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Recent Developments

Modeling the inter-annual variability of salinity in the lagoon of Venice in relation to the water framework directive typologies

Michol Ghezzo [a,*], Alessandro Sarretta [b], Marco Sigovini [a], Stefano Guerzoni [a], Davide Tagliapietra [a], Georg Umgiesser [a,c]

[a] *Institute of Marine Science – National Research Council, (ISMAR-CNR), Arsenale - Tesa 104, Castello 2737/F, 30122 Venice, Italy*
[b] *Joint Research Centre JRC, via Enrico Fermi, 2749 – 21027 Ispra (VA), Italy*
[c] *Coastal Research and Planning Institute, CORPI, Klaipeda University, H. Manto 84,92294 Klaipeda, Lithuania*

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ABSTRACT

The Water Framework Directive (2000/60/EC) requires member states to classify and enhance the ecological quality of water bodies in accordance with their type. To estimate the effect on type of the natural variability of lagoons, we applied a two-dimensional hydrodynamic model to the lagoon of Venice. The model calculated the mean annual spatial distributions of two variables: salinity and residence time. The standard deviation of salinity was also included, in order to estimate the variation of salinity values around the mean, which is associated with the instability of the mean salinity value.

A highly detailed numerical grid was calibrated and high-frequency tributary discharge data were used.

The simulations, under realistic forcing conditions, are based on the years 2003 and 2005. The former was characterized by low precipitation, around 30% less than the typical value.

A comparison of model results and measurements shows the high reliability of the model in reproducing the spatial distribution and temporal evolution of salinity.

We found strong inter-annual variation in salinity, standard deviation of salinity and residence time. The effect on the typing process is that the most representative types shift from one category to another.

On the basis of the spatial patterns of the variables and their superposition, we identified types that described the bulk of the lagoon.

This numerical tool offers support for lagoon management on various levels, in terms of both WFD requirements and other applications, by: (1) providing unbiased and objective zoning indications for the basin; (2) evaluating the response of water quality elements; (3) establishing the reference status of a water body; and (4) establishing a hierarchical division of a lagoon that can be used to select an appropriate number of sampling stations for monitoring.

1. Introduction

Coastal transitional ecosystems are defined by Tagliapietra et al. (2009) as “coastal water bodies with limited seawater supply”. Alternatively, if we follow the definition proposed by the Water Framework Directive, transitional waters can be identified as “bodies of surface water in the vicinity of river mouths which are partly saline in character as a result of their proximity to coastal waters but which are substantially influenced by freshwater flows” ((European Community, 2000), art. 2(6)). Depending on freshwater influence, coastal lagoons are assigned by the Directive to either “transitional waters” or “coastal waters” (Tagliapietra and Volpi Ghirardini, 2006). Both definitions recognize the importance of salinity and implicitly admit the presence of spatial variation of salinity in the water bodies.

Transitional environments, especially lagoons, are characterised by strong spatial heterogeneity, extreme values and broad fluctuations of several environmental variables (Rosselli et al., 2009). Chemico-physical processes determine gradients and patchiness (Attrill, 2002) for each variable, which in turn leads to patchy or gradient-based distribution of biological components (Levin et al., 2001; McLusky and Elliott, 2004; Pèrez-Ruzafa et al., 2010).

* Corresponding author. Tel.: +39 041 2404758; fax: +39 041 5204126.
E-mail addresses: michol.ghezzo@ve.ismar.cnr.it (M. Ghezzo), alessandro.sarretta@ismar.cnr.it (A. Sarretta), marco.sigovini@ve.ismar.cnr.it (M. Sigovini), stefano.guerzoni@ve.ismar.cnr.it (S. Guerzoni), davide.tagliapietra@ismar.cnr.it (D. Tagliapietra), georg.umgiesser@ismar.cnr.it (G. Umgiesser).

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The identification of environmental gradients and their interaction with the biota in transitional ecosystems is key to the development of a framework for the assessment of environmental quality. The Water Framework Directive itself (henceforth, WFD) states that chemico-physical and hydro-morphological elements, together with biological communities, should be considered when assessing the ecological status of water bodies ((European Parliament, 2000), Annex II). However, the biological community responds more strongly to some of these parameters than others. Salinity and residence time, the latter a measure of seawater renewal or confinement, are recognized as the main factors and as proxies of the overall gradient (McLusky and Elliott, 2004; Franco et al., 2008; Pèrez-Ruzafa et al., 2007).

The spatial biological variation recognized in all lagoons (particularly in micro-mesotidal lagoons, Barnes (1994), with substitution of species along environmental gradients, was related to seawater renewal by Guèlorge and Perthuisot (1983). They defined the main factor controlling the distribution of organisms and the features of populations as "the time of renewal of the elements of marine origin at any given point". They called it "confinement" since it is strictly related to the degree of separation (seclusion) from the sea and the distance from seaward inlets. Since a widely accepted mathematical definition of confinement is still lacking, hydrodynamic parameters such as residence time could be used as a proxy.

The literature on the effect of salinity variation on the biota is extensive. At the community level, a model of benthic invertebrate species richness along a marine-freshwater salinity gradient, based on studies performed on the Baltic Sea and associated systems, was initially proposed by Remane (1934), who described the overall reduction in the number of species in the presence of progressively decreasing salinity levels. Various authors have discussed different aspects of the model, and proposed modifications (Barnes, 1989; Hedgpeth, 1967; Odum, 1988). De Jonge (1974) underlines the need to correlate organism distribution with average salinity and its fluctuation, and to consider not only the number of species but also the composition of the fauna. Telesh and Khlebovich (2010) discussed the concept of "critical salinity" as a physiological and evolutionary barrier for marine and freshwater fauna. Several studies have identified salinity as one of the most influential environmental variables for the composition and abundance of invertebrate communities in transitional waters (Williams, 1998, 2001; Pinder et al., 2005; Piscart et al., 2005). Salinity is also a major factor in the distribution of individuals and species among fish (Maci and Basset, 2009; Marshall and Elliott, 1998) and submerged aquatic vegetation (Howard and Mendelssohn, 1999; Biber and Irlandi, 2006; Lirman et al., 2008).

Assuming salinity and residence time as the main proxies of the "composite gradient" in transitional waters, the effect on organisms of their spatial and temporal variability is remarkable. The spatial and temporal variability of salinity in transitional waters depends on freshwater inputs, precipitation and evaporation rates, exchange with the sea and hydrodynamic transport. The spatial and temporal variability of hydrodynamic transport (residence time or renewal time) depends on freshwater inputs, precipitation and winds, and exchange with the sea, a key role being played by the morphology of the basin, which in turn is modified by the hydrodynamics.

Organisms of transitional ecosystems react in similar ways to pollution, salinity change (Wilson, 1994), and more generally to the extreme and variable conditions of transitional environments, making it difficult to separate responses to anthropogenic stress from responses to natural variation. Transitional ecosystems can be viewed as naturally stressed environments, particularly if compared to marine conditions (Elliott and McLusky, 2002; McLusky and Elliott, 2007). The term "Estuarine Quality Paradox" has been introduced by Dauvin et al. (2007) and by Elliott and Quintino (2007) to refer to this concept. In transitional environments, where natural and anthropogenic stresses are often associated, one way to approach the problem is to quantify the natural variability and the resulting stress and then subtract this from the anthropogenic stress.

The classification of transitional waters on the basis of salinity is an open question. The Remane model (Remane, 1934) and subsequent studies of the role of salinity gradients in structuring benthic communities form the basis of the "Venice system" (Venice System, 1959; Segerstraale, 1959). Given the complexity of the relationship between community structure and salinity, some authors have proposed overlapping limits between classes in their classification systems (Greenwood, 2007; Bulger et al., 1993; Wolf et al., 2009). Attrill (2002) preferred salinity range to absolute salinity values, as variation in salinity (and in environmental factors generally) may be more important in structuring communities than extreme values. He also explicitly used salinity range as a proxy for a set of variable conditions.

