Hydraulic zonation of the Lagoons of Marano and Grado, Italy. A modelling approach.

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Abstract

The hydraulic regime-based zonation scheme of the Lagoons of Marano and Grado (Italy) has been derived by means of numerical models. A finite element modelling system has been used to describe the water circulation taking in account different forces such as tide, wind and rivers. The model has been validated by comparing the simulation results against measured water levels, salinity and water temperature data collected in several stations inside the lagoons. The analysis of water circulation, salinity and spatial distribution of passive tracers released at the inlets, led to a physically-based division of the lagoons system into six subbasins. The derived classification scheme is of cru-

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cial value for understanding the renewal capacity and pollutants distribution patterns in the lagoon.

Key words: Marano and Grado Lagoons, Finite element model, Zonation scheme, Salinity distribution

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1. Introduction

Coastal lagoons are recognised as highly unpredictable environments characterized by high spatial and temporal bio-geo-chemical variability (Pérez-Ruzafa et al., 2005; Viaroli et al., 2007; Tagliapietra et al., 2009; Roselli et al., 2009). This variability is produced by strong salinity and temperature gradients, limited volumes, shallow waters, close coupling between benthic and pelagic domains, and restricted connections to the adjacent sea (Loureiro et al., 2006; Torréton et al., 2007).

Hydraulic circulation and diffusive processes in coastal and lagoon environments is a factor of primary importance influencing 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. These factors are considered to be critical for the dispersion of nutrients and pollutants (Rigollet et al., 2004).

A good ecological status and good chemical status across European waters need to be achieved by 2015, as required by the Water Framework Directive (WFD) of the European Union (EU) (CEC, 2000). To achieve these aims, the WFD contemplates the classification of coastal systems in typologies, defined on the basis of abiotic factors (including salinity, temperature, oxygen and nutrients) to describe a group of specific environments.

In the case of the Lagoons of Marano and Grado, a coastal system located in the northern Adriatic Sea, two major subbasins were identified in the past: 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 marshes and several channels, receiving freshwaters from several adjacent rivers. 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).

Due to the high spatial and seasonal variability of the biochemical properties, the zonation of lagoons cannot be derived explicitly only from geographical features as was tried in the past, but rather using physical properties simulated by means of numerical models.

The aim of this paper is to develop an application of a 2D, freely-available, finite element model to the Lagoons of Marano and Grado simulating the current regime and the salinity distribution in order to derive a hydraulic regime-based zonation scheme. The finite element method permitted to follow the details of bathymetry and morphology of the lagoon, describing the areas of special interest with higher resolution. 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.

1.1. Study site

The lagoon of Grado and Marano, in the northern part of the Adriatic Sea (Italy), is an important ecological system, both for the habitats of numerous vegetal and animal species. At present, six sandbars separate the Lagoon of Marano and Grado from the Adriatic Sea. Inlets subdivide barrier islands into segments with a length from 1 to 6 Km, and a width of about 1 or 2 Km (Fig. 1). The area stretches out for about 160 km^2, 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 lagoons are close to a heavily industrialized area with a multiplicity of environmental contamination sources. In the lagoons fishing activities and aquaculture systems take place. Recent investigations have been carried out for the dredging of the lagoon channels and they have underlined high mercury (Hg) concentrations in the bottom sediments and biota of the whole Lagoon (Covelli et al., 2001, 2008).

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. Bosa and Petti (2004) and Petti and Bosa (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 forcing were used in this studies and no model calibration was performed.

2. Model description

A framework of numerical models (named SHYFEM) has been applied to the coastal lagoons of Marano and Grado. These models consist of a two-dimensional hydrodynamic model, a transport and diffusion model and a radiational transfer model of heat at the water surface. The modelling system here applied has been developed at ISMAR-CNR *(Institute of Marine Science - National Research Council)* (Umgiesser et al., 2004, 2003). It has already been applied successfully to several coastal environments (Ferrarin and Umgiesser, 2005; Ferrarin et al., 2008a; Umgiesser and Bergamasco, 1995; Ferrarin et al., 2008b; 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. Hydrodynamic model

The model resolves the shallow water equations in their formulations with water levels and transports:

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

$$\frac{\partial V}{\partial t} + fU + gH\frac{\partial \zeta}{\partial y} + RV + Y = 0 \tag{1b}$$

$$\frac{\partial \zeta}{\partial t} + \frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0 \tag{1c}$$

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

$$U = \int_{-h}^{\zeta} u \, dz \qquad V = \int_{-h}^{\zeta} v \, dz \tag{2}$$

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

$$R = \frac{g\sqrt{u^2 + v^2}}{C_b^2 H} \tag{3}$$

with C_b the Chezy coefficient which varies with the water depth as

$$C_b = k_s H^{1/6} \tag{4}$$

where k_s is the Strickler coefficient.

The terms X and Y of equations 1a and 1b 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:

$$\begin{aligned} X &= u\frac{\partial U}{\partial x} + v\frac{\partial U}{\partial y} - \frac{1}{\rho}\tau_x^s - A_H(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2}) \\ Y &= u\frac{\partial V}{\partial x} + v\frac{\partial V}{\partial y} - \frac{1}{\rho}\tau_y^s - A_H(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2}) \end{aligned} \tag{5}$$

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

$$\tau_x^s = \rho_a c_D |u^w| u_x^w \qquad \tau_y^s = \rho_a c_D |u^w| u_y^w \tag{6}$$

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 5 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 has the advantages of been unconditionally stable with respect to the gravity waves, the bottom friction and the Coriolis terms and allows the transport variables (U and V) to be solved explicitly without solving a linear system. Compared to a fully implicit solution of the shallow water equations only solving implicitly for the water levels, it reduces the dimensions of the matrix to one third without increasing the computational load.

The terms treated semi-implicitly are the divergence terms in the continuity equation and the Coriolis term and the pressure gradient in the momentum equation. The bottom friction is treated fully implicit, while all other terms are treated explicitly. 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 order: 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, with velocities at the centre of the element and water level at the node, 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).

