computed variables of the hydrodynamic model DYNHYD, velocities and water levels, allow the computation of mass fluxes, volumes and pollutant concentrations during successive water quality simulations, through the modules EUTRO and TOXI of WASP.

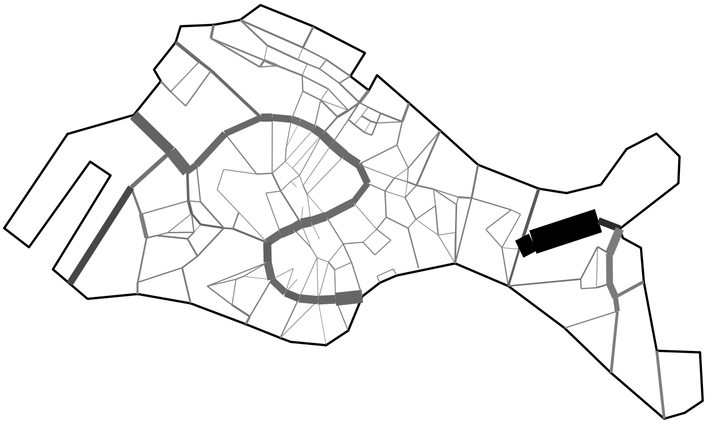


Fig. 4. – Grid of the 1-dimensional model of the channel network of Venice: the length and width of the channels are in scale; the color intensity (grey values) is proportional to the depth.

The model has been implemented in the channel network of Venice, using the values of length, width and depth of the channels previously obtained by De Marchi, along with the geometrical information that join each node to the entering channels and each channel to its extreme nodes. The grid of the model is represented in fig. 4; it is constituted by 174 nodes and 251 links: each link represents a real channel or a

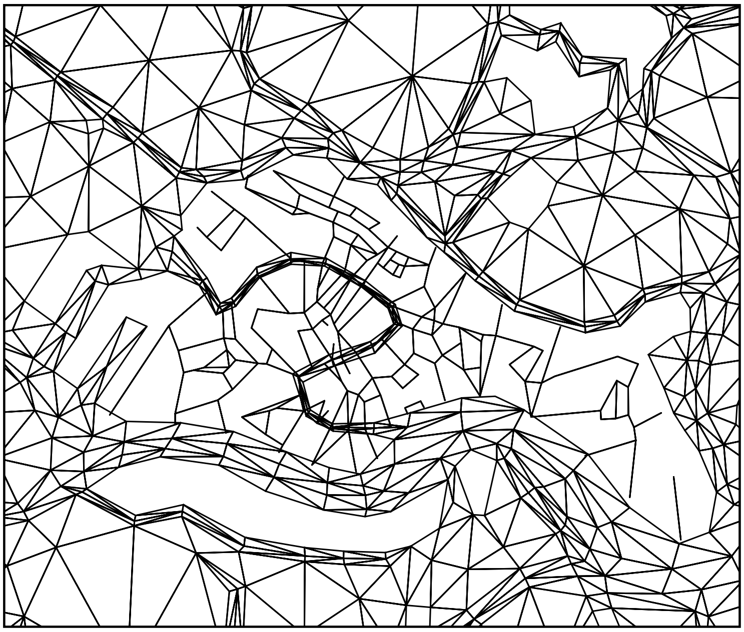


Fig. 5. – Coupling between the 2-dimensional model of the Venice Lagoon and the 1-dimensional model of the inner channels of Venice. It can be seen how the channel network fits nicely into the existing finite-element model grid of the Venice Lagoon.

TABLE I. – *Summary of simulations carried out.*

	Period	Description	Available data
Sensitivity analysis	generic	spring tide, no wind	none
	generic	spring tide, bora	none
	generic	spring tide, sirocco	none
	generic	neap tide, no wind	none
Hydrodynamic calibration, verification	27-28 April 1991	spring tide and wind	data 1990-92, Cannaregio
	2-4 February 1992	spring tide and wind	data 1990-92 , S. Polo
	28-30 June 1992	spring tide and wind	data 1990-92, Castello
	11-12 March 1998	spring tide and wind	data 1998, field work 1 s
	10-12 May 1998	spring tide and wind	data 1998, field work 2 s
	4-5 March 1998	neap tide and wind	data 1998, field work 1 q
	1-2 June 1998	neap tide and wind	data 1998, field work 3 q
Salinity calibration	11-12 March 1998	spring tide and wind	data 1998, field work 1 s

segment of channel and each node represents an intersection among channels. A channel is therefore made out of one or more segments.

The equations and the manner of representation of the channel network are in short very similar to those of Orlob's model used by De Marchi; the greater flexibility, the possibility to realize simulation with arbitrary duration and to have more points of tidal input, the public availability of DYNHYD and its integrated interface with the water quality model, made it the model of choice for this application.

3·2.3. Coupling between the models. The two models are coupled in the sense that the 2-dimensional model of the Venice Lagoon provides the boundary conditions for the 1-dimensional model of the inner channels of Venice. The coupling occurs on the boundary of the city, in the points where the inner channels flow into the lagoon: in such points, that constitute the open boundary of the inner channels model, the values of sea surface elevation calculated by the model of the lagoon are imposed for the whole duration of the simulation.

In this way the inner channels model is provided with realistic boundary conditions from the finite-element model of the lagoon. These water levels already include the physics of the tidal propagation in the lagoon such as phase shift, tidal amplification and also the effects of the wind stress.

On the other hand, the 2-dimensional model considers the city of Venice as an island with only one channel, the Grand Canal, crossing it. Therefore there is no information from the water levels in the inner channels flowing back to the 2-dimensional model. The coupling is only *one way*.

This kind of coupling surely represents a simplification of the real situation where the two systems mutually influence each other and interact across their system boundary. In the simulated system, instead, there is no feedback from the channels to the lagoon model. However, the simplification seems to be justified since the water area covered by the channel system is negligible with respect to the area covered by the whole lagoon.