A well-known classification of lagoons according to water exchange with the sea was developed by Kjerfve and Magill (1989), who considers leaky, restricted and choked lagoons with gradually decreasing seawater exchange and thus increasing seawater renewal time.

The difficulty of constructing a single classification system valid for all transitional environments lies in the heterogeneity within and among these systems and in their high temporal variability. The complex response by the community to variation in environmental factors further complicates the establishment of a common system of classification.

European Directive 2000/60/EC establishes a framework for water policy and includes strategies to safeguard the ecological and chemical status of water resources. To achieve these aims it requires the characterisation of water bodies by the identification of "types" at appropriate spatial scales (European Commission, 2003).

The classification of water bodies in terms of quality, which takes account of abiotic and biotic elements, environmental pressures and resulting impacts, is based on these types.

This entails identifying areas with well-defined physical characteristics and serves to ensure common reference conditions. A water body thus classified as belonging to a specific type is considered homogeneous and represents the unit that will be used for assessing compliance with the Directive's environmental objectives.

The WFD describes two systems for specifying types in transitional waters. System B, which is the most common, makes reference to obligatory descriptors (Latitude, Longitude, tidal amplitude and salinity) and to optional descriptors, of which residence time is one.

However a complete typology for transitional waters has not yet been defined (Hering et al., 2010). The Common Implementation Strategy (CIS) working groups are seeking to develop commonly agreed typologies at the European level. Other European groups are working on the issue of intercalibration between member states (Vincent et al., 2003; Hering et al., 2010).

Although the implementation guidance of the Directive recognises the natural temporal variability of biological quality elements (European Commission (2003), Section 4.2 and 4.7), little is said about temporal variations in the abiotic parameters on which the typologies are based. In this regard it is merely suggested that the characteristics of a water body should be determined by considering mean annual values (European Commission (2003), Section 3.2.3) without reference to the length of the timeseries. As a consequence, different temporal scales could be considered.

Numerical models can be used to simulate the hydrodynamic and transport process in a basin, and can also represent the spatial and temporal variability of salinity and evaluate hydrodynamic transport scales in several points of the basin.

The WFD does not refer to the use of numerical models. It explicitly mentions modelling as a suitable method only to extrapolate reference conditions ((European Parliament, 2000), Annex II art. 1.3) when a reference site is not available. Hojberg et al. (2007) points out that monitoring and modelling are inter-dependent (Holt et al., 2000; Parr et al., 2003; Irvine, 2004; Moschella et al., 2005; Dabrowski and Berry, 2009), but when implementing the monitoring obligations of the WFD, models are rarely used in practice. It is important to note that the acceptable level of monitoring precision and confidence in the WFD is not well described. Rather, it is a subjective issue that depends on socio-economic interests and the risk strategy of the decision-makers. Hattermann and Kundzewicz (2010) analyzes how numerical models could be used at various stages in the application of the WFD.

While the WFD treats the use of numerical models only marginally, the literature contains extensive references to their application to the study of several aspects of lagoon dynamics and lagoon management. Numerical models can be used to calculate hydrodynamic transport in transitional environments on the scale of the whole basin and to calculate its spatial variability within basins (Wang et al., 2004; Cucco et al., 2006, 2009; Gourgue et al., 2007; Jouon et al., 2006). The results can be used to distinguish the circulation in different parts of the basin, to identify areas that are at higher risk of accumulating substances (Cucco and Umgiesser, 2006; Luick et al., 2007; Wang, 2009; Rapaglia et al., 2010) and to determine the main forcing factors and/or processes conditioning residence time itself (Tartinville et al., 1997; Wijeratne and Rydberg, 2007; Plus et al., 2009; Malhadas et al., 2010; Huang et al., 2010; Cavalcante et al., 2011) Salinity can also be successfully simulated in transitional waters (Solidoro et al., 2004a; Huang, 2007; Huang et al., 2002) and numerical models can be used to study the spatial and temporal variability of coastal lagoons (Obrador et al., 2008; Lopes et al., 2010; Faure et al., 2010). In addition, numerical models have been used to advance proposals for the zoning of shallow basins (Ferrarin et al., 2008, 2010), and to evaluate the consequences of different management strategies (Tsihrintzis et al., 2007; Gong et al., 2008; Hakanson and Duarte, 2008). The adoption as normal practice of the calibration and validation of every module of the model, together with the modelling quality assurance procedures, allows the associated error to be accurately estimated and ensures the reliability of numerical models.

We use a hydrodynamic numerical model to simulate the circulation of water masses and the dispersion of a passive tracer, in order to develop an objective, transparent, and cheap method for typing lagoons, classified as transitional waters by the WFD. This method can be applied to different years to explore the inter-annual variability of the descriptors and its effect on the typing process. It may represent a first step in the evaluation of natural variability and could be adapted to identify the natural stresses on organisms in future studies. Finally, the results do not purport to offer a conclusive solution to the typing of lagoons, but they can be employed to suggest management approaches for the lagoon of Venice.

The present study takes account of a limited number of variables, in agreement with the Directive's suggestions (European Commission (2003), Section 3). Working within the System B framework, we considered annual mean salinity (an obligatory factor) and mean residence time (an optional factor). Following Tagliapietra and Volpi Ghirardini (2006), our approach to the typing process takes account only of abiotic parameters. The final resolution of the Symposium of the Venice System (Venice System, 1959), which established a classification system for Marine Waters based on salinity, recommended the use of additional details in addition to the average values, including the salinity range over different timescales. The words “poikilohalinity” and “homoiohalinity” indicate unstable (variable) and stable (constant) salinity respectively; other studies have proposed several statistical measurements of the variability of salinity (De Jonge, 1974). From these considerations, we decided to introduce a new factor: the annual standard deviation of salinity, in order to take account of the variability around the mean value.

The following sections illustrate the criteria used to select the sites, factors and methods, and then the results obtained. Section 2 sets out the reasons for choosing the Lagoon of Venice as a case study, describes the lagoon's main characteristics and justifies the three descriptors adopted in the present study. Section 3 presents a short overview of the methods employed in identifying water body types, explains the advantages of using a numerical model combined with datasets to perform the typing process and describes in detail the method adopted. Section 4 illustrates the results obtained and Section 5 presents our conclusions and considerations on water body management.

2. Selection and description of the case study

The Lagoon of Venice is a complex system, characterized by a number of gradients and a mosaic of environments and morphologies that are the result of complex environmental and anthropic drivers. It is one of the biggest in the Mediterranean and the biggest in Italy. This unique natural environment, of high ecological value, is subject to a difficult coexistence with human activities, such as industry, tourism, fisheries and pressures from the drainage basin. An appropriate management system is thus fundamental. Several studies, including monitoring activities and previous applications of numerical models, provide sufficient expertise to apply a numerical model and a sufficiently broad dataset to calibrate it and validate it.

The Venice lagoon is located in the northwest Adriatic Sea (45° 24′ 47” N, 12° 17′ 50” E), it has a surface area of about 550 km^2, with a north-south length of 50 km and a mean horizontal width of 15 km. Approximately 436 km^2 are subject to tidal excursion, while the remainder has been closed off to create fish-farms with limited and artificially regulated water exchange (Guerzoni and Tagliapietra, 2006). Three inlets on the western side of the lagoon allow water exchange with the sea. From north to south, these are named Lido, Malamocco and Chioggia (mean depth 14, 17 and 8 m respectively) and are shown in Fig. 1. The bathymetry of the lagoon is variable, since it includes navigable channels, subtidal flats and intertidal features such as salt-marshes. The latter are alternately submerged and exposed for varying periods of time with a frequency that depends on tidal cycles. In terms of depth distribution 5% of the lagoon is deeper than 5 m and 75% is less than 2 m. The mean depth is 1.2 m, but there are some areas with depths greater than 30 m (Molinaroli et al., 2007).

