HYDRODYNAMIC MODELING OF THE LAGOONS OF MARANO AND GRADO, ITALY

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Abstract. A finite element hydrodynamic model has been used to describe the water circulation and the water transport times of the Lagoons of Marano and Grado, Italy. The hydrodynamic circulation of the lagoon has been simulated taking into account different forces such as tide, wind and rivers. The model has been validated by comparing the simulation results against measured water levels and salinity and water temperature data collected in several stations inside the lagoons. Once the model has been validated, water residence time have been estimated for two different scenarios.

Keywords: Marano and Grado Lagoons, Finite element model, Hydrodynamics, Residence Times.

1. INTRODUCTION

Hydraulic circulation in coastal and lagoon environments is a factor of primary importance for most of the physical and biogeochemical processes. Interseasonal and interannual variations in hydraulic forcing could drastically change the biogeochemical processes in the lagoon both by changing the salinity and turbulence. In the case of the Lagoons of Marano and Grado these factors are considered to be critical for the dispersion of pollutants and nutrients (Matassi *et al.*, 1991; Brambati, 2001; Covelli *et al.*, 2001; Covelli *et al.*, 2008).

The lagoon of Grado and Marano, in the northeastern part of the Adriatic Sea (Italy), is delimited by the rivers Isonzo and Tagliamento, and it is separated from the sea by a long shore bar composed of isles and more or less persistent sand banks (Fig. 1). The area stretches out for about 16,000 ha, with a length of nearly 32 km and an average width of 5 km. Most of the lagoon is covered by tidal flats and salt marshes and some areas are constantly submerged (tidal channels and subtidal zones).

The lagoon system of Grado and Marano has been always formally divided in two major sub-basin: the lagoon of Marano and the lagoon of Grado. The Marano lagoon is a semi enclosed tidal basin, limited by the Tagliamento River delta westward. It is shallow, with a few areas above the sea level and several channels, receiving freshwaters from the adjacent rivers. Conversely, the Grado lagoon is shallower, has a series of morphological relieves (islands) and marshes, and receives freshwater from a single tributary, the Natissa river (Marocco, 1995).

The lagoon basin is characterised by semi-diurnal tidal fluxes (65 and 105 cm mean and spring tidal range, respectively). Small rivers flow into the lagoon, mostly in the western sector (Marano Lagoon), which drain waters coming from the spring line. The overall amount of average freshwater discharge was estimated in about 70-80 $m^3\ s^{-1}$ (Ret, 2006).

The scientific hydrodynamic investigations of the Lagoons of Marano and Grado started in the first half of the last century. Measured variation in physical and chemical parameters or measured water currents were initially used to describe the water circulation pattern (Dorigo, 1965). Only during the recent years hydrodynamic models have been applied to the Marano and Grado Lagoons. Petti and Bosa (2004) and Bosa and Petti (2004) applied a 2D finite volume model to the lagoon of Marano and Grado for studying the sediment transport and the dispersion of a dissolved pollutant in the lagoon environment. Idealized forcings were used in this studies and no model calibration was performed.