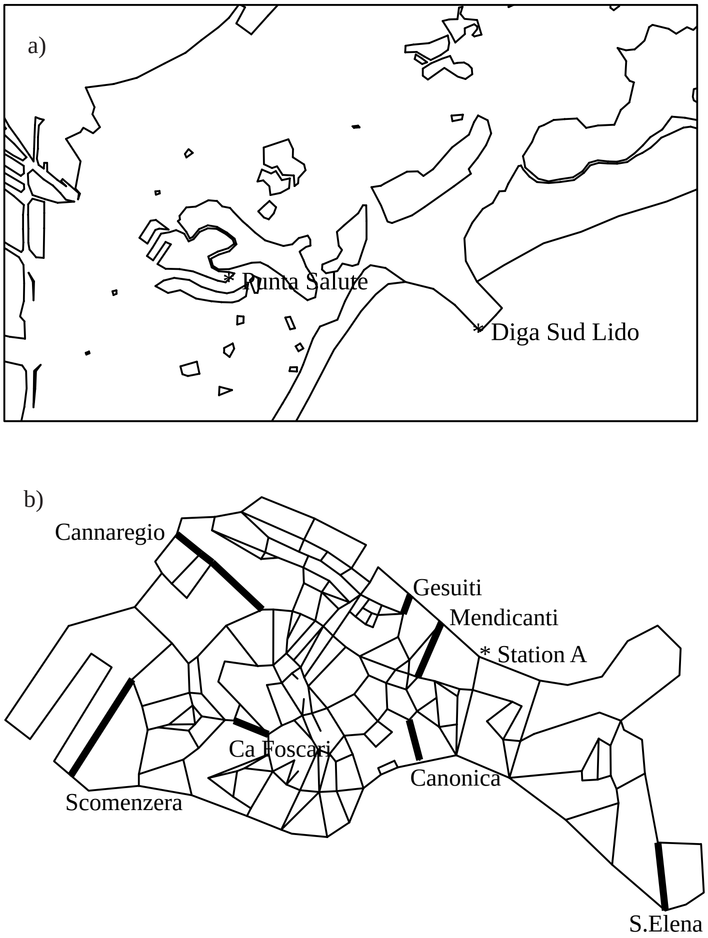


Fig. 6. – Location of the various channels and sites of the field measurements in the Venice Lagoon (top) and in the Venice island (bottom).

The coupling between the grids of the two models is represented in fig. 5.

Because the SHYFEM model has already been calibrated, the calibration of the coupled model is performed by varying the Manning coefficient in the DYNHYD model to obtain the best fit with the experimental data.

4. – Results

In this section the results of the hydrodynamic simulations in the Venice Lagoon and the channel network in Venice are presented. The discussion involves only water elevation and current velocities and, to a certain extent, also the salinity field in the Venice Lagoon. The results of the water quality modeling will be described in a subsequent work.

The coupled model of the system constituted by the Venice Lagoon and by the inner channels of Venice has been used for the following simulations:

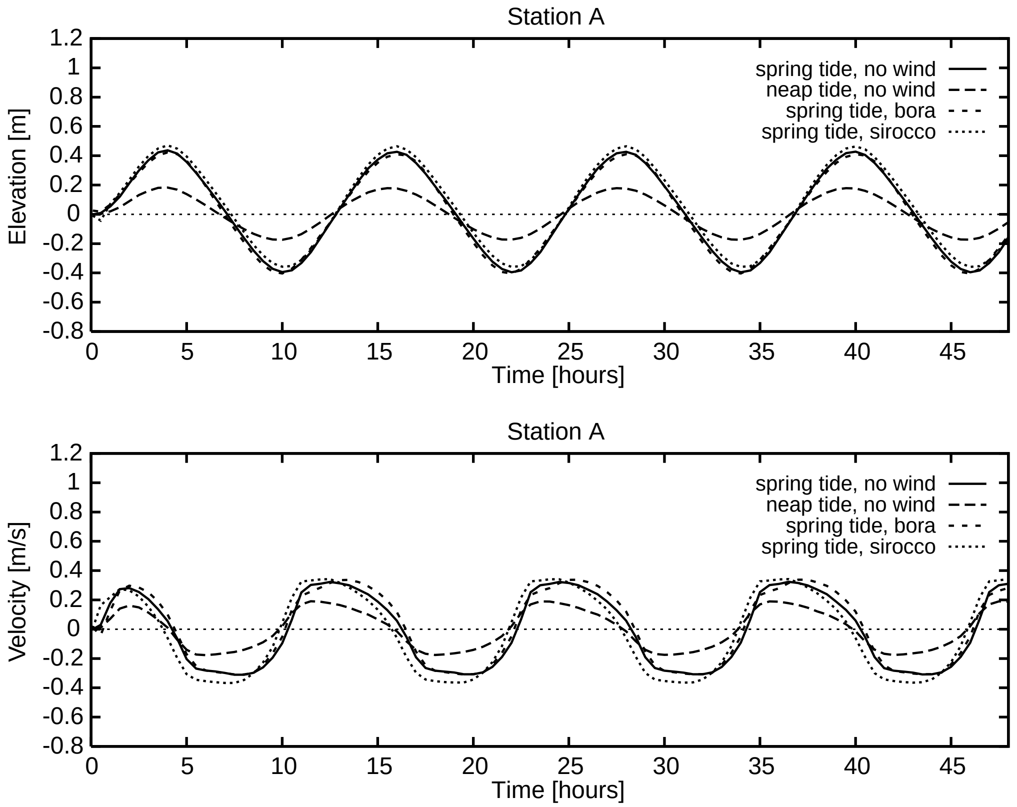


Fig. 7. – Sensitivity analysis, SHYFEM model of the Venice Lagoon: water elevation and velocity in Station A, computed in the 4 simulations with different idealized forcings.

– a sensitivity analysis has been carried out, to investigate the hydrodynamic behavior of the system, in the presence of various idealized forcings: a sinusoidal tide of a period of 12 hours and amplitude of 40 cm (spring tide) or 15 cm (neap tide); different meteorological conditions (no wind, bora wind or sirocco wind) with a constant wind speed of 10 m/s;

– a set of simulations has been realized to calibrate the coupled hydrodynamic model, through the data collected during the period 1990-92 and during the 1998 in the framework of the UNESCO project "Inner channels of Venice"; the coupled model has been forced by real data of tide and wind;

– the preliminary calibration of the salinity module, focusing only on the 2-dimensional model of the Venice Lagoon, through the salinity data collected during 1998.

The simulations carried out are listed in table I. Figure 6 gives an overview of the channels and sites of the field measurements.

4·1. *Sensitivity analysis.* – The model results of the sensitivity analysis can be seen in figs. 7 and 8. Time series of water elevation and current velocity in station A, situated along the northern boundary of Venice, are plotted in fig. 7. The results show some

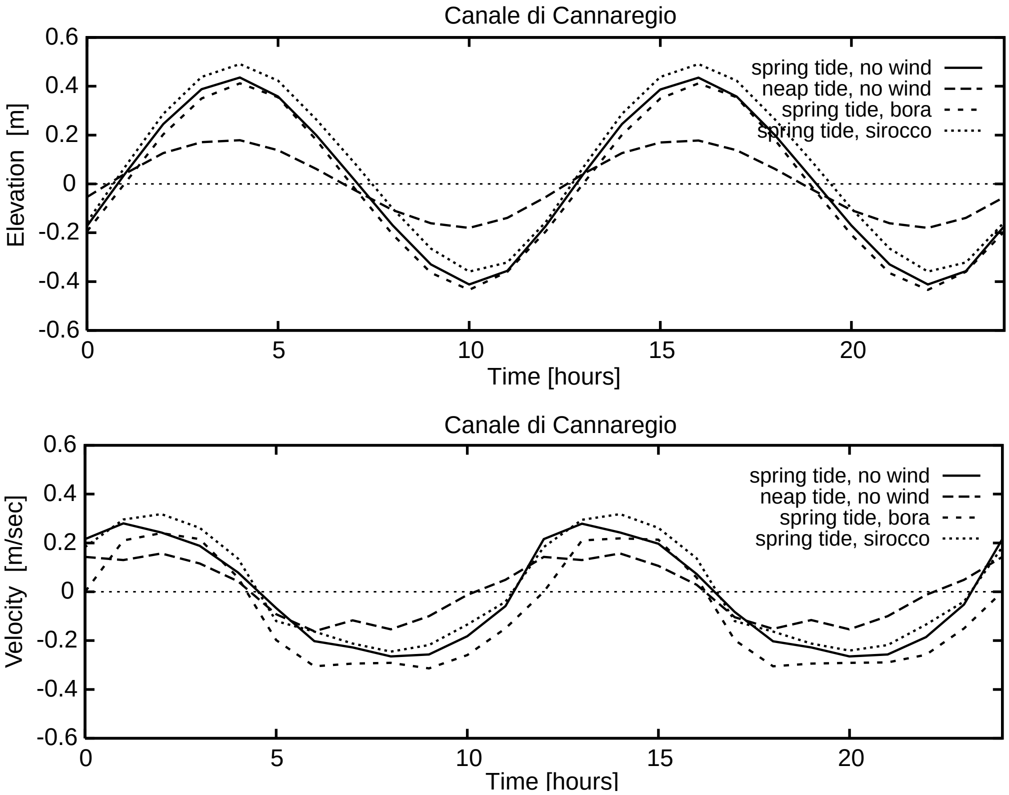


Fig. 8. – Sensitivity analysis, DYNHYD model of the Venice inner channels: water elevation and velocity in the Canale di Cannaregio, computed in the 4 simulations with different idealized forcings.

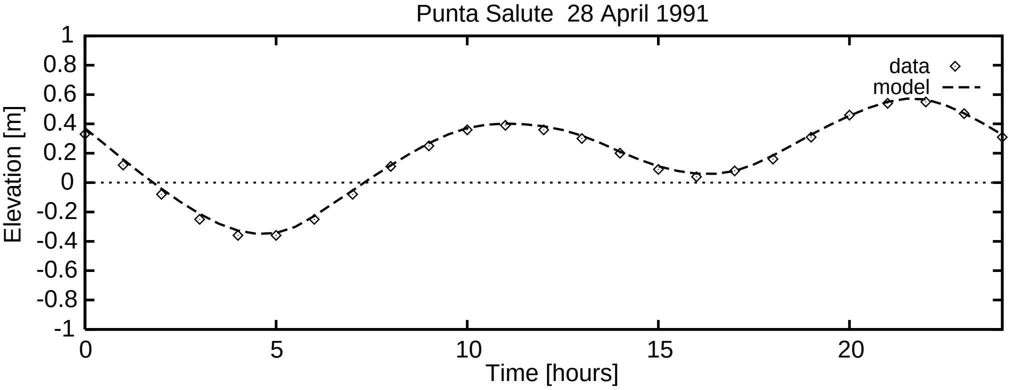


Fig. 9. – Simulation 27-28 April 1991, SHYFEM model of the Lagoon: water elevation at Punta Salute, computed by the model and measured.

general features of the hydrodynamic behavior of the lagoon: the effect of the sirocco wind is to increase the average water level compared to the case of no wind; the bora wind, instead, acts to slightly reduce this average surface elevation. The reason for this behavior is that bora winds push the water masses southward, creating a slight depression close to the Venice island. Sirocco winds act in the opposite sense.

As far as the current velocities are concerned, fig. 7 shows that during sirocco wind the current inversion and the velocity peaks occur earlier than in the case of no wind. Bora winds retard the current inversion and peak values. Neap tides are characterized by a highly nonlinear form of the velocity curve. Moreover, during neap tide, the curves of water elevation and current velocity both show an anticipation with respect to the spring tide.