The mean water volume of the lagoon is around 59010^6 m^3 and the exchange of water through the inlets in each tidal cycle represents about a third of the total volume of the lagoon (Gaćic et al., 2004). The tidal exchange of seawater and the inflow of freshwater from several rivers determine the lagoon's brackish character and the seasonal spatial gradients in the distribution of abiotic and biotic variables.

The DRAIN project (1999–2000) estimated that inputs of freshwater to the lagoon from the drainage basin (surface area 1850 km^2) amount to an annual mean flux of around 35.5 m^{3}s^{-1} (Zonta et al., 2005). The main rivers with natural discharge regimes are the Silone (accounting for 23% of the total flux) and the Dese

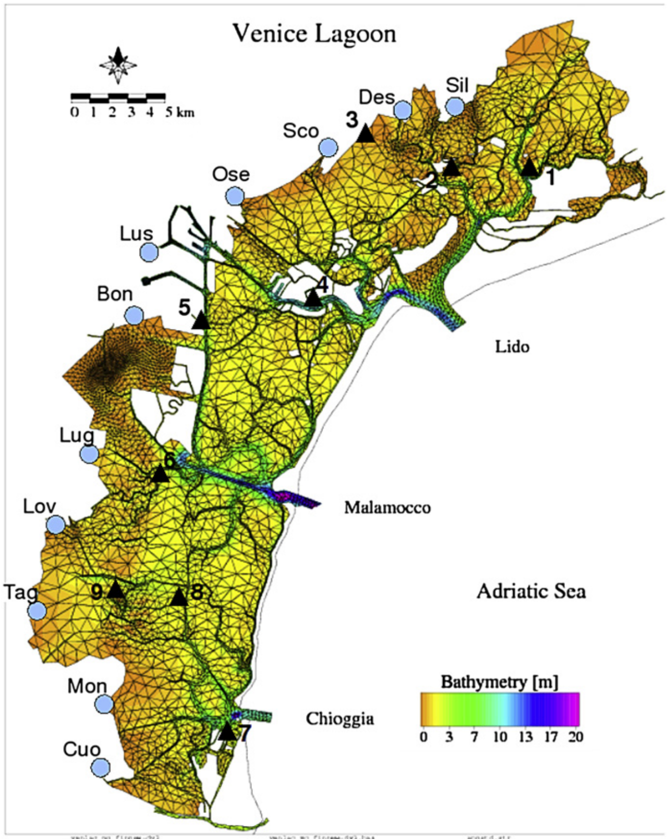

Fig. 1. Venice lagoon, numerical grid, bathymetry, rivers and APAT tide gauges.

(21%) together with the navigable channels called Naviglio Brenta (14%) and Taglio Nuovissimo (13%). The most important rivers are located in the northern part of the lagoon, which receives more than 50% of the annual discharge from the drainage basin (Zuliani et al., 2005). Most stretches of the rivers entering the southern part of the lagoon are artificially regulated.

The Venice lagoon can be classified as a microtidal environment (mean tidal range less than 1 m), with a mean tidal range of 61 cm, which decreases to 35 cm during neap tide and increases to 79 cm during spring tide (Tagliapietra et al., 2007). It is defined as a polyhaline lagoon, with salinity varying along a gradient from the landward side to the sea (Guerzoni and Tagliapietra, 2006; ICRAM, 2007; Solidoro et al., 2004a,b). Following Kjerfve and Magill (1989), it could be defined as "restricted" lagoon, where tide and wind are the main forcing factors of circulation. Salinity and residence time may be considered the main variables characterizing the system's conditions, and are also related to its trophic state (Solidoro et al., 2004b; Bianchi et al., 1999).

For the purposes of the WFD, the lagoon falls into the Transitional Waters category for the Mediterranean Ecoregion. Applying system B to the Venice Lagoon, we made the following considerations: Latitude and Longitude are not relevant in this case due to the limited variability of both (the lagoon can be enclosed within a square whose sides are around half a degree in length, corresponding to 50 km). Therefore, salinity (both annual mean and range) was the only obligatory factor adopted for the definition of types.

Several systems for classifying water bodies, based on various approaches (ICRAM, 2007; CVN, 2004a; CVN, 2004b; Zanon, 2006) are available in the local literature. Solidoro et al. (2004a) applied the same numerical model used in this study, with lower spatial and temporal resolution, and divided the lagoon into 3 areas with respect to salinity and 11 areas with respect to internal exchanges.

3. Selection and description of the method

Several European studies have applied the requirements of the WFD to case studies of coastal and transitional waters (Schernewski and Wielgat, 2004; Bulger et al., 1993). Their methods include the combined use of GIS and numerical modelling techniques, as well as statistical approaches based on water quality databases (Urbanski et al., 2008; Basset et al., 2006). Some studies have adopted transitional water typologies based on hydro-morphological characteristics such as morphology, tidal range and salinity (Carstens et al., 2004; Tagliapietra and Volpi Ghirardini, 2006; Kagalou and Leonardos, 2008). Others studies have also included human activities, pressures and nutrient loads (Boix et al., 2005; Ferreira et al., 2006). The published papers based on the implementation of the WFD to transitional waters in the Mediterranean ecoregion do not include reference sites or reference criteria but identify "a priori" typologies based on WFD system B descriptors. One way to approach the typing process is to define broad types (e.g.. Moss et al., 2003) but these have yet to be determined for transitional waters (Borja et al., 2009). Another approach is to draw up a detailed typology reflecting ecological gradients and community structures, moving towards a site-specific assessment (Hering et al., 2010).

Some studies consider the possible consequences of inter-annual variation. Lucena-Moya et al., 2009) includes the effect of intra-annual salinity variation on phytoplankton and invertebrate communities by introducing a classification into subtypes. Wolf et al. (2009) approached the longitudinal zoning of tidal marshland streams by combining the abiotic salinity classification proposed by the WFD with a biotic classification based on the salinity preference scores of benthic macroinvertebrate fauna. Galvan et al. (2010) approached the heterogeneity within and between transitional waters by adopting a hierarchical classification system. This study combined hydrological and morphological indicators and applied a circulation model to estimate some parameters.

Mathematical models have been applied to several aspects of the WFD, from the estimation of indexes for the biological community (Ponti et al., 2008; Mistri et al., 2008) to the assessment of chemico-physical status (Garcia et al., 2010; Bald et al., 2005) and ecological status (Nielsen et al., 2003). Yang and Wang (2010) suggested introducing a model for managing diffuse source pollution into the Programme of Measures associated with River Basin Management Plans. Martins et al. (2009) combines classical monitoring of water status with modelling of hydrodynamics, water quality and ecological aspects. Nobre et al. (2010) presents an example of ecosystem modelling as a tool for Integrated Coastal Zone Management and the adoption of an ecosystem-oriented approach to marine resource management. The use of numerical models to simulate ecological aspects as required by the WFD and the establishment of reference situations by modelling are discussed by (Nielsen et al., 2003; Wasson et al., 2003).

In Section 1 we discussed how salinity and residence time can be considered as the main environmental proxies in complex transitional waters, and how the temporal variability of the parameters can be a useful descriptor itself. Often the temporal and spatial coverage of salinity data is too limited to provide an adequate picture of its variability (Wolf et al., 2009). The costs of a sampling grid able to reflect the spatial and temporal variability of the main parameters, or even just salinity, are sometimes too high (Irvine, 2004). To solve this problem and to evaluate the implications of the variability of this parameter for the typing process, we developed a numerical salinity model with high spatial and temporal resolution, comparing the result with a limited number of continuous, strategically located sampling points. This method has the advantage of being less expensive than high-frequency monitoring with high spatial resolution; the model makes it possible to estimate residence time in every element of the grid and to obtain a map showing annually averaged values. To represent inter-annual variability, we applied the model to two years, 2003 and 2005, which were very different from the climatological and hydrological point of view.

This study adopted the SHYFEM model (https://sites.google.com/site/shyfem/), which was developed expressly for coastal lagoons (Umgiesser and Bergamasco, 1995). It has already been applied successfully to the Venice Lagoon (Umgiesser et al., 2004; Bellafiore et al., 2008; Ferrarin et al., 2008) where it has been used to simulate residence time and salinity Cucco et al. (2006); Solidoro et al. (2004a). A full description of the model can be found in Umgiesser et al. (2004).

3.1. Grid and model set-up

With respect to the grids used in previous studies, (Solidoro et al., 2004a; Umgiesser et al., 2004) the spatial resolution and the detail of the contours have been improved in order to better represent the bathymetric gradient at reduced computational cost. The main channels crossing the islands have been introduced and the spatial resolution of the shoals and some saltmarshes has been increased in order to improve the simulation of the currents in shallow water and the wet/dry behaviour of the saltmarshes. The grid itself consists of 8029 nodes and 14021 elements (compared to 4367 nodes and 7858 elements in the previous grid) and the bathymetric data adopted were collected in the year 2000 (Molinaroli et al., 2009).

Simulations start on January 1st and are 1 year long. They represent the years 2003 and 2005, for which the salinity measurements have good spatial and temporal coverage respectively. The model was applied in its two-dimensional version to the lagoon only. The set-up adopted and the method applied to calibrate the modelled water levels are the same as in Umgiesser et al. (2004), where equations and the details of the numerical treatment can be found. In all simulations, realistic forcing factors with a maximum admissible time-step of 300 s and a spin-up time of 5 days were adopted. The initial water level and velocity values were set to 0 and the initial salinity was assigned spatially interpolated values from experimental data corresponding to the start time of the simulation.

The timeseries for precipitation and wind (speed and direction) were considered in this application to be spatially homogeneous in the domain. The same principle was adopted for air temperature, solar radiation, relative humidity and cloud cover, which were used to calculate the effect of evaporation on water level and salinity. To consider the effect of freshwater inputs, the daily discharges of 11 rivers were included. Their location is shown in Fig. 2.

3.2. The data

The real forcing data used for the model and the comparison data for salinity were processed for both simulated years (2003 and 2005). The tide level data used to force the open boundary levels were collected at each of the seaward inlets every 5 min by the Venice Tide Forecasting Centre, which manages a network of automatic weather and tide gauges in the lagoon (http://www.comune.venezia.it/). The meteorological data were collected every hour in 2003 and 2005 by the Italian National Research Council's Institute of Marine Sciences (ISMAR-CNR, Venice city). Missing data were retrieved with reference to the corresponding meteorological data measured in Venice city by the Cavanis Institute (www.cavanis.org).

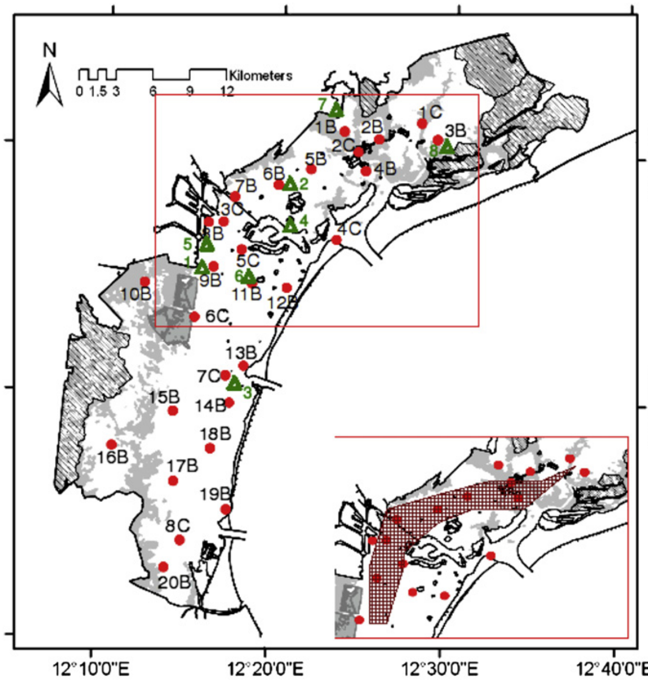

Fig. 2. MELa stations (red circles) and SAMA stations (green triangles). Cross-hatching in close-up shows area where model overestimates salinity. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Comparison of meteorological characteristics in 2003 and 2005 with the long-term average (1959–2004) shows that 2003 had lower annual precipitation and higher air temperature (544 mm and 14.8 C), while 2005 (788.6 mm and 13.7 C) was similar to long-term trends (1954–2004 annual average: 789.5 mm and 13.6 C). Analysis of monthly precipitation (Pennacchi and Benedetti, 2005, 2006) shows that both years had a maximum in April, and from July to October rainfall in 2005 was much higher than in 2003 (the sum of the values for these months is equal to 450.8 mm in 2005 and 172.8 in 2003).

In both years annual wind intensities and annual wind directions were in agreement with literature data for the region (Gaćic et al., 2009; De Biasio et al., 2008), which indicate NE (Bora, close to 29% of the whole examined database in the last cited paper) and SE (Sirocco, close to 3%) as the main wind directions. 2003 had stronger winds than 2005, with more frequent Bora events, particularly in the winter months, and less frequent Sirocco events in the spring and summer months. These differences may have led to shorter residence times in 2003, especially in areas with more extended wind fetch.

Table 1
Classes of salinity, standard deviation of salinity and residence time.

Salinity	PSU	Std.Dev. S		Residence time	Days
Class	range	Class	Range	Class	Range
Oligohaline	0–5	Stable	0–2	Open	0–5
Mesohaline	5–18	Medium	2–4	Restricted	5–15
Polyhaline	18–30	Unstable	>4	Confined	>15
Euhaline	>30				

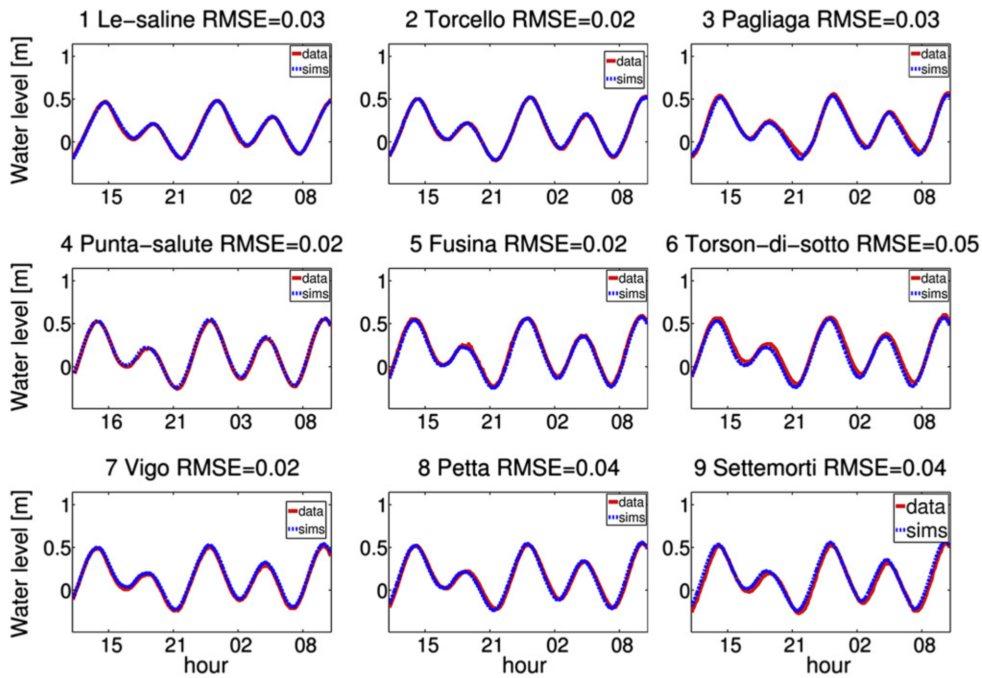

Fig. 3. Comparison of measured and simulated water levels in 9 stations shown in Fig. 1.