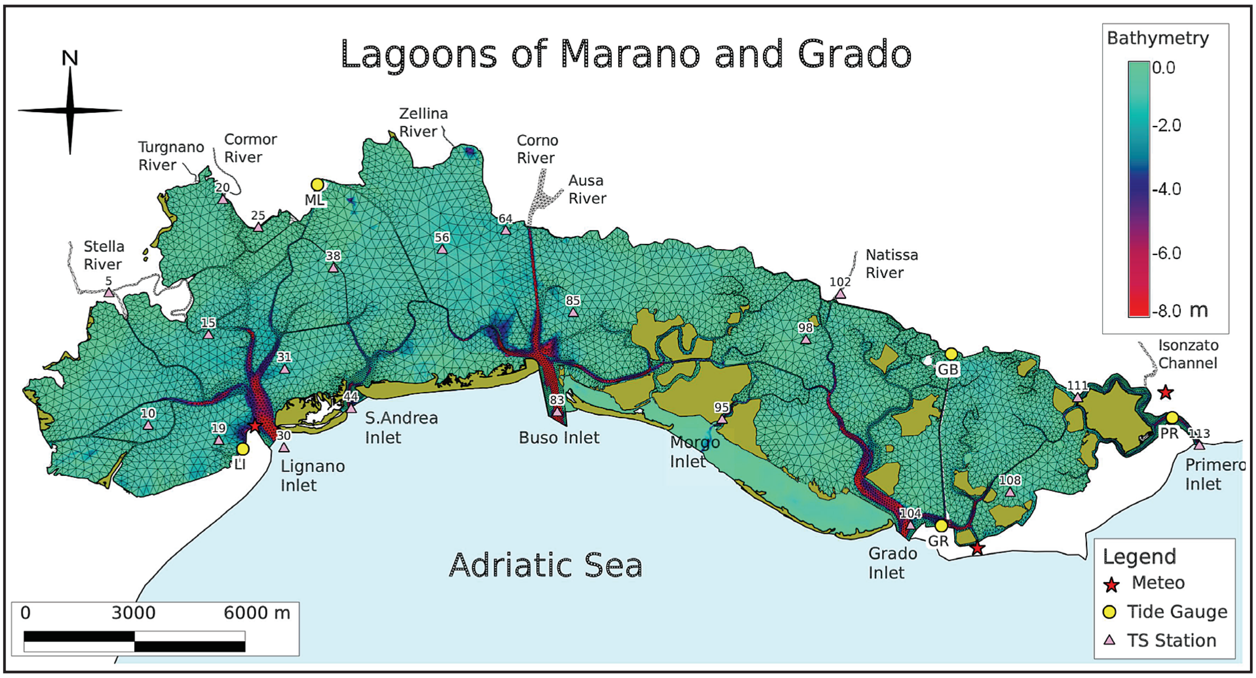

Fig. 1 Bathymetry of the Marano and Grado Lagoons obtained by using the grid of the numerical model, superimposed. Circles mark the location of the tidal gauges. Stars indicate the location of the meteorological stations. Triangles mark the salinity and temperature monitoring stations.

The aim of this paper is to develop an application of the finite element SHYFEM model to the Lagoons of Marano and Grado simulating the current regime and the water transport times in order to derive a hydraulic regime-based zonation scheme. The hydrodynamic circulation of the Lagoon of Marano and Grado has been simulated taking into account different forcing, such us wind, rivers, and sea-lagoon exchange. The model has been validated for the Lagoons of Marano and Grado by comparing the simulation results against field measurements.

2. MODEL APPROACH

The hydrodynamic model SHYFEM here applied has been developed at ISMAR-CNR *(Institute of Marine Science - National Research Council)* (Umgiesser and Bergamasco, 1995). It has already been applied successfully to several coastal environments (Ferrarin an Umgiesser, 2005; Ferrarin *et al.*, 2008; Umgiesser *et al.*, 2004; Bellafiore *et al.*, 2008). The finite element method allows for the possibility to follow, strictly, the morphology and the bathymetry of the system. In addition, it is able to better represent zones where hydrodynamic activity is more important, such as in the narrow connecting channels.

2.1. Governing equations

The model resolves the *Shallow Water Equations* in their formulations with water levels and transports:

$$\frac{\partial U}{\partial t} - fV + gH\frac{\partial \zeta}{\partial x} + RU + X = 0 \qquad (1)$$

$$\frac{\partial V}{\partial t} + fU + gH\frac{\partial \zeta}{\partial y} + RV + Y = 0 \qquad (2)$$

$$\frac{\partial \zeta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \qquad (3)$$

where f is the Coriolis parameter, ζ is the water level, γ is the gravitational acceleration, ρ is the water density, $H = h + \zeta$ is the total water depth, and U and V the vertically-integrated velocities (total or barotropic transports):

$$U = \int_{-h}^{\zeta} u\,dz \qquad V = \int_{-h}^{\zeta} v\,dz \qquad (4)$$

with u and v the velocities in x and y direction and h the undisturbed water depth. R is the friction coefficient which is expressed as:

$$R = c_b \frac{\sqrt{u^2 + v^2}}{H} \qquad (5)$$

with c_b the bottom drag coefficient. The bottom drag itself is not a constant but varies with the water depth as:

$$c_b = \frac{g}{C^2} \qquad C = k_s H^{1/6} \qquad (6)$$

where C is the Chezy coefficient and k_s is the Strickler coefficient.

The terms X and Y of equations and contain all other terms like the wind stress, the nonlinear terms and those that need not be treated implicitly in the time discretization. They read:

$$X = u\frac{\partial U}{\partial x} + v\frac{\partial U}{\partial y} - \frac{1}{\rho}\tau_x^s - A_H\left(\frac{\partial^2 U}{\partial^2 x} + \frac{\partial^2 U}{\partial^2 y}\right)$$
$$Y = u\frac{\partial V}{\partial x} + v\frac{\partial V}{\partial y} - \frac{1}{\rho}\tau_y^s - A_H\left(\frac{\partial^2 V}{\partial^2 x} + \frac{\partial^2 V}{\partial^2 y}\right) \quad (7)$$

where τ_x^s and τ_y^s are the wind stress acting at the surface of the fluid computed as:

$$\tau_x^s = \rho_a c_D |u^w| u_x^w \quad \tau_y^s = \rho_a c_D |u^w| u_y^w \quad (8)$$

where ρ_a is the air density, u_x^w and u_y^w the wind speed in x and y direction at standard height (10 m) and $|u^w|$ its modulus and c_D the wind drag coefficient. The last term in equation represents the horizontal turbulent diffusion with A_H the horizontal eddy viscosity.

At the open boundaries the water levels are prescribed in accordance with the Dirichlet condition, while at the closed boundaries only the normal velocity is set to zero and the tangential velocity is a free parameter.

The model uses a semi-implicit algorithm for integration in time, which combines the advantages of the explicit and the implicit scheme. The terms treated semi-implicitly are the divergence terms in the continuity equation and the Coriolis term, the pressure gradient and the bottom friction in the momentum equation; all other terms are treated explicitly. It is unconditionally stable with respect to the gravity waves, the bottom friction and the Coriolis terms and allows the transport variables to be solved explicitly without solving a linear system. Compared to a fully implicit solution of the shallow water equations solving a linear system for the water levels, it reduces the dimensions of the matrix to one third.

The spatial discretization of the unknowns has been carried out with the finite element method, partially modified with respect to the classic formulation. This approach was necessary to avoid high numerical damping and mass conservation problems, due to the combination of the semi-implicit method with the finite element scheme (Galerkin method). With respect to the original formulation, here the water level and the velocities (transports) are described by using form functions of different orders, being the standard linear form function for the water level, but stepwise constant form function for the transports. This will result in a grid that resembles a staggered grid often used in finite difference discretization. A more detailed description of the model equations and of the discretization method is given in (Umgiesser *et al.*, 2004).

2.2. Water Residence Time

The water transport time scale has been used as fundamental parameter for the understanding of the ecological dynamics that interest lagoon environments (Gong *et al.*, 2008). Assuming that advection and diffusion can be reasonably considered the main physical processes that influence the cleaning capacity of a lagoon ecosystem water compartment, the water transport time scale could be modelled with eulerian techniques. These method have been already applied to the Venice Lagoon (Cucco and Umgiesser, 2006; Cucco *et al.*, 2009) and the computed water residence time agrees well with the apparent age of water calculated using the ratio of ^{224}Ra and ^{228}Ra (Rapaglia *et al.*, in press). An exhaustive description of these transport time scales is given by (Cucco *et al.*, 2009).

In this study the eulerian water residence time has been defined as the time required for each element of the lagoon area to replace most of the mass of a conservative tracer, originally released, with new water.

To compute the spreading and the fate of the tracer, a solute transport model has been used. The model solves the advection and diffusion equation, which, in the 2D vertically integrated form, is given as:

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = K_h\left(\frac{\partial^2 C}{\partial^2 x} + \frac{\partial^2 C}{\partial^2 y}\right) \quad (9)$$

where C is the depth integrated concentration of a passive tracer, u and v are the barotropic velocities and K_h is the horizontal turbulent diffusion coefficient. Fluxes through the bottom have been neglected here. The transport and diffusion equation is solved with a combination of first and second order explicit scheme based on the total variational diminishing (TVD) method.

3. APPLICATION TO THE MARANO AND GRADO LAGOONS

3.1. The simulation set-up

The numerical computation has been carried out on a spatial domain that represents the lagoon of Marano and Grado through a finite element grid which consists of 20,586 triangular elements (11,500 nodes) with a resolution that varies from about 200 m in the tidal flats part, to few meters in the inner channels (Fig. 1). The finite element method allows high flexibility with its subdivision of the numerical domain in triangles varying in form and size. It is especially suited to reproduce the geometry and the hydrodynamics of complex shallow water basins such as the lagoon of Marano and Grado with its narrow channels and small islands.

In this study, no spatial distinction of the bottom friction has been made inside the lagoon, and the Strickler coefficient has been considered homogeneous over the whole lagoon and set equal to 32 $m^{1/3}$ s^{-1}. Similar values have been used in the hydrodynamic modeling of Venice and Cabras lagoons (Umgiesser *et al.*, 2004; Ferrarin and Umgiesser, 2005). The drag coefficient for the momentum transfer of wind has been set to $2.5 \cdot 10^{-3}$. All simulations presented in this work have been carried out using a maximum time step of 100 s.

4. RESULTS

4.1. Model validation

This set of simulation was carried-out to validate the model against available experimental water level, salinity and water temperature data collected in the lagoons. The years of reference for this simulation was the 2007 and real forcing data were used in this one-year long simulation.

The simulation was forced by observed values of wind (red star in Fig. 1). Open boundaries are treated by defining observed water levels (marked with the yellow circle LI, GR and PR in Fig. 1), salinity and water temperature at the inlets and defining the fluxes of fresh water from the major tributaries. Continuous river discharge time series have been obtained from water level measurements (kindly provided by Unità Operativa Idrografica di Udine) and converted to river flows through calibrated relationship.

4.1.1. Water level

Water level is hourly measured in Marano Grado and Grado Belvedere gauge station (yellow circle MA and GB in Fig. 1). Model results are generally in good agreement with the measured water level with a correlation coefficient close to 1 in all the stations and RMSE of about 4 cm. The model reproduces well the tidal wave propagation inside the lagoon and the wind set-up.

4.1.2. Salinity and water temperature

Water temperature and salinity is measured monthly in more than 20 stations inside the lagoons (marked with triangles in Fig. 1).

Salinity data comparison shows that the model catches the salinity variability in the lagoon (Fig. 2) and reproduces well the fluxes between the lagoon and the sea. The simulation result shows that there is west-east salinity gradient in the lagoon (Fig. 3) and rivers are responsable of a great daily excursion in the salinity of the western part of the lagoon.

Water temperature is well simulated by the model and does not show a significant spatial variability within the lagoons.

4.2. Water Residence Time

Additional simulations were carried out to reproduce the effect induced by the main meteorological and tidal forcing on the lagoon hydrodynamics. Two situations were investigated. In the first scenario, only the tide forces the basin. In the other, the typical wind regimes, the Bora from NE, were prescribed together with the tide.

As characteristic tides, oscillation of 0.5 m with a period of 12 hours was selected. The above mentioned values are held representative of normal oscillations of tides. For the wind forcing, the wind regimes considered were chosen to be constant in time and space, with typical wind speeds of 12 m/s. The wind forces the model for the total duration of the simulations. Average discharge has been imposed to the rivers.

4.2.1. No wind

In the first case only the tidal forcing is considered and no wind is prescribed. The results are evaluated after the spin-up period.

Residence times range between values of few days, close to the inlets, and values over 20 days in the inner lagoon areas. The average value computed for the whole basin is 5.8 ± 4.3 days. Qualitatively, the distribution is mainly dependent on the relative distance from the inlets and on the presence of channels, which can lower the residence time. The areas connected to these channels are directly influenced by the sea and consequently their water residence times are lower. In Fig. 4 the spatial distribution obtained from a tidal simulation is plotted.

4.2.2. Tide and Bora wind

When the tidal forcing is supplemented by the wind action, the lagoon circulation changes radically. The wind imposed on the model is from NE and its intensity is of 12 m/s. The current velocity induced by the wind and the tide is vigorous all over the lagoon.

Due to its direction and intensity, this wind is able to increase the circulation both in the west and in the east areas. The hydrodynamic pattern is completely wind dominated, and therefore, the tidal variability plays a minor role.

The water residence times have been plotted in Fig. 5. The average residence time and the standard deviation value are 1.9 ± 1.6 days for the whole basin. The average and standard deviation values are therefore much lower that in the tide only case. The Bora wind driving the water to the west pushes the water in the west part of the lagoon to exit from the embayment and to be quickly renewed.

5. CONCLUSIONS

A 2D, freely-available, hydrodynamic model, which can handle unstructured triangular meshes, has been applied to the Marano and Grado Lagoons. The model has been fully validated comparing simulation results against observed water level, salinity and water temperature data. The model is able to reproduce the tidal propagation in the lagoon, the salinity distribution and the fluxes between the lagoon and the sea.

The seasonal salinity variations are well described by the model which faithfully simulates the experimental data. Results from the thermal radiative model show that the water temperature is through all the year similar to the air temperature, due to the low thermal inertia of the lagoon. The computed water temperature fits with the data gained during the field observations.

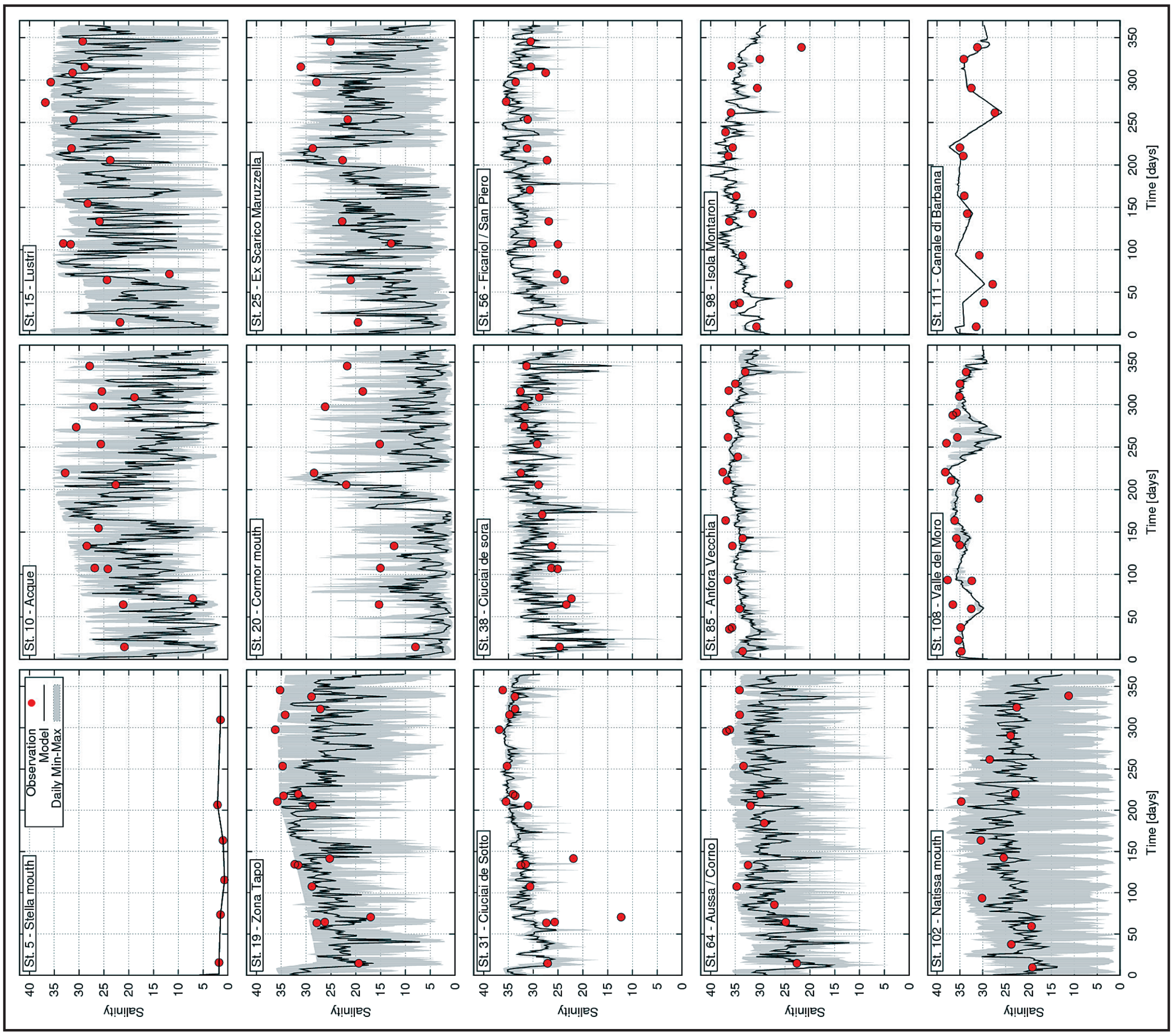

Fig. 2 Measured and simulated salinity in the lagoons of Marano and Grado. The red circles represent the measured values. The black line represents the modelled daily averaged salinity, while the grey band represents the daily salinity range.

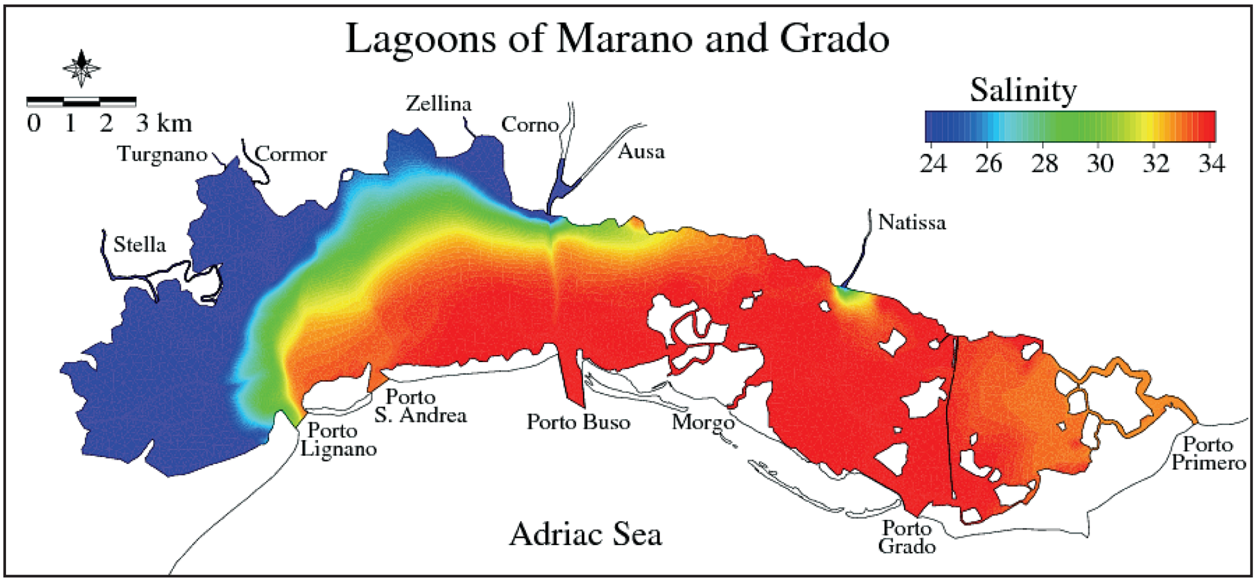

Fig. 3 Annual average salinity distribution as computed by the model.

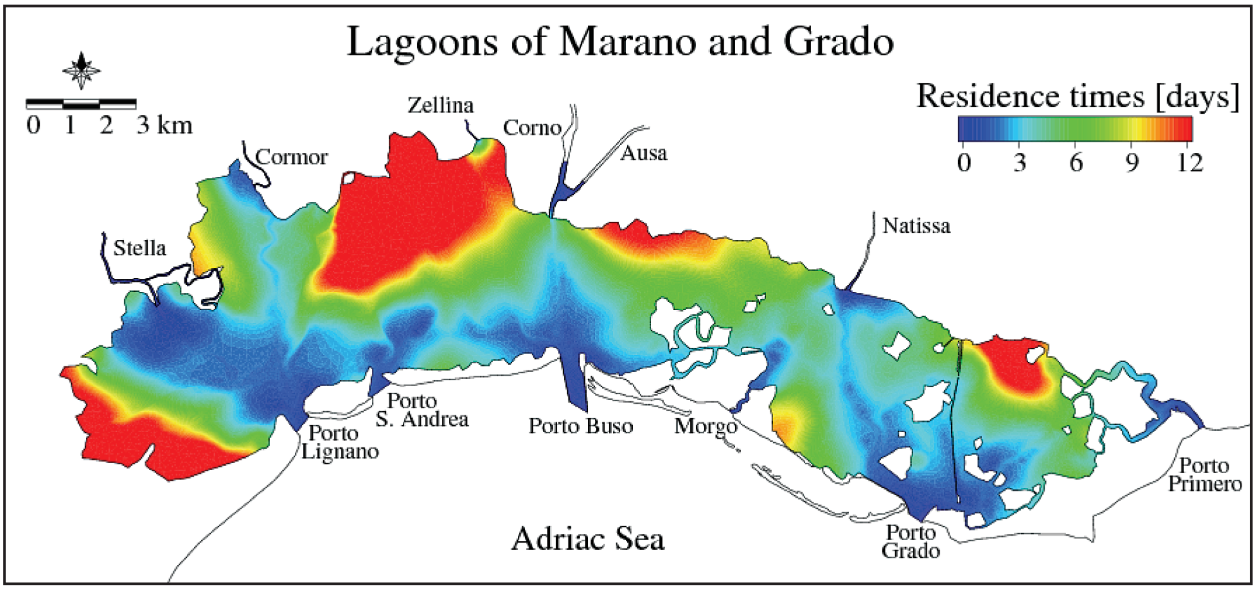

Fig. 4 Modelled residence time in the case of tide only.

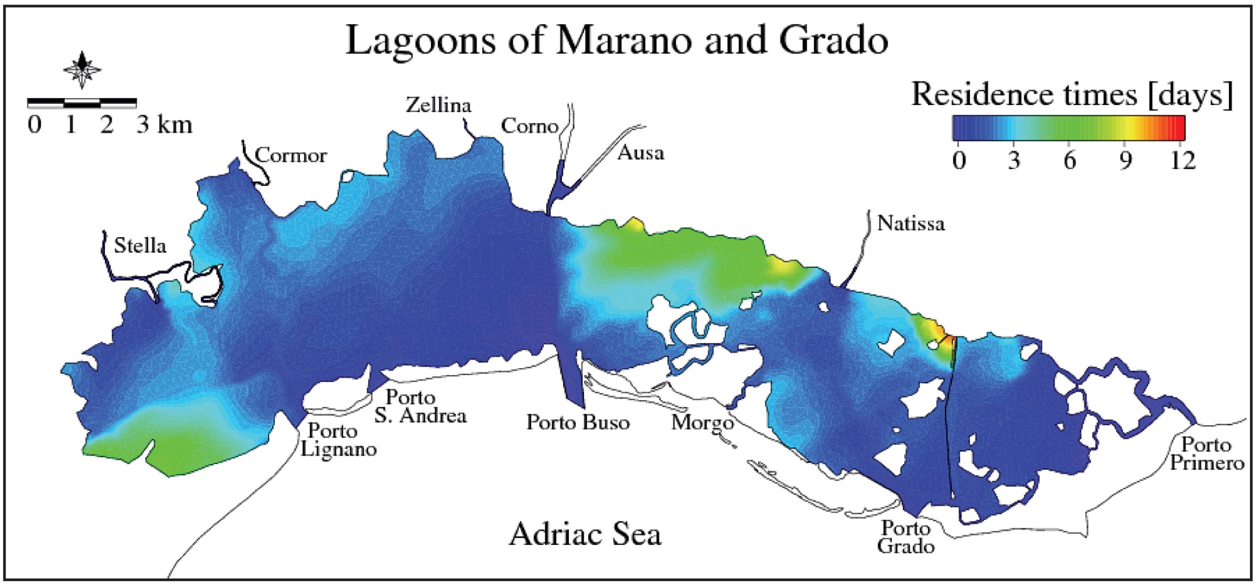

Fig. 5 Modelled residence time in the case of tide and wind from NE.

The residence time was defined as the time required for each element of the lagoon area to replace most of the mass of a conservative tracer, originally released, with new water. Computing the diffusion and transport equation of this passive tracer the residence time distribution in the Marano and Grado Lagoons was found.

Two typical idealized scenarios were investigated: tide only and tide with wind forcing. When wind forcing is taken into consideration the circulation in the lagoon is increased. The effect of the Bora wind on the water circulation lower the residence time respects the case of tide only.

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