Figure 8 shows the results of the sensitivity analysis in an inner channel of Venice: the *Canale di Cannaregio*, that communicates directly with the lagoon (for the location of the various channels see fig. 6). As in Station A, the water elevation increases in the case of sirocco and decreases slightly with bora. Examining the behavior of the other channels, it can be noted that the water elevation shows the same shape and the same variability with the meteorological conditions: this fact seems to indicate that the dependence of the water elevation in the channels on the boundary conditions (the water levels along the city limit) is stronger than the dependence on the internal dynamics or network geometry.

The water velocity is generally shifted to higher values during sirocco and to lower values during bora. In this case positive values correspond to northward flow, which means that even in the channel system, sirocco winds succeed in pushing water northward, whereas bora winds in pushing it southward. This feature can be noted also in the phase lag of the current inversion during bora winds, particularly during rising tide, that is due to the continuous acceleration of the water masses by the wind stress in southward direction.

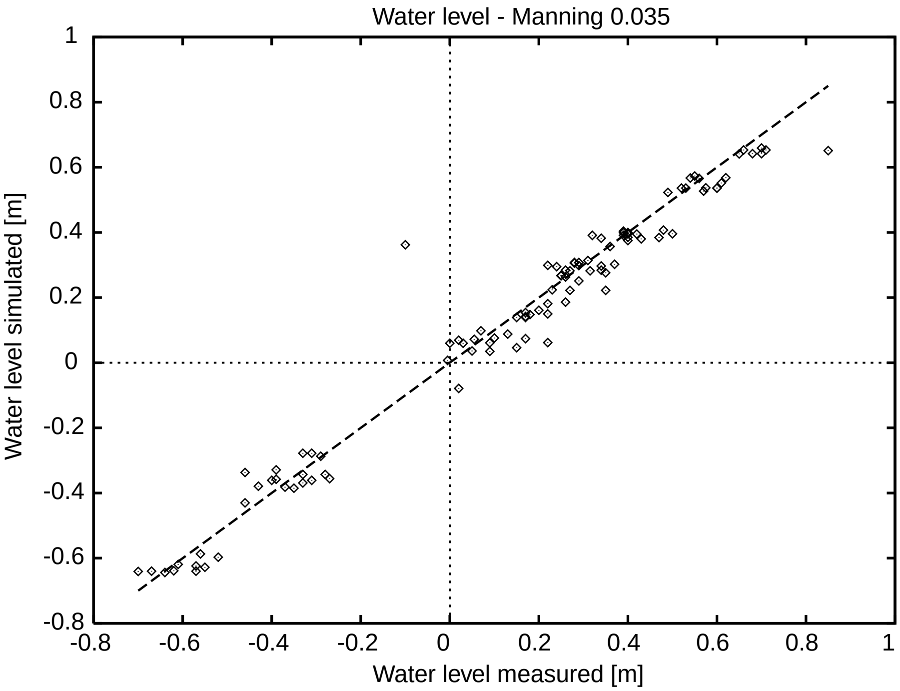
4·2. *Hydrodynamic calibration.* – The coupled model has been first calibrated with the hydrodynamic data of the UNESCO database, collected during 1990-92 (see table I).

In a first step the calibration of the 2-dimensional model has been verified for the above-mentioned period. The results of the verification are shown in fig. 9 and refer to Punta Salute. They show the time series of water elevation compared to the experimental data, for the simulation of the 27-28 April 1991: the SHYFEM model reproduces the water level accurately. There was no need in a further calibration of the finite-element model.

The calibration of the DYNHYD model of the Venice inner channels has been carried out by comparing the model results with the data in 19 channels (107 single

TABLE II. – *Results of the sensitivity analysis over the Manning coefficient.*

Manning	$\overline{\Delta\zeta}$ (cm)	$\overline{\Delta v}$ (cm/s)
0.020	4.2 ± 3.4	12.1 ± 10.7
0.030	4.2 ± 3.4	6.2 ± 6.0
0.035	4.2 ± 3.4	6.1 ± 5.6
0.040	4.2 ± 3.4	6.6 ± 5.7
0.050	4.2 ± 3.4	7.9 ± 6.7



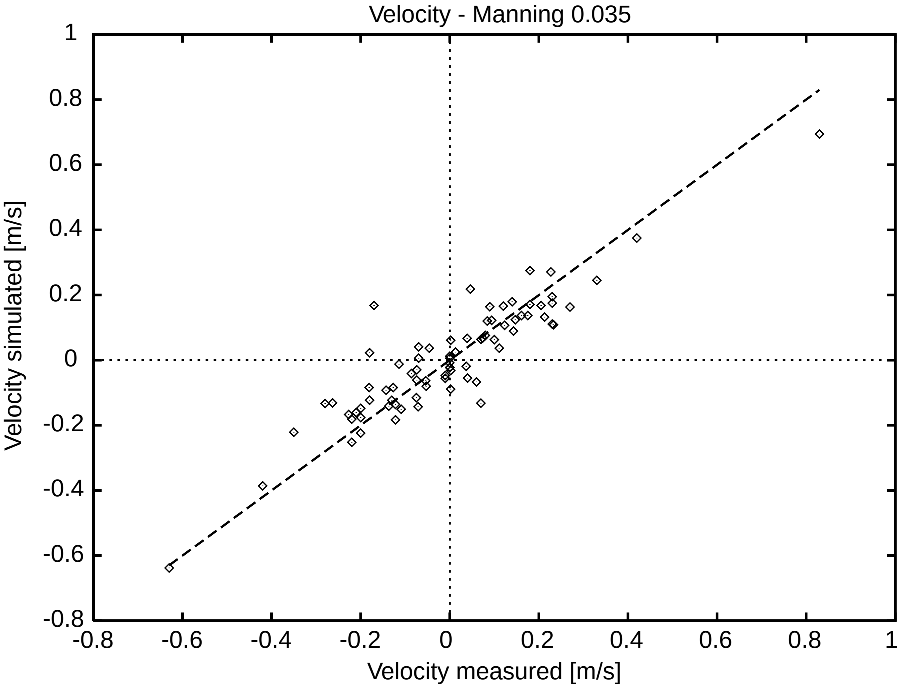
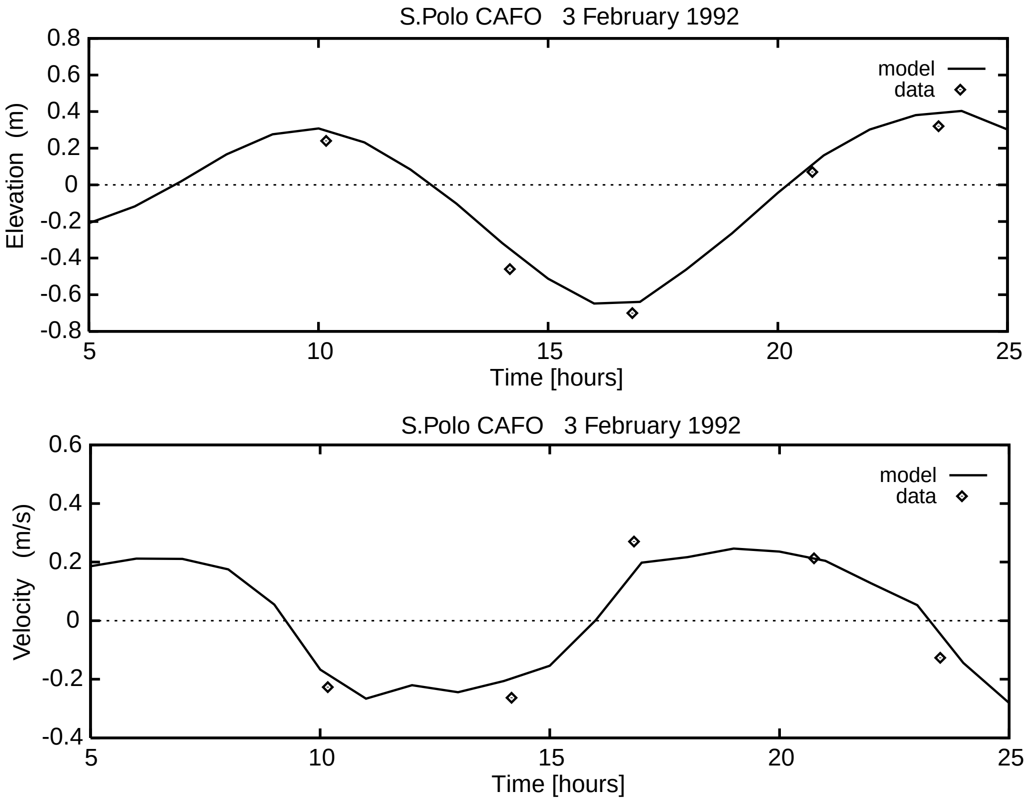


Fig. 10. – Scatter plots with Manning coefficient 0.035, for the calibration of the water levels and current velocities.


S.Polo CAFO 3 February 1992

S.Polo CAFO 3 February 1992

Fig. 11. – Simulation 2-4 February 1992, DYNHYD model of the Venice inner channels: water elevation and velocity in the Rio di Ca' Foscari, computed and measured. The Manning coefficient was 0.035.

measurements of water levels and 79 of current velocities) of the city collected during the 1990-92 period. The tuning parameter (the Manning coefficient, related to the bottom friction) has been retained constant for all channels, and has been varied to obtain the best global agreement with the data.

For all water level measurements the difference ($\Delta\zeta = |\zeta_{\text{meas}} - \zeta_{\text{sim}}|$) between the measured ($\zeta_{\text{meas}}$) and the simulated data (ζ_{sim}) has been computed and an average error $\overline{\Delta\zeta}$ and its variability have been calculated from these data. This has been done for Manning coefficients ranging from 0.020 to 0.050. The same procedure has been applied also to the current velocities, to obtain $\overline{\Delta v}$. The results can be seen in table II.

The value 0.035 of the Manning coefficient provided totally the best fit with measurements. During the calibration it has been noted that the velocity is much more sensitive to the variations of the Manning coefficient than the water elevation. This is partially due to the fact that the water elevation is imposed at the boundary (limit of the Venice island), whereas the velocity is free to adjust dynamically to the friction parameter.

Two scatter plots have been produced for the Manning value of 0.035 comparing the measured and simulated data (fig. 10). As can be seen, the water levels are well

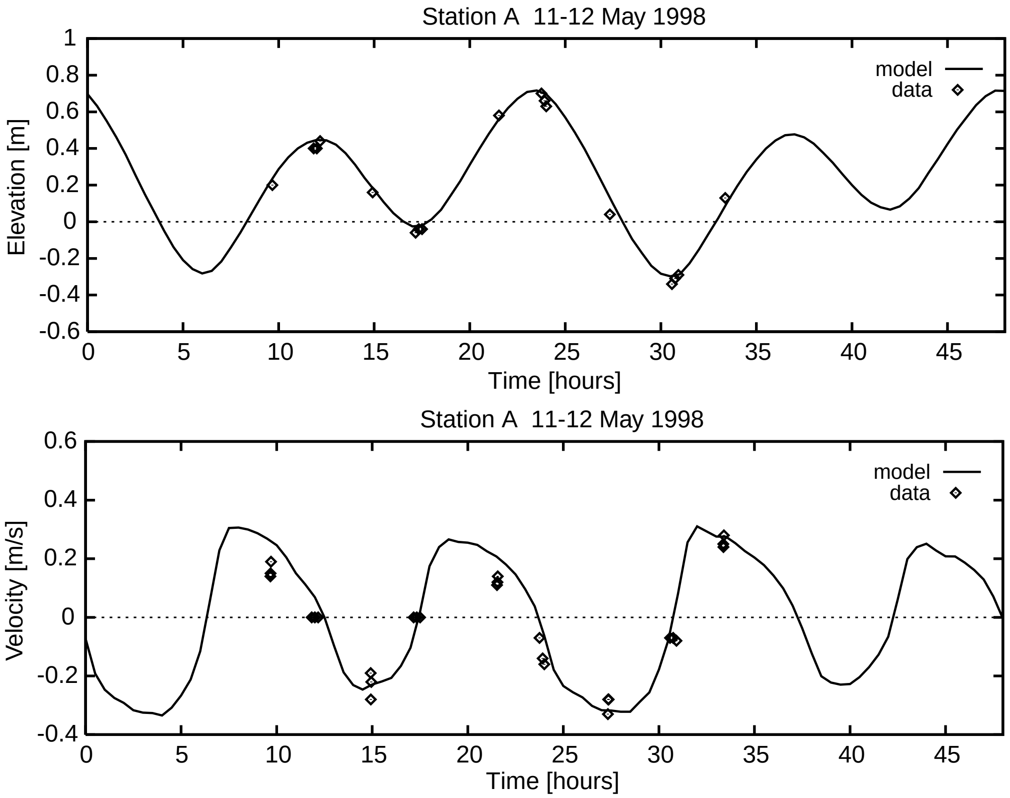


Fig. 12. – Simulation 10-12 May 1998, SHYFEM model of the lagoon: water elevation and current velocity in Station A, computed by the model and measured.

reproduced by the 1-dimensional model, whereas the current velocities show little less agreement. Two points in the level scatter plot that are clearly measurement errors (verified with data from nearby channels) have not been considered in the calculus of the mean error.

Figure 11 shows the time series of water elevation and current velocity in the *Canale di Ca' Foscari* in the simulation of 2-4 February 1992, with Manning coefficient 0.035: the model simulates faithfully both the water elevation and the current velocity. In general, it can be said that the elevation is reproduced with greater accuracy than the velocity.

The calibrated model has been verified with the 1998 data: the results are shown in figs. 12 and 13. The time series of water elevation and current velocity in Station A, computed by the SHYFEM model in the simulation of 11-12 May 1998 and measured, are plotted in fig. 12: the agreement with the experimental data is quite good, particularly for the water elevation, confirming that the SHYFEM model requires no further calibration.

The simulations with DYNHYD have been carried out again with a Manning coefficient of 0.035. The results in Station B (*Rio dei Mendicanti*), computed in the simulation of 10-12 May 1998 and measured, are shown in fig. 13. It can be seen that the

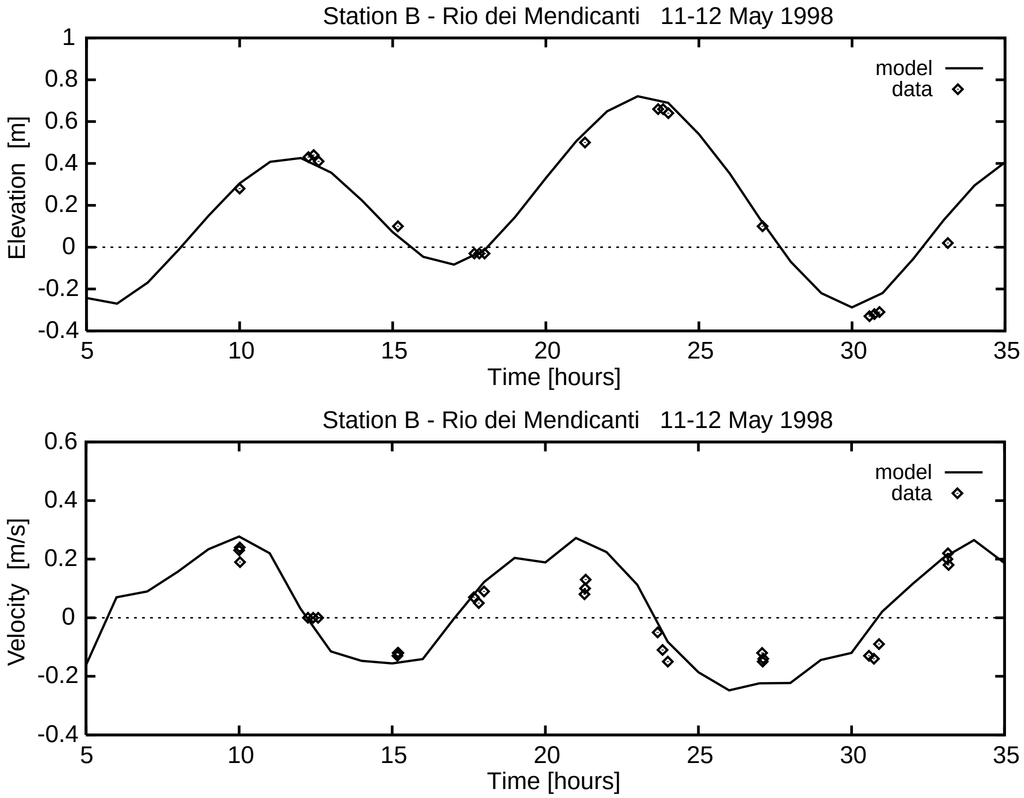


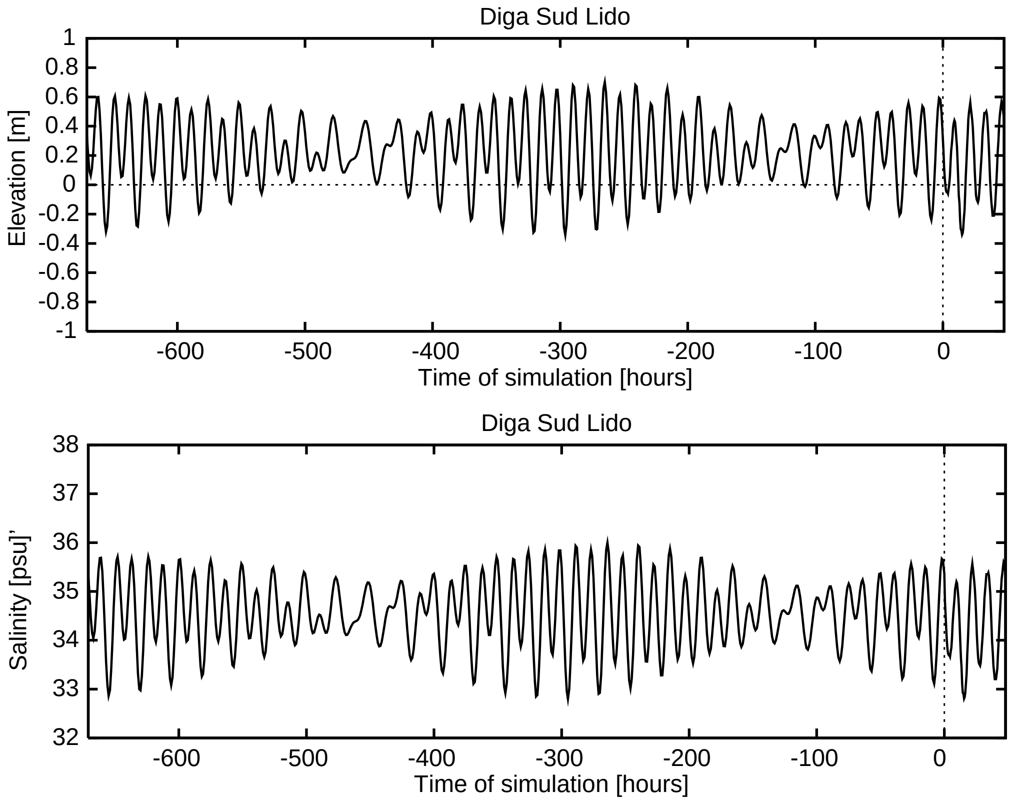
Fig. 13. – Simulation 10-12 May 1998, DYNHYD model of the Venice inner channels: water elevation and velocity in Station B, Rio dei Mendicanti, computed and measured. The Manning coefficient was 0.035.

model reproduces the water elevation with good accuracy. The current direction is simulated faithfully, whereas the model overestimates the speed in the peaks. Therefore, the Manning coefficient could be locally modified, in successive simulations to improve the model performance.

4·3. *Salinity calibration.* – The SHYFEM model can simulate the transport and diffusion of salinity: it is therefore possible to compute the distribution of such a passive tracer around the Venice island, providing the boundary conditions of salinity for the water quality module EUTRO of the model WASP.

A preliminary calibration of the salinity module has been carried out through a simulation of the SHYFEM model to reproduce the salinity measured in Station A, during the field work 11-12 March 1998. Due to the relatively long time for the salinity field to achieve a quasi-steady state, the simulation had a duration of 30 days. The model was forced by the astronomical tide for the first 28 days, to reach steady state, and by real tides and real winds for the last 2 days.

The effect of the eight main rivers that flow into the lagoon was included in the model imposing at each river the average rate of flow measured in the period


Diga Sud Lido

Diga Sud Lido

Fig. 14. – Simulation 11 February-12 March 1998, SHYFEM model of the lagoon: sea surface elevation and salinity at Diga Sud Lido. $T = 0$ at 0 of 11 March 1998. The last two days of the simulation correspond to the field measurements.

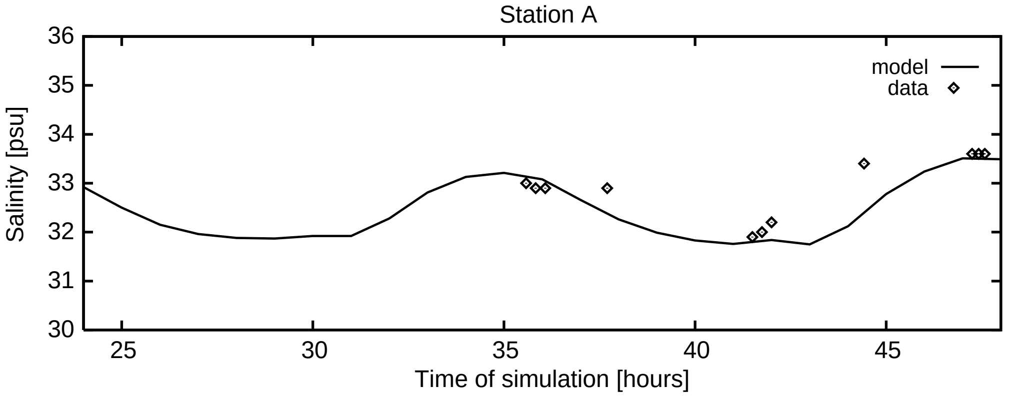

Station A

Fig. 15. – Simulation 11 February-12 March 1998, SHYFEM model of the lagoon: computed and measured salinity at Station A. $T = 0$ at 0 of 11 March 1998.

April-May 1983, for a total discharge of 34 m^3/s [11]; a constant value of 5 psu has been imposed for the river salinity.

Salinity measurements were not available at the inlets during any field work in 1998. It was therefore decided to use a semi-empirical formula for the description of the salinity variations at the inlets. In this formula an average salinity value is modulated with the tide, varying by a fixed range and imposing a phase lag. The salinity S_{inlets} imposed at the inlets is given by

$$S_{\mathrm{inlets}} = S_{\min} + \frac{\eta(t + \Delta t) - \eta_{\min}}{\eta_{\max} - \eta_{\min}} (S_{\max} - S_{\min}) , \tag{9}$$

where $S_{\max}$ and $S_{\min}$ are the extreme values of the salinity, η is the water elevation imposed at the inlets, with extreme values $\eta_{\max}$ and $\eta_{\min}$, t is the time, Δt is the time lag. This formula has been derived accordingly to observations carried out by CNR during the 1970s [12].

This variable salinity imposed at the inlets is the tuning parameter for the calibration: the extreme values have been varied to obtain the best agreement between the model results and the experimental data in Station A.

Figures 14, 15 and 16 refer to the salinity calibration. The tide and the salinity imposed as forcings at the three inlets are shown in fig. 14: the salinity varies between the extreme values of 32.8 and 36 psu, with a time lag of $\Delta t = -1$ hour.

In fig. 15 the time series of salinity computed by the model at Station A is plotted together with the experimental data collected during the field work of 11-12 March 1998: the agreement between computed values and data appears good.

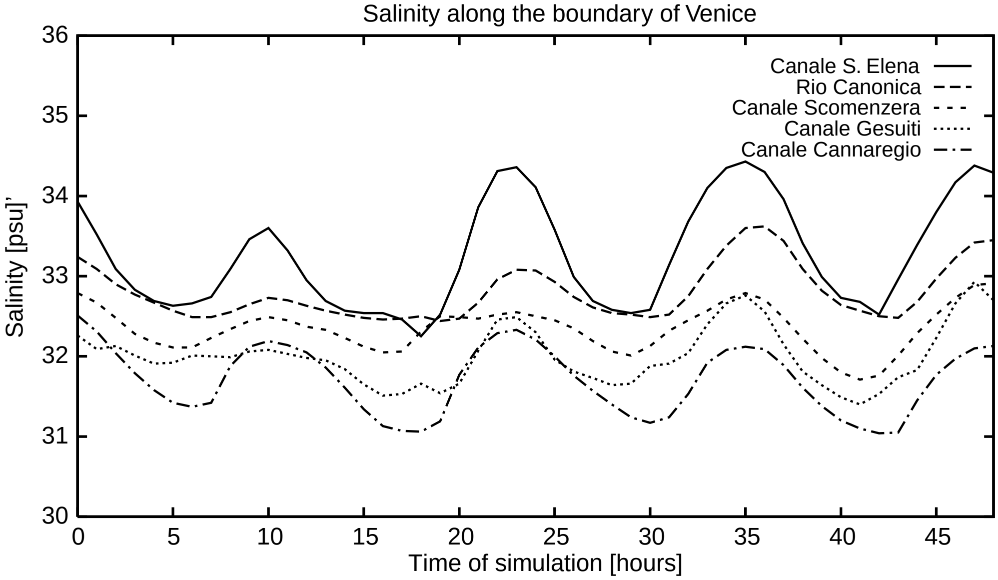


Fig. 16. – Simulation 11 February-12 March 1998, SHYFEM model of the lagoon: computed salinity along the limit of the Venice island. $T = 0$ at 0 of 11 March 1998. An average salinity gradient can be observed between the points around Venice: due to the input of fresh water by the rivers, the average salinity is lower on the northern side (*Canale di Cannaregio* and *Canale dei Gesuiti*).

To show the spatial and temporal variability, the salinity computed by the finite element model in 5 points along the boundary of Venice is shown in fig. 16: the variability due to the tidal cycle can be observed in all points, as well as a constant salinity gradient among points situated in different areas of the city. The points along the northern boundary of Venice (*Canale dei Gesuiti* and *Canale di Cannaregio*) show a lower average salinity, compared to the points situated along the southern boundary (*Canale di S. Elena* and *Rio della Canonica*): this is due to the fresh water input from the rivers that has a higher influence on the northern side of Venice.

5. – Conclusions

An existing shallow-water finite-element model of the Venice Lagoon has been used to simulate the currents and the tidal elevation around the city of Venice. The model is also capable to simulate the salinity field (along with any other conservative scalar property) in the lagoon. This computed data is used to drive the actual model of the channel network of Venice, the one-dimensional link node model WASP of the EPA.

The elevation data computed by the finite-element model is used in the 1D link-node model DYNHYD as the boundary condition for the hydrodynamic runs carried out in the channel network. Due to the good reproduction of the propagation of the tidal wave in the Venice Lagoon by the finite-element model, the hydrodynamic features can be reproduced well also in the channel network.

Results show an excellent agreement of the hydrodynamic parameters with the data obtained by field measurements carried out during the years 1991-92 and during the whole 1998. It is normally not necessary to calibrate the single channels by changing the friction coefficient. Taking the Manning coefficient to 0.035 for all channels is sufficient to obtain good agreement with the observational data.

Major differences between observations and simulations can be found only in channels, where the observed velocity is very small (less than 10 cm/s). Instead of calibrating these channels, it is believed that a re-adjustment and check of the bathymetry of the channel could give better results. This check on the bathymetry data will be carried out later in the project.

The salinity has been modeled by imposing a sinusoidal behavior on the lagoon inlets. Since there is no data available at the inlets, a pseudo-empirical formula has been used. The values are calibrated to the salinity values measured at Station A close to the Venice island and generally show a good agreement with the data. Other salinity data were not available, so it has not been possible to verify the salinity calibration.

Finally, a sensitivity analysis has been carried out to understand the influence of neap and spring tide, and the effect of bora and sirocco winds on the water levels and current velocities in the network channel. This sensitivity analysis indicates some phase lag in the current reversal depending on the wind regime used. It also shows a general shift of the water elevation curve towards lower (bora) or higher (sirocco) values due to the water set-up generated inside the Venice Lagoon.

In the remaining part of the project, the water quality module EUTRO of the WASP model will be applied to the channel network. Using the hydrodynamic parameters (currents, circulation, water levels) that have been simulated by DYNHYD, the ecological parameters are simulated in order to describe the water quality (nutrients, phytoplankton, detritus, etc.) of the inner channels of Venice.

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