Sensitivity analysis confirmed that river discharge is the most important factor for improving the accuracy of the model's reproduction of salinity values. For this reason, averaged daily discharges were adopted as river inputs for each of the 11 rivers included in the model. For both years, the discharge data were collected from the Drainage Basin Authority. The data differ from those of the DRAIN project in terms of the time and location of the measurements. Analysis of monthly discharge data shows that maximum flows generally occurred in February–March and October–November in all rivers, whereas the low-water period was from June to September. Each river shows inter-annual variability in its annual and monthly discharges. It is important to note three aspects: i) total annual discharge in 2003 was less than in 2005 (21 m^3s^{-1} and 29 m^3s^{-1} respectively); ii) for all rivers, annual mean discharges in 2003 and 2005 were different, but not all rivers had lower discharges in 2003 than in year 2005; iii) although the total annual discharge for all rivers was lower in 2003 than in 2005, there were cases in which the monthly discharge of the same river in the same month was higher in 2003 than in 2005, meaning that the variability of the discharge was higher in 2003 with respect to 2005.

Finally the correlation between river discharge and precipitation inside the lagoon is low, showing that the freshwater inputs imposed in the model are not redundant.

The salinity measurements for 2003 were collected at 28 stations pertaining to the MELa project (Fig. 2, red circles) with monthly sampling during ebb tide. The salinity data for 2005 (Fig. 2, green triangles) were collected by the SAMANET automatic network (Ferrari et al., 2004) every 30 min at 8 sampling points.

Comparison of salinity at the sampling points used for both 2003 and 2005 shows that the difference between years in terms of the annual average and the annual maximum salinity is small. The most important differences concern the annual minimum values and therefore the annual salinity range. At some points the standard deviation is greater in 2003 than in 2005 because this depends not only on the total quantity of freshwater but also on the temporal distribution of the inputs.

The data were used to initialise the numerical model and to evaluate the model's performance both spatially, at various sites in the lagoon, and temporally, at high temporal resolution. The first of these steps ensures that the model is representative of salinity throughout the lagoon, and the second ensures that the model is able to reproduce the temporal variability of salinity at each point.

3.3. The typing process

We considered the descriptors belonging to System B of the WFD: annual mean salinity, annual standard deviation of salinity and annual mean residence time, for the reasons set out in Section 1.

The typing of the lagoon was carried out by defining classes (ranges) of values for each considered variable and generating the corresponding maps. Subsequently the classified maps of two or

Table 2
Comparison of measured and simulated water level data at various points of domain in 2003. n = number of records, r = linear correlation coefficient, RMSE = root mean square error, BIAS = difference between mean of observations and simulations and SI = scatter index, calculated as the RMSE normalized with observed mean.

Station	1	2	3	4	5	6	7	8	9
Name	Le Saline	Torcello	Pagliaga	Punta Salute	Fusina	Torson di Sotto	Vigo	Petta di Bo'	Settemorti
n	2621	2621	2621	873	2621	2621	2621	2621	2621
r	0.99	0.99	0.99	1.00	1.00	0.99	1.00	0.99	0.99
RMSE	0.03	0.03	0.04	0.02	0.03	0.05	0.03	0.04	0.05
BIAS	−0.02	−0.01	0.01	−0.01	0.02	0.04	−0.02	0.01	−0.02
SI	0.14	0.11	0.15	0.09	0.09	0.18	0.11	0.16	0.17

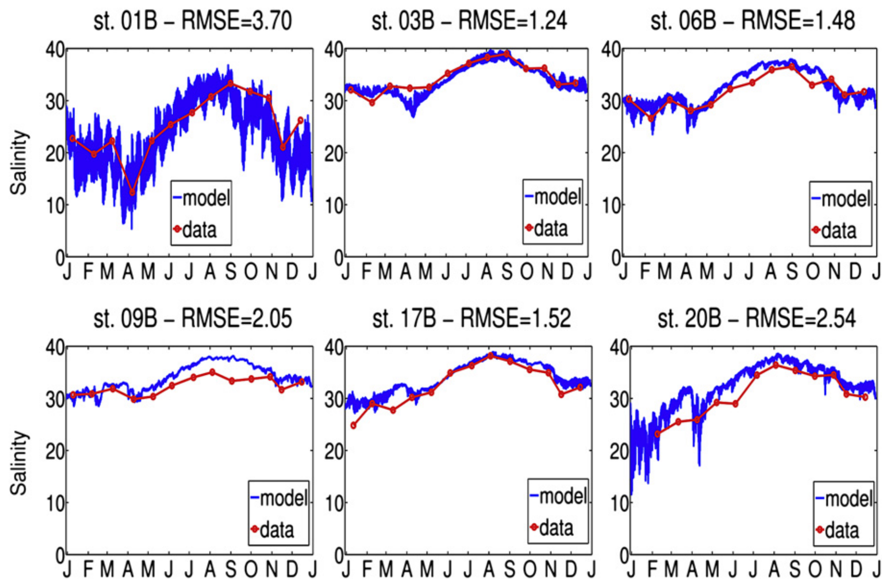

Fig. 4. Comparison of measured and modeled salinity in 2003.

more variables were superimposed. The resulting map shows areas characterised by different combinations of classes for each considered variable.

Table 1 shows the defined classes and their ranges.

The annual mean salinity was divided into 4 classes, as in the Directive, except that the two least saline categories were combined into one. The salinity ranges are thus 0–5, 5–18, 18–30 and higher than 30, which coincide with the intervals of the Venice System, and correspond to oligohaline, mesohaline, polyhaline and euhaline respectively.

The classes for the annual standard deviation of salinity were defined after analysing the distribution of values. The extreme standard deviation values were excluded because they were not very frequent and most of them were recorded in areas characterised by special conditions (such as salt marshes). Given the distribution of values in the domain, we decided to divide the annual standard deviation of salinity into 3 classes with ranges of 0–2 (low), 2–4 (medium), and higher than 4 (high). They represent the degree to which the sampling point is characterised by the mixing of waters with differing salinity. Thus, low standard deviation may be associated with stability, medium standard deviation with moderate variability and high standard deviation with high variability.

The calculation of residence time followed the method described in Cucco and Umgiesser (2006). Residence time in the lagoon with real forcing factors depends on the wind regime and ranges from more than a month to a few days. Specifically, a long, strong Bora event can "clean" the basin very fast, whereas a Sirocco event can slow the water renewal process by restricting the outflow through the inlets. Long, strong Bora events happen frequently, whereas Sirocco events are more isolated and spread out over the year and are of long duration and strong intensity only in November, which is the period characterised by "high water" phenomena. Wind data for both 2003 and 2005 followed this pattern. In order to evaluate the mean residence time in an annual simulation under real forcing conditions, the residence time was thus calculated every 2 months, corresponding to different real forcing conditions. The average of the 6 replicates represents our assessment of the annual mean residence time under real forcing conditions. The residence time ranges considered are 0–5 days, 5–15 days and higher than 15 days, which may be related to the "open", "restricted" and "confined" classes respectively. The upper and lower bounds of the ranges were chosen on the basis of geomorphological considerations: in both 2003 and 2005, the isoline of 15-day residence time roughly coincided with the line of the salt marshes in the southern part of the lagoon. In the northern

Table 3
Comparison of measured and simulated salinity data at various points of domain in 2003. n = number of records, r = linear correlation coefficient, RMSE = root mean square error, BIAS = difference between mean of observations and simulations and SI = scatter index.

Station	n	r	RMSE	BIAS	SI	Station	n	r	RMSE	BIAS	SI
B01	13	0.95	3.71	2.15	0.15	B15	12	0.93	1.03	−0.23	0.03
B02	13	0.67	3.72	−1.31	0.12	B16	11	0.82	3.70	0.36	0.12
B03	13	0.93	1.24	0.49	0.04	B17	13	0.97	1.52	−1.08	0.05
B04	13	0.88	2.10	−1.04	0.07	B18	13	0.96	0.60	0.04	0.02
B05	12	0.93	1.61	−0.48	0.05	B19	12	0.90	1.11	0.56	0.03
B06	13	0.93	1.49	−0.78	0.05	B20	12	0.93	2.54	−1.77	0.08
B07	13	0.89	2.01	−1.30	0.06	C1	12	0.96	1.57	0.94	0.05
B08	12	0.74	2.60	−1.43	0.08	C2	13	0.95	2.66	1.14	0.09
B09	13	0.91	2.05	−1.42	0.06	C3	12	0.90	1.63	0.00	0.05
B10	13	0.62	4.69	0.14	0.17	C4	13	0.98	0.66	0.38	0.02
B11	13	0.94	0.83	−0.42	0.02	C5	13	0.89	1.12	−0.42	0.03
B12	13	0.98	0.43	−0.17	0.01	C6	13	0.81	2.26	0.68	0.07
B13	13	0.92	0.81	−0.41	0.02	C7	13	0.99	0.83	0.55	0.02
B14	12	0.85	1.05	0.25	0.03	C8	13	0.95	1.18	0.51	0.03
mean		0.90	1.81	−0.14	0.06						

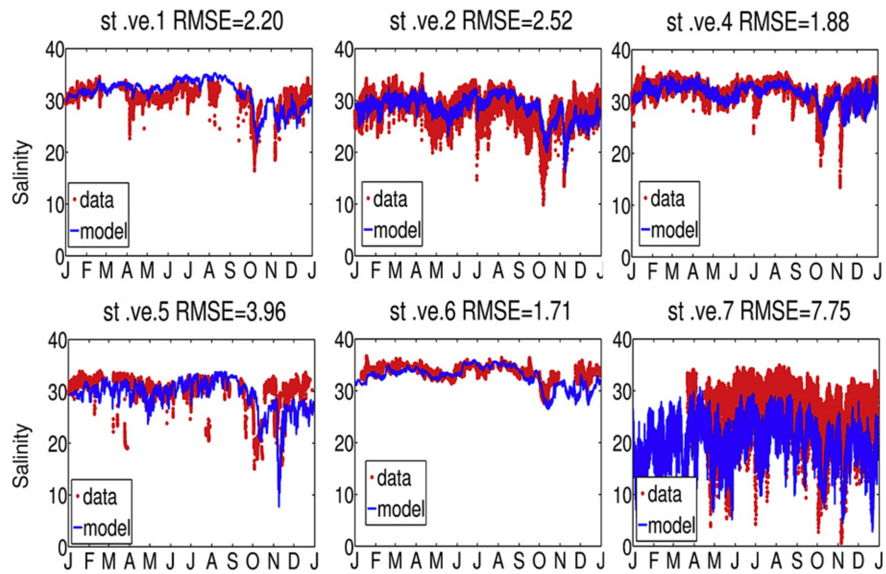

Fig. 5. Comparison of measured and modeled salinity in 2005. Stations 1, 2 and 7 of SAMA monitoring network are close to stations B09, B06 and B01 of MELa monitoring project shown in Fig. 4.

part of the lagoon the lines still coincide, but less precisely. Finally the isoline of a 5-day residence time marks the limit of marine influence in the area of the lagoon around the inlets. The combination of two variables with their respective classes gives rise to either 12 theoretical types (annual mean salinity with standard deviation of salinity, annual mean salinity with annual mean residence time) or 9 theoretical types (annual mean residence time with standard deviation of salinity). The combination of all the variables gives rise to 36 theoretical types. The next step is the simplification of the superimposed maps in accordance with the size of the areas, followed by the assignment of each area to a specific type.

4. Results and discussion

4.1. Spatial (MELa, 2003) and temporal (SAMA, 2005) variability

The hydrodynamic model was calibrated in a calm period with reference to water level data collected by ISPRA in the year 2003. Fig. 3 shows the comparisons of measured and simulated water levels at different points in the lagoon and Table 2 shows the statistics calculated for each point, during the whole simulation. The minimum error of the model is 2 cm and the maximum error is 5 cm, with the error increasing from the seaward inlets to the landward side of the lagoon.

Fig. 4 shows a comparison of measured and modeled salinity timeseries data at 6 stations in the year 2003. The statistics calculated for each sampling point in 2003 are shown in Table 3. The position of each station is shown in Fig. 2. The correlation coefficient ranges from 0.67 to 0.99 and the error of the modeled salinity varies from a minimum of 0.4 to a maximum of 4.7. The model overestimates values during the summer period, especially in the inner north-central area, which extends beyond the city of Venice (cross-hatched area in Fig. 2). This is probably a consequence of the uncertainty concerning freshwater input, considering that only the main sources are included in the model (without the discharges from less important channels, Venice city or other human settlements on the islands) and that errors in the measured discharges may be significant. The stratification of salinity may be significant in the north-central area because of the interaction between river discharges and the complex morphology of this area.

Stations 10B, 16B, 2B and 1B have higher root mean square error (RMSE) values. The first two are behind the southern salt marsh line, where mixing processes are more complex. Station 10B has a low correlation coefficient, whereas 16B has a high correlation coefficient, indicating that in 10B the freshwater inputs are not properly estimated, whereas this effect is less pronounced in 16B. Stations 2B and 1B are situated in a complex system of river inputs and salt marshes: station 1B has high variability because of freshwater inputs and station 2B is bordered by salt marshes in a very shallow area, and its low correlation coefficient is the consequence of high evaporation and the modulation of freshwater inputs by salt marshes.

Fig. 5 and Table 4 show corresponding statistics for the 6 stations in 2005. The correlation coefficient ranges from 0.34 to 0.69 and the RMSE varies from 1.7 to 7.7. The model reproduces the main pattern of variation, but the variability of the measurements is greater than the simulated values. Station 5, just off the industrial zone, is slightly underestimated, probably because the model does not consider freshwater inputs from the zone itself. Station 7 shows high RMSE values and is systematically underestimated: this station is located in a channel near the mouth of the Dese river system and there is probably a stratification effect that the model is not able to reproduce in this application.

Table 4
Comparison of measured and simulated salinity data at various points of domain in 2005. n = number of records, r = linear correlation coefficient, RMSE = root mean square error, BIAS = difference between mean of observations and simulations and SI = scatter index.

Station	n	r	RMSE	BIAS	SI
1	12804	0.61	2.21	−0.50	0.07
2	16541	0.64	2.53	−0.60	0.09
3	15192	0.69	1.31	0.52	0.04
4	14766	0.64	1.88	0.68	0.06
5	11116	0.34	3.96	1.15	0.13
6	12886	0.64	1.71	0.83	0.05
7	12768	0.57	7.75	6.06	0.35
mean	13724	0.60	3.05	1.17	0.11

Annually averaged maps were calculated for each variable in each simulation (Fig. 6). The main characteristic of each map is a transversal gradient, which reflects the mixing processes of fresh and salt water. The standard deviation of salinity increases from the sea to the land and from the seaward inlets to the river mouths, and the residence time gradient is similar. Annual mean salinity increases from the land to the sea.

The differences between the 2003 and 2005 maps are shown in the bottom row of Fig. 6. They indicate the inter-annual spatial variability of each parameter as determined by the model. Annual mean salinity in the year 2003 is greater than in the year 2005 (showing a positive difference in most parts of the lagoon and a spatially averaged difference of nearly 3). This result is in agreement with the lower annual rainfall and river discharge of 2003. In

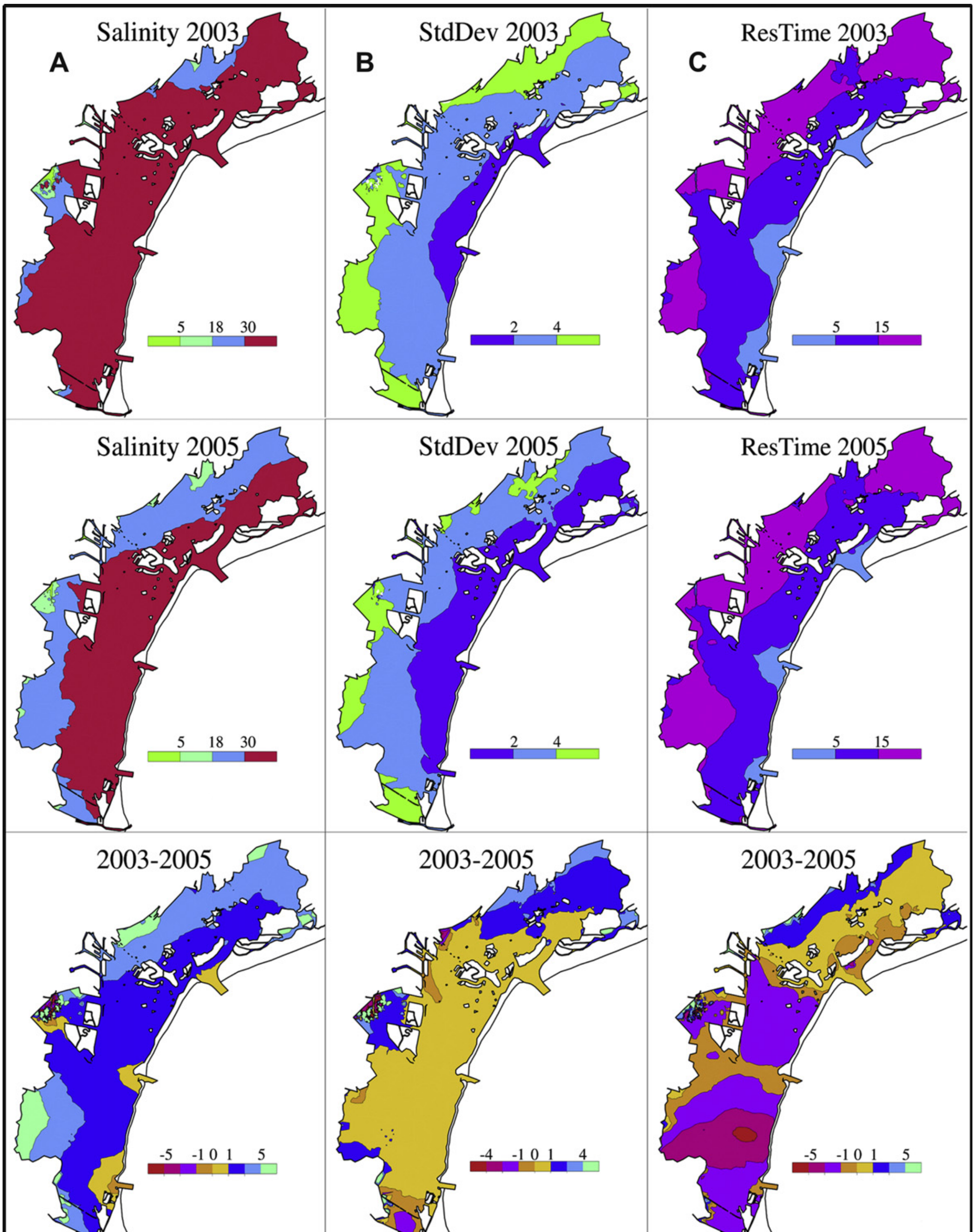

Fig. 6. Maps of annual average salinity (left panel, A), standard deviation of salinity (central panel, B) and average residence time (right panel, C). Top row refers to 2003 (A03, B03, C03), middle row refers to 2005 (A05, B05, C05) and bottom row shows the difference between 2003 and 2005.

this case the spatial distribution of the differences is similar to the spatial distribution of residence time, highlighting the role of mixing processes. In most of the lagoon, the difference between 2003 and 2005 in standard deviation of salinity is between −1 and 1, with a spatial average of nearly 1. The difference is positive and higher than 1 in the northern part of the lagoon and in isolated areas along the landward shore: this means that the standard deviation in 2003 is greater than in 2005 in areas where the effect of freshwater discharge is greater. This behaviour can be explained by local freshwater discharges: in 2003 they were generally lower but more erratic. The difference between 2003 and 2005 in terms of residence time is both positive and negative, with spatially averaged values of 1.3 and −1.6 respectively. The residence time is longer (3–5 days) in 2003 than in 2005 in the northern part of the lagoon, mainly along the landward shore, where the influence of river discharge is important. It is shorter in the central and southern part of the lagoon (where the differences range from −1 to −3 days), perhaps due to the different wind regime in the two years. It is important to note that the difference in residence time indicates a basic division of the lagoon into two parts: a northern basin, with positive differences, and a south-central basin, with negative and less evident differences. The south-central basin can in turn be divided by another strip of zero difference running across the lagoon from the Malamocco inlet along its main channel (the most important artificial channel in the lagoon)

4.2. Proposed typologies and water bodies in the Venice lagoon

A geographical analysis tool was used to superimpose the distribution of two or three variables in 2003 and 2005. Comparison of the resulting maps indicates that the spatial distribution of each type in the lagoon can change noticeably: the surface area of a specific type may change or one type can be replaced by another.

For example, Fig. 7 shows the combination of annual average salinity with residence time in 2003 (left panel) and in 2005 (right panel), and the histogram of the log-transformed surface area of each possible type in the two years. The numerical matrix under the histogram contains the numerical labels of the 12 possible combinations of salinity and residence time classes. The most extensive types correspond to the combination of the "open" class with the "euhaline" class (14), the "restricted" class with the mesohaline, polyhaline or euhaline salinity classes (22, 23, 24), and the "confined" residence time class with the "mesohaline, polyhaline or euhaline" salinity classes (32, 33, 34). The histogram in the picture shows that the restricted mesohaline and restricted polyhaline types (22, 23) and the confined mesohaline and confined polyhaline types (32, 33) are more extensive in 2005, whereas the others are less extensive. This is a consequence of the larger inputs of freshwater in 2005. To simplify the number of combinations we subsequently assimilated types with an area less than 10 km^2 to the most extensive adjacent type. In our example this means that the restricted mesohaline type (22) and the confined mesohaline type (32) were included in the restricted polyhaline type (23). The partitioning obtained from the combination of standard deviation of salinity with residence time is similar to the partitioning derived from the combination of mean salinity with residence time, indicating that standard deviation of salinity is important not in establishing boundaries but in providing additional information about the stability of the types. Because 2005 represents a typical year in terms of the annual averages of the climatic forcing factors, we assume that the types and the spatial partitioning obtained from the combination of mean salinity with residence time in that year can be taken as the reference situation. The next step is to associate each defined type in the 2005 map with the corresponding standard deviation class, in order to indicate its stability. This led to the identification of 9 types (expressed as a combination of mean salinity, residence time and standard deviation of salinity), spatially partitioning the Venice lagoon into the water bodies schematically shown in Fig. 8.

In this partitioning, three water bodies correspond to the areas near the three inlets: two are of the "open euhaline stable" type, whereas the less stable water body, corresponding to the area of the southernmost inlet, is of the "open euhaline medium" type (note: Bellafiore and Umgiesser (2010) showed that the Chioggia inlet is influenced by the coastal freshwater discharge of the river Brenta, the mouth of which is near the inlet itself). The most extensive water body in the lagoon, which might be divisible on the basis of other factors not considered in our study, is the "restricted euhaline medium" type. The extreme southern and northern parts of the lagoon are divided into water bodies of specific types. The areas on the landward side belong to the same types, although they are spatially separated. Our results shows that it is possible to consider a hierarchical partitioning of the Lagoon of Venice. As an initial approximation based on the broadest partitioning criteria, our results indicate that the lagoon can be divided into an extensive polyhaline sub-basin and a reduced northern sub-basin with specific characteristics. This division reflects the results obtained by Tagliapietra et al. (2007), which identifies most of the Venice lagoon as microtidal, except for the northern part which appears to be nanotidal (mean tidal range less than 0.5 m). From a more detailed point of view, the Venice lagoon can be divided into 14 water bodies. This partitioning reflects some aspects of the study of (Molinaroli et al., 2009), which is based on the division of the Venice lagoon into the classical four sub-basins. The northern sub-basin (A), identified as still in a quasi-natural condition, contains water bodies of 7 different types, making it the most complex sub-

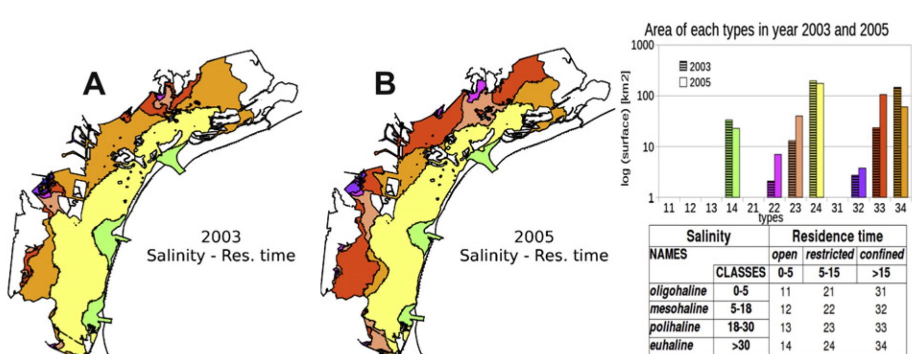

Fig. 7. Superimposition of maps of annual average salinity and residence time (panel A = 2003, panel B = 2005). Histogram shows log-transformed surface area covered by each type in 2003 (pinstriped) and 2005. Colour legend of the maps corresponds to colour legend of histogram.

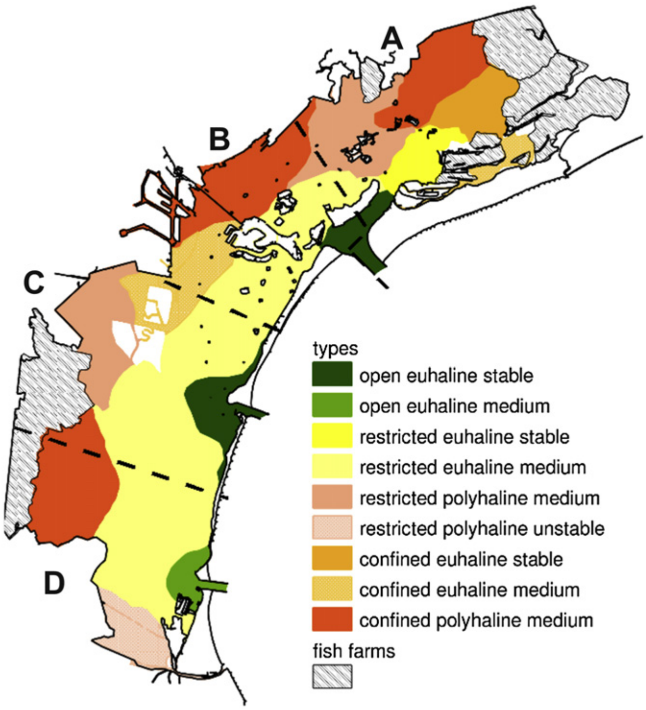

Fig. 8. Comparison of types and water bodies identified in this study with the 4 sub-basins as in Molinaroli et al. (2009).

basin. The northern-central and southern-central sub-basins (B and C) correspond to the most disturbed areas of the lagoon and include water bodies of 5 different types. The southernmost sub-basin (D), which is partly still in a semi-natural condition, includes water bodies of 4 types.

5. Conclusions

We developed a model which is able to reliably reproduce the spatial and temporal evolution of salinity in most parts of the Venice lagoon, and thus to provide a good assessment of its variability. The model is also able to calculate the residence time and takes into account the inter-annual variability of the studied parameters. Most of the data used by the model are available via the usual monitoring programmes and thus, with little economic effort, this numerical tool offers support for lagoon management on various levels, in terms of both WFD requirements and other applications. The model makes it possible to tackle several open questions concerning the management strategies of transitional environments, such as:

1. How to sub-divide a basin into water bodies. Local authorities often assume a division of a basin into distinct water bodies without explaining the objective criteria adopted for the zoning. The method developed in this study can be applied to different lagoons and provides unbiased and objective zoning indications for the basin. A numerical model simulating the abiotic factors can be adopted as a tool for designing monitoring programs, showing the position and the size of the types in different years. Taking Fig. 7 as an example, it is possible to identify which type accounts for the largest portion of the lagoon, or alternatively, which type is most likely to shift from a dry year to a standard year (unstable). On the other hand, the model can be employed to estimate the variation of salinity associated with input of water from the drainage basin, which generally contains a high concentration of nutrients and pollutants derived from human activities. This knowledge, together with knowledge of the residence time, can be a used as an operational tool to evaluate the response of water quality elements (including biological elements), helping to distinguish natural from anthropogenic stresses.
2. How to manage the spatial and temporal variability of descriptors in transitional waters. Interannual variation in the annually averaged values of the parameters is considerable, and depends on the meteorological and hydrological characteristics of the year in question. The resulting variability of types and their spatial distribution is significant, and the typology of the system could be regarded as changing from year to year. This means that a given water body can belong to one type in one year and to a different type in another year, in other words that not only the borders of the water bodies are fuzzy, but their types too. This could be a problem for managers, since water bodies are the prescribed unit for management, monitoring and the achievement of quality targets, and are assumed to belong to a fixed type, which is not always true. The model can solve this problem by identifying a variable that indicates the stability of each type, or by detecting whenever the type itself shifts from one class combination to another. This aspect is important when establishing the reference status of a water body, since the Directive does not consider the inter-annual variability of types in transitional environments.
3. Finally, this study demonstrated that the tool can also be used to perform a hierarchical division of a lagoon. Thus, according to the purpose, either approximate or finely detailed typologies can be adopted, for example to select the adequate number of sampling stations for monitoring.

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