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- Comparative study of 10 Mediterranean lagoons using a 3-D hydrodynamic model
- Characterization of flushing, mixing efficiency, and water renewal
- Classification of lagoons based on water renewal time and exchange rate

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Comparative hydrodynamics of 10 Mediterranean lagoons by means of numerical modeling

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Abstract A comparison study between 10 Mediterranean lagoons has been carried out by means of the 3-D numerical model SHYFEM. The investigated basins are the Venice and Marano-Grado lagoons in the Northern Adriatic Sea, the Lesina and Varano lagoons in the Southern Adriatic Sea, the Taranto basin in the Ionian Sea, the Cabras Lagoon in Sardinia, the Ganzirri and Faro lagoons in Sicily, the Mar Menor in Spain, and the Nador Lagoon in Morocco. This study has been focused on hydrodynamics in terms of exchange rates, transport time scale, and mixing. Water exchange depends mainly on the inlet shape and tidal range, but also on the wind regimes in the case of multi-inlet lagoons. Water renewal time, which is mostly determined by the exchange rate, is a powerful concept that allows lagoons to be characterized with a time scale. In the case of the studied lagoons, the renewal time ranged from few days in the Marano-Grado Lagoon up to 1 year in the case of the Mar Menor. The analysis of the renewal time frequency distribution allows identifying subbasins. The numerical study proved to be a useful tool for the intercomparison and classification of the lagoons. These environments range from a leaky type to a choked type of lagoons and give a representative picture of the lagoons situated around the Mediterranean basin. Mixing efficiency turns out to be a function of the morphological complexity, but also of the forcings acting on the system.

1. Introduction

Lagoons are highly productive areas that are situated in the transitional areas at the land-ocean boundary [*Pérez-Ruzafa et al.*, 2011a]. They are important to mankind because many industrial, commercial, and recreational activities are concentrated in these regions [*