Baroclinic pressure gradients have not been included in the equations, even if horizontal salinity gradient exists in the Lagoons of Marano and Grado (unpublished data) that give rise to these terms. A simple scale analysis (see Umgiesser et al. (2004) for details) shows that, the barotropic pressure gradients are at list 30 times bigger than the baroclinic ones. Therefore, to a first approximation, the baroclinic pressure gradients may be neglected.

2.2. Transport and diffusion model

To compute the spreading and the fate of the tracer (salinity and temperature), 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:

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = K_h(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2}) + E \tag{7}$$

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

In the case of salinity the source/loss term E in equation 7 represents the difference between evaporation and precipitation through the surface [kg m^{-2} s^{-1}].

2.3. Thermal radiative model

The variation in the water temperature of the Marano and Grado Lagoons was studied using a thermal radiative model (Dejak et al., 1992). The term E in equation 7 represents here the heat source $Q/\rho c_w H$, where ρ is the water density, c_w is the specific heat of water (c_w=3991 J kg^{-1} ^{o}C^{-1}), H is the depth of fluid layer and Q is the heat flux [W m^{-2}] between the atmosphere and the sea, computed by the thermal radiative model as follows:

$$Q = Q_s + Q_b + Q_e + Q_h \tag{8}$$

where each term represents a physical process:

- Q_s is the sun's energy flux through the sea surface (short wave radiation);
- Q_b is the net heat flux between the atmosphere and the sea (long wave radiation);
- Q_e is the heat flux generated by evaporation-condensation processes;
- Q_h is the heat flux generated by conduction-convection processes.

3. The model set-up and simulations

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 300 m in the tidal flats part, to few meters in the inner channels (Fig. 1). The bathymetry of the lagoon, obtained combining several dataset, has been interpolated onto the grid.

The finite element method allows for 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.

The principal hydraulic forcing of the Lagoons of Marano and Grado are the tide and the wind. The lagoon basin is characterised by semi-diurnal tidal fluxes. The predominant wind for the region of interest is the Bora from north-east (Petti and Bosa, 2004).

Small rivers flow into the lagoon, mostly in the western sector (Marano Lagoon), which drain waters coming from the resurgences line. The estimated overall amount of average freshwater discharge is about 70-80 m^3 s^{-1} (Ret, 2006). The average discharge of the tributaries is reported in Table 1.

In this study, no spatial distinction of the bottom friction has been made inside the lagoon, and the Strickler coefficient (k_s) 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 Lagoon (Umgiesser et al., 2004; Ferrarin and Umgiesser, 2005). The drag coefficient for the momentum transfer of wind (c_D) has been set to 2.5 10^{-3}. An uniform diffusion coefficient K_h=0.3 m^2 s^{-1} was assumed. The horizontal turbulent viscosity A_H has been computed using the model proposed by Smagorinsky (1963).

The initial condition is always the calm state. This is certainly no problem for the current velocity and the water level, since these quantities approach a dynamic state very fast (less then a day). Spin up time of 5 days was chosen for the short-term hydrodynamic simulations. For the one year-long simulation, salinity and temperature values measured at the monitoring stations in November 2006 have been chosen as initial condition and 30 days was considered as spin up period.

In order to investigate the water circulation and derive a zonation scheme we have devised different scenarios. Three scenarios have been investigated:

- one-year real forcing simulation to validate the model and describe the seasonal distribution of salinity and water temperature;
- idealized simulations to investigate the effect of different forcing (tide and wind) on the hydrodynamic circulation;
- idealized simulation to delineate the area of influence of the different inlets through the dispersion of passive tracers.

4. Results

4.1. One-year long simulation

A one-year long simulation was carried-out to validate the model against available experimental water level, salinity and water temperature data collected in the lagoons. The year of reference for this simulation was 2007, when both real forcing data and validation data were available. The choice of the year of reference is not crucial, from the hydrodynamic point of view, since the water transport time scale (the theoretical time necessary to replace the complete volume of the lagoon with new water coming from the sea and from the rivers) of the Lagoons of Marano and Grado is of the order of one or two days. In addition the rivers, which drain waters coming from the resurgences line, do not exhibit a significant seasonal variability.

The simulation was forced by observed values of wind measured hourly at the three locations marked with stars in Fig. 1. Open boundaries are treated by defining hourly observed water levels (marked with circles LI, GR and PR in Fig. 1) and monthly salinity and water temperature (marked with triangles 30, 44, 83, 95, 104 and 113 in Fig. 1) at the inlets and defining the fluxes of fresh water from the major tributaries. Continuous daily river discharge time series have been obtained from water level measurements (kindly provided by Unità Operativa Idrografica di Udine) through calibrated relationships.

4.1.1. Water level

Water level is hourly measured at Marano Lagunare and Grado Belvedere gauge stations (marked with circles ML and GB in Fig. 1). As showed in Fig. 2, the model reproduces the tidal wave propagation inside the lagoon and the wind set-up. Model results show a satisfactory agreement with the measured water level with a correlation coefficient close to 1 in all the stations and average root mean square error (RMSE) of about 4 cm.

4.1.2. Salinity and water temperature

Water temperature and salinity is measured monthly at 15 stations inside the lagoons (marked with triangles in Fig. 1). The observations were made always during flood tide, to allow sampling in the shallow tidal flats.

The model catches the temporal and spatial variability of the salinity data collected during field observations (Fig. 3) and reproduces well the fluxes between the lagoon and the sea. The statistical results for the salinity for all 15 monitoring stations is summarized in Table 2. The root mean square error (RMSE) for the simulated period ranges between 1.8 to 7.3 and the average BIAS, computed as the difference between mean of the observations and simulations, amounts to 1.4. The average scatter index (SI), equal to the ratio of the RMSE and the averaged value of the observations, amounts to 0.18, and the average correlation coefficient amounts to 0.5.

The tide modulates the river discharges creating a daily salinity excursion of more than 10 in the western part of the lagoon and in the areas close to the mouths of the Ausa-Corno and Natissa rivers. This can be seen both in Fig. 3, where the daily excursion is represented by the gray band.

Comparing the computed data with the measured data (Fig. 4) we found that the model describes well the seasonal cycle of the Marano and Grado Lagoons water temperature, which varies from about 5 ^{o}C, or less, in January to more than 30 ^{o}C in July. The accuracy of the model is measured by the statistical properties reported in Table 2. The statistical results for the water temperature show that the average root mean square error (RMSE) is 2.2 ^{o}C and the average BIAS amounts to -0.6 ^{o}C. The correlation coefficient is close to 1 for all monitoring stations and the average scatter index (SI) amounts to 0.14.

The simulated water temperature does not show a significant spatial variability within the lagoons. The rivers do not have a significant influence on the water temperature pattern, apart from a small area near their mouths. The water temperature in the Stella mouth varies between 10 and 20 ^{o}C during the year.

4.2. General circulation features

Once the model was validated, it was used 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 regime considered was chosen to be constant in time and space, with typical wind speeds of 10 m s^{-1} (Petti and Bosa, 2004). An average water discharge values have been imposed for the rivers in all simulations.

4.2.1. Tide induced circulation

In the first case only the tidal forcing is considered and no wind is prescribed. The tide has been imposed at the beginning of the main inlets (see Fig. 1). The results are evaluated after the spin-up period.

The water circulation during flood and ebb tide is shown in figures 5a and 5b. The propagation of the tidal wave is mainly sustained by the major channels and then extends to the shallow water areas. The tide propagates along the major channels with a velocity of about 40-60 cm s^1 and then enters in the shallow areas where the velocity quickly decreases to below 10 cm s^{-1}.

The tidally-induced flow generates a total average water exchange rate through all lagoon inlets on the order of 5000 m^3 s^{-1}. Hydrodynamic model results reveal that the Lignano, Buso and Grado inlets are the most important in terms of water fluxes, with respectively about 35, 30 and 22 % of the total water discharge between the lagoon and the sea (Table 3). In case of tidal forcing only, the proportion of the fluxes through the inlets remains basically unchanged during both ebb and flood phase.

The rivers do not strongly influence the circulation, apart from the area near their inlets.

4.2.2. Tide and wind induced circulation

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 10 m s^{-1}. Due to the shallow character of the lagoon, the current velocity induced by the wind and the tide is vigorous all over the basin.

To separate the oscillatory tide motion from the effect of the wind forcing the circulation in the lagoon, the residual currents have been investigated. If one looks at the current average over a longer period (2 weeks), the tidal current averages out. What is left are the so-called residual currents (Umgiesser, 2000). These residual currents show the effect of the wind and tides as non-linear and topographic induced effects. They are important because they give the net effect of water movement during the study period and they determine the predominant spreading of a dissolved or particulate substance inside the lagoon.

Due to its direction and intensity, this wind is able to increase the circulation both in the western and in the eastern areas (Fig. 6). The hydrodynamic pattern is completely wind dominated, and therefore, the tidal variability plays a minor role. The Bora wind driving the water to the west creates a current in the western Marano basin, which favours the inflow of water from the Buso inlet and the outflow from the S.Andrea and Lignano inlets.

The effect of the wind action over the lagoon circulation is confirmed by the analysis of the water fluxes through the inlets (Table 3). Contrary to what happens in the case of tidal forcing only, a strong asymmetry in the inlet water discharges between flood and ebb phase is present when NE wind is blowing.

5. Discussion and conclusion

In this application the hydraulic regime-based zonation scheme of the Marano and Grado Lagoon system is derived by combining the results gained with the application of the calibrated model framework.

Following Kjerve (1986) the Lagoons of Marano and Grado could be classified as a leaky lagoon with strong tidal influence. Such type of lagoon can be subdivided into more than one basin separated by the watersheds. In these areas the converging flows show little hydrodynamic activity, but allow some exchange of water between neighbouring basins (Umgiesser, 1997). Watersheds are zones subjected to more or less pronounced spatial shifts, where there is a marginal superimposition between adjacent basins; in this sense, coastal lagoons with more than one inlet can be considered as systems of lagoons rather than single lagoons (Tagliapietra and Volpi Ghirardini, 2006).

To delineate the area of influence of the different inlets an additional simulation has been performed following the method proposed by Solidoro et al. (2004) has been adopted. Six different numerical tracers have been released at the six inlets, and their dispersion under idealized (tide oscillation of 0.5 m with a period of 12 hours) conditions, up to the steady state distribution, has been simulated. Each tracer was set at its own release point to a predefined common concentration value. As shown in Fig. 7, each point of the lagoon was then assigned to a specific inlet, depending upon which of the six tracers was at steady state condition present in the highest concentration, and upon where such tracer was released. According the distribution of passive tracers released at the sea boundaries and considering only the three main inlets (see section 4.2), the lagoon, at a first glance, can be divided into three subbasins. The western subbasin is mainly driven by the Lignano inlet, the central one refers to the Buso inlet, and the eastern one which is mainly influenced by the Grado inlet.

The second step was to discriminate areas in which the influence of the riverine input is more important than the influence of the exchanges with the sea through the inlets, from areas where the opposite is true. To achieve this goal, the annual (2007) average salinity (Fig. 8a) and the average daily standard deviation of the salinity (Fig. 8b) have been computed. The one-year simulation result shows that there is a clear west-east salinity gradient in the lagoon (Fig. 8a). The average salinity values are lower (∼20) in the western part of the lagoon, due to the fresh water discharged by the Stella, Turgnano and Cormor rivers, and higher in the eastern region (∼34), which is mostly influenced by marine waters.

An interesting feature is the presence of a narrow band (1-2 km width) in which, according to the Venice System for the classification of marine waters (Venice System, 1958), the environment rapidly varies from mesohaline to euhaline. The 24 salinity isoline, which has been first proposed as boundary value by Bulger et al. (1993) to delineate a biologically-based estuarine salinity zonation, has been chosen as boundary between different subbasins. In the case of the Marano and Grado Lagoons, this value is in correspondence to a daily salinity standard deviation higher than 10 (Fig. 8b). This analysis suggested a further subdivision of the Lignano and Buso subbasins into two marine and brackish areas.

The eastern part of the lagoons system, which is mainly influenced by the Grado inlet, could be considered physically divided by the bridge connecting the main land to the city of Grado into two subbasins, GRA-1 and GRA-2.

The final hydraulic regime-based zonation scheme, consisting of six areas, is presented in Fig. 9 and the physical characteristics of them are reported in Table 4. This zonation scheme represents a situation averaged over the different seasons and the boundary between the subbasin should not be regarded as a sharp delimiters.

The western subbasins, LIG-1 and LIG-2, refer both to the Lignano inlet, but the LIG-1 receives the fresh water from the Stella, Turgnano and Cormor rivers. The LIG-1 subbasin is the shallowest one with an average depth of 0.66 m and, having an average salinity of 15.3, could be classified, according to Venice System (1958), as mesohaline. The LIG-2 sector has an average depth of 1.15 m and an average salinity of 31. The central area, which refers to the Buso inlet, has been divided into two areas, BUS-1 and BUS-2. We observe that the BUS-1 is the largest one and has an average depth and salinity of respectively 1.1 m and 33.7. The BUS-2 area has polyhaline characteristics receiving fresh water from the Corno, Ausa and Zellina rivers. The GRA-1 area receives also the marine water that enters from the Morgo inlet, while the GRA-2 is also driven by the Primero inlet. The lower salinity of the GRA-2 zone (33.3) with respect to the GRA-1 one (34.4) could be attributed to fresh water of the Isonzo river entering through the Primero inlet. It has to be noted that, except from the LIG-1 and BUS-2 areas, the rest of the lagoon, having average salinity higher than 30, could be classified as euhaline.

Results from the thermal radiative model show that the water temperature is homogeneous over the whole lagoon through all the year, due to the low thermal inertia of the lagoon.

The zonation here presented has not only taken into account the average values of temperature and salinity, but also its variability. This variability is in certain areas due to the interaction of the tide and the river inflow, and cannot be found in the data (which is collected every month), but only through the application of the model. These areas of strong parameter variations can be reliably identified by the model, which should be therefore seen as a compliment to measurements, if continuous monitoring cannot be afforded. Salinity can vary from 5 to 35, and this puts a constraint, together with the degree of confinement, on the biota living in these areas. It is natural to expect that in these areas only well adapted plants and animals can survive and biodiversity is reduced (Tagliapietra et al., 2009). A zonation taking into account these factors will more likely be successful in identifying areas of different typologies and distinguish areas of differing characteristics. A more detailed hydrobiological study will be the subject of future publications.

Acknowledgements

This research was funded by ARPA FVG. The authors wish to thank Dott. Rossin Pietro for providing bathymetry, tide, meteorology and validation data and the Unità Operativa Idrografica di Udine, Servizio Idrografico Ragionale, for providing water level and water discharge of the main rivers flowing into the lagoons. The authors thank Dr. Davide Tagliapietra, Dr. Marco Sigovini and Dr. Michol Ghezzo for the precious suggestions provided during this work.

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List of Tables

List of Figures

Table 1:

Name	Mean discharge [m^3 s^{-1}]
Stella	35.4
Turgnano	0.5
Cormor	9.3
Zellina	1.1
Corno	4.6
Ausa	10.0
Natissa+Terzo	10.3
Isonzato	0.5
TOTAL	71.7

Table 2:

	Salinity				*Water temperature [$^o C$]*			
Station	RMSE	BIAS	SI	R^2	RMSE	BIAS	SI	R^2
5 - Stella mouth	0.0	0.0	0.00	1.00	0.2	0.1	0.02	0.99
10 - Acque	6.3	3.4	0.24	0.62	1.5	-0.1	0.10	0.98
15 - Lustri	7.3	4.1	0.24	0.32	1.4	0.1	0.08	0.97
19 - Zona Tapo	5.6	3.5	0.17	0.71	1.2	-0.7	0.07	0.99
20 - Cormor mouth	7.2	-0.4	0.40	0.64	3.3	0.4	0.22	0.96
25 - Ex scarico M.	8.8	1.7	0.36	0.22	3.4	-0.7	0.22	0.98
31 - Ciuciai de sotto	6.2	3.4	0.19	0.51	1.3	-0.7	0.08	0.98
38 - Ciuciai de sora	6.2	3.9	0.21	0.20	2.8	0.4	0.17	0.97
56 - Ficariol	4.2	0.8	0.15	0.37	2.0	0.6	0.12	0.98
64 - Aussa/Corno	4.9	2.3	0.15	0.50	2.3	-0.5	0.14	0.98
85 - Anfora vecchia	1.8	-0.7	0.05	0.59	1.7	-1.2	0.11	0.99
98 - Isola Montarion	4.6	2.1	0.14	0.33	4.1	-2.5	0.27	0.98
102 - Natissa mouth	4.3	-1.4	0.23	0.53	4.4	-2.3	0.29	0.97
108 - Valle del Moro	2.9	-0.5	0.08	0.37	2.4	-1.5	0.15	0.97
111 - Can. Barbana	2.6	1.5	0.08	0.71	1.2	-0.8	0.07	0.99
Average	4.8	1.4	0.18	0.50	2.2	-0.6	0.14	0.98

Table 3:

	Tide only		*Tide and NE wind*	
Inlet	Flood	Ebb	Flood	Ebb
Lignano	34.5	34.7	28.3	40.5
S.Andrea	7.2	7.5	5.9	10.3
Buso	30.7	30.3	38.3	23.3
Morgo	1.6	1.7	1.1	2.0
Grado	22.6	22.3	21.5	22.2
Primero	3.4	3.5	4.9	1.7

Table 4:

Sub-basin	Area $[\mathrm{m}^2\times10^6]$	Depth [m]	Volume $[\mathrm{m}^3\times10^6]$	Av. Salinity	Av. Water Temp. ^{o}C
LIG-1	2.73	0.66	1.85	15.3	15.3
LIG-2	2.65	1.15	3.18	31.0	16.0
BUS-1	3.29	1.10	3.55	33.7	16.0
BUS-2	0.34	0.68	0.23	23.2	15.8
GRA-1	2.91	0.72	1.94	34.4	15.6
GRA-2	1.51	0.74	1.10	33.3	16.0

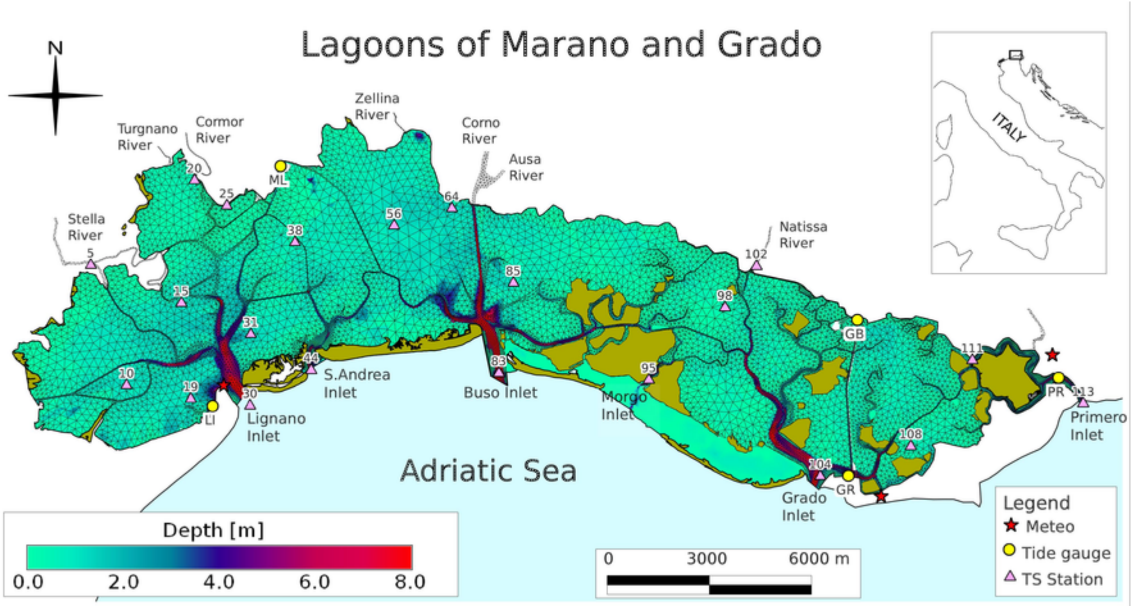

Lagoons of Marano and Grado
N
Turgnano River
Cormor River
Zellina River
Corno River
Ausa River
Stella River
Natissa River
ITALY
5
10
15
19
20
25
30
31
38
44
56
64
83
85
95
98
102
104
108
111
113
ML
LI
GB
GR
PR
S.Andrea Inlet
Lignano Inlet
Buso Inlet
Morgo Inlet
Grado Inlet
Primero Inlet
Adriatic Sea
Depth [m]
0.0
2.0
4.0
6.0
8.0
0
3000
6000 m
Legend
Meteo
Tide gauge
TS Station

Figure 1:

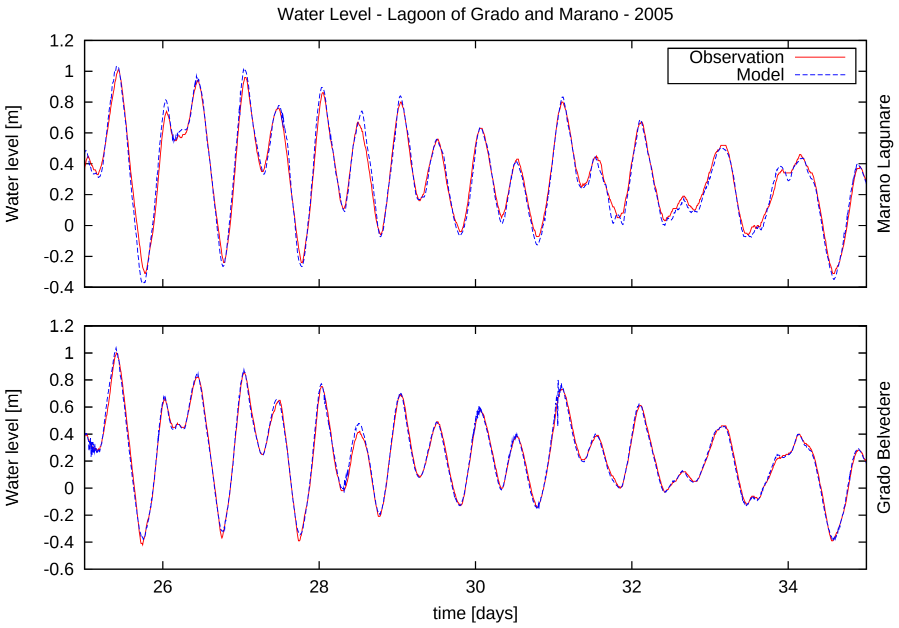

Water Level - Lagoon of Grado and Marano - 2005
Observation
Model
Water level [m]
Marano Lagunare
Grado Belvedere
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
26
28
30
32
34
time [days]

Figure 2:

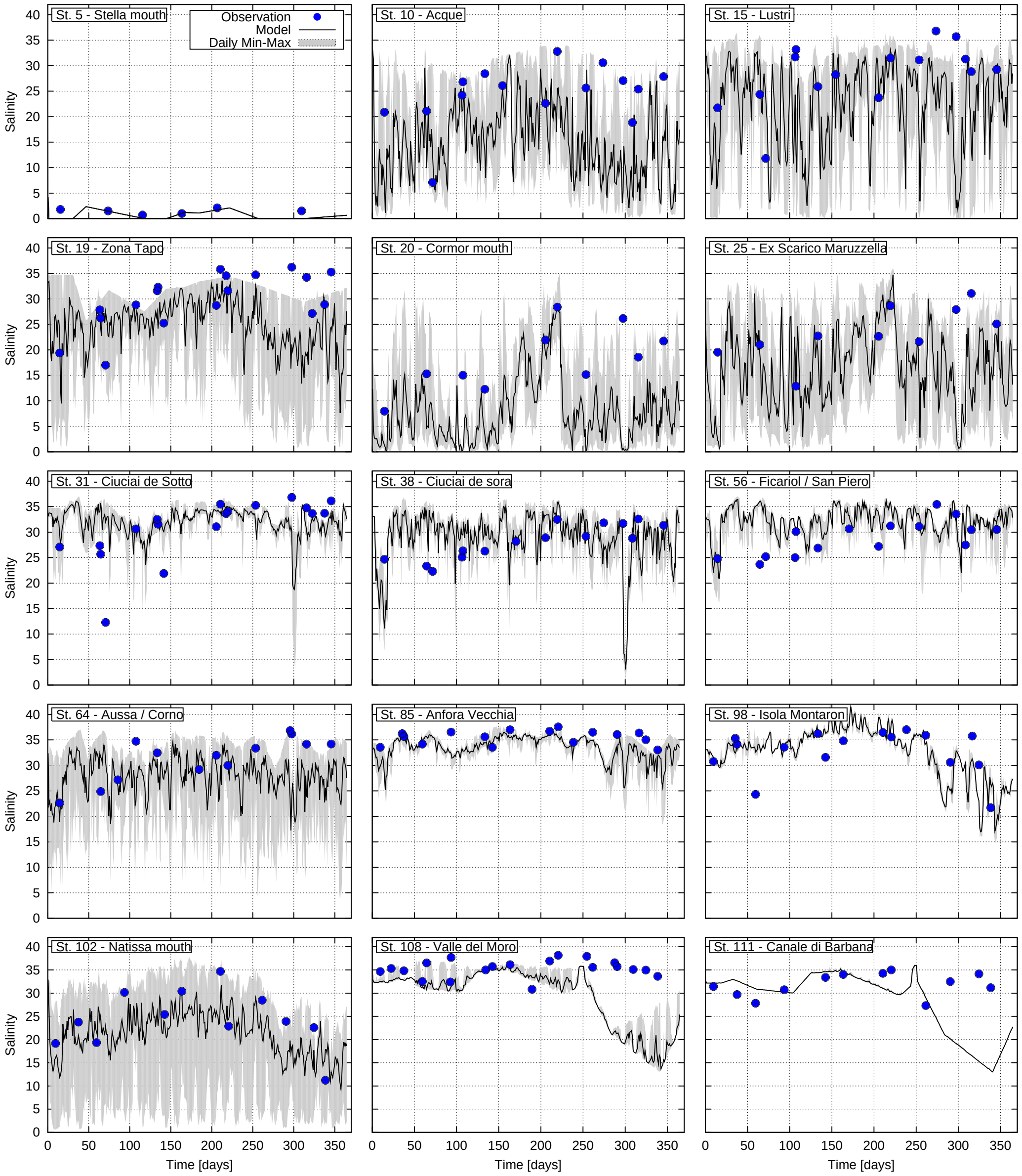
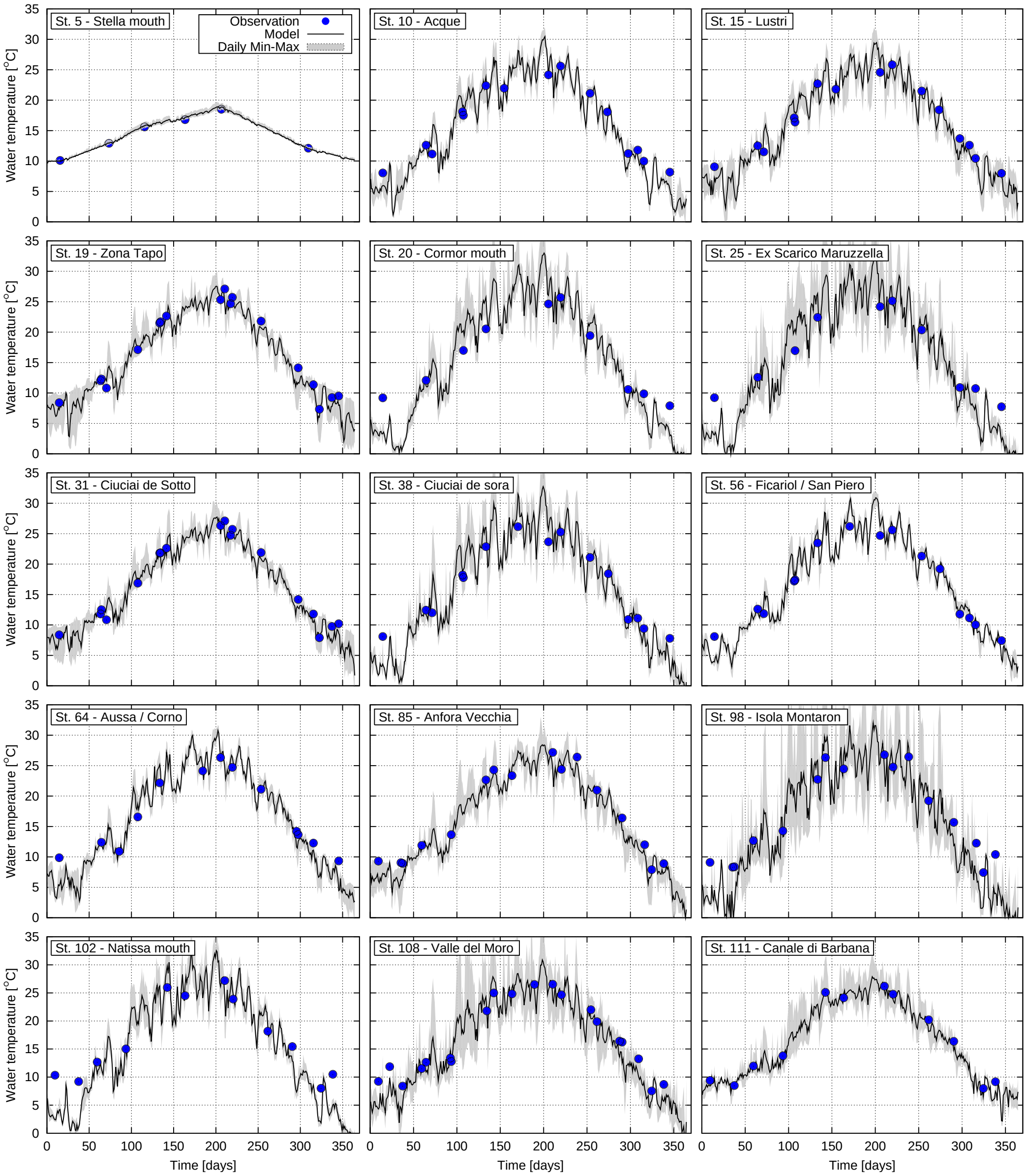

St. 5 - Stella mouth
Observation
Model
Daily Min-Max
St. 10 - Acque
St. 15 - Lustri
St. 19 - Zona Tapo
St. 20 - Cormor mouth
St. 25 - Ex Scarico Maruzzella
St. 31 - Ciuciai de Sotto
St. 38 - Ciuciai de sora
St. 56 - Ficariol / San Piero
St. 64 - Aussa / Corno
St. 85 - Anfora Vecchia
St. 98 - Isola Montaron
St. 102 - Natissa mouth
St. 108 - Valle del Moro
St. 111 - Canale di Barbana
Salinity
0
5
10
15
20
25
30
35
40
Time [days]
0
50
100
150
200
250
300
350

Figure 3:



St. 5 - Stella mouth
Observation
Model
Daily Min-Max
St. 10 - Acque
St. 15 - Lustri
St. 19 - Zona Tapo
St. 20 - Cormor mouth
St. 25 - Ex Scarico Maruzzella
St. 31 - Ciuciai de Sotto
St. 38 - Ciuciai de sora
St. 56 - Ficariol / San Piero
St. 64 - Aussa / Corno
St. 85 - Anfora Vecchia
St. 98 - Isola Montaron
St. 102 - Natissa mouth
St. 108 - Valle del Moro
St. 111 - Canale di Barbana
Water temperature [°C]
0
5
10
15
20
25
30
35
0
50
100
150
200
250
300
350
Time [days]

Figure 4:

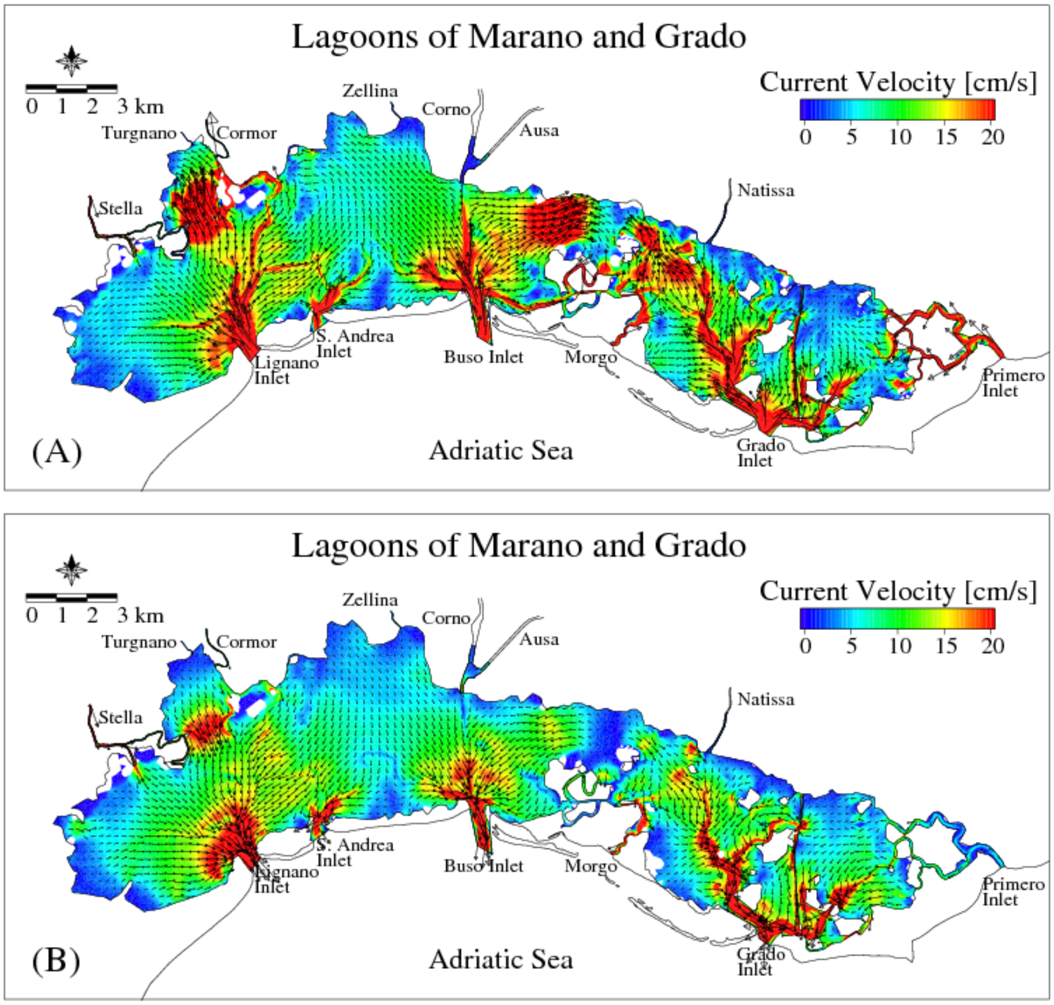

Lagoons of Marano and Grado
0 1 2 3 km
Current Velocity [cm/s]
0 5 10 15 20
Zellina
Corno
Ausa
Turgnano
Cormor
Stella
Natissa
S. Andrea Inlet
Lignano Inlet
Buso Inlet
Morgo
Primero Inlet
Grado Inlet
Adriatic Sea
(A)
Lagoons of Marano and Grado
0 1 2 3 km
Current Velocity [cm/s]
0 5 10 15 20
Zellina
Corno
Ausa
Turgnano
Cormor
Stella
Natissa
S. Andrea Inlet
Lignano Inlet
Buso Inlet
Morgo
Primero Inlet
Grado Inlet
Adriatic Sea
(B)

Figure 5:

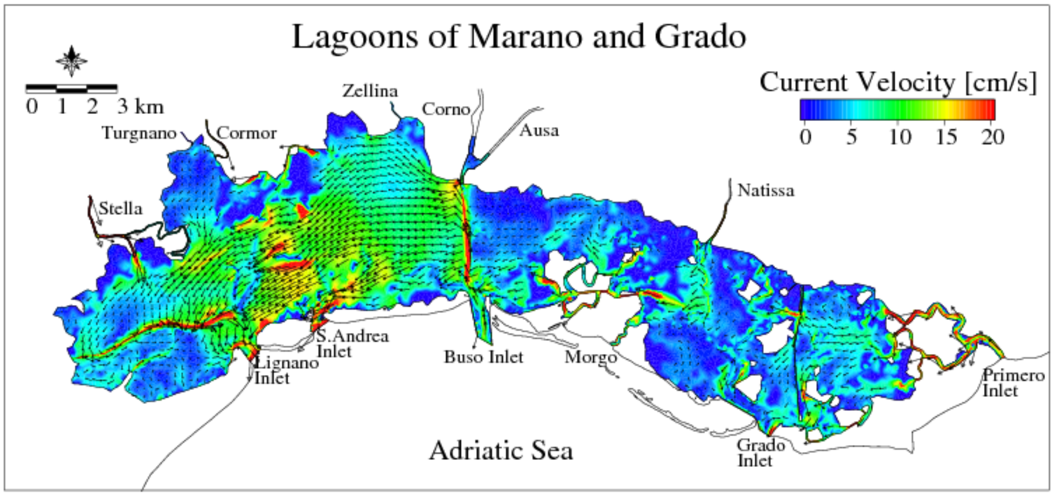


Figure 6:

Figure 7:

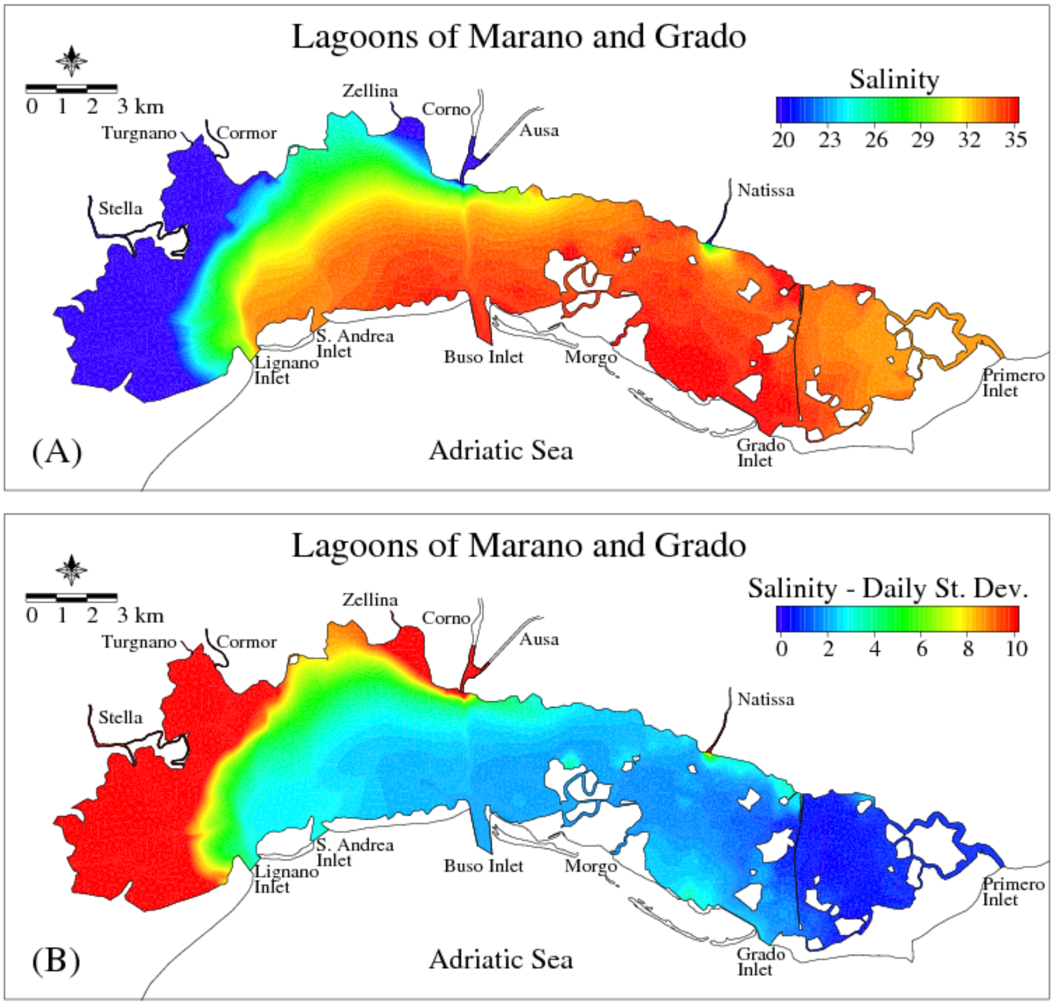

Lagoons of Marano and Grado
0 1 2 3 km
Salinity
20 23 26 29 32 35
Zellina
Corno
Ausa
Turgnano
Cormor
Stella
Natissa
S. Andrea Inlet
Lignano Inlet
Buso Inlet
Morgo
Primero Inlet
Grado Inlet
(A)
Adriatic Sea
Lagoons of Marano and Grado
0 1 2 3 km
Salinity - Daily St. Dev.
0 2 4 6 8 10
Zellina
Corno
Ausa
Turgnano
Cormor
Stella
Natissa
S. Andrea Inlet
Lignano Inlet
Buso Inlet
Morgo
Primero Inlet
Grado Inlet
(B)
Adriatic Sea

Figure 8:


Lagoons of Marano and Grado
N
Zellina River
Turgnano River
Cormor River
Corno River
Ausa River
BUS-2
Stella River
Natissa River
LIG-2
BUS-1
LIG-1
GRA-1
GRA-2
S.Andrea Inlet
Buso Inlet
Morgo Inlet
Lignano Inlet
Primero Inlet
Grado Inlet
Adriatic Sea
0
3000
6000 m

Figure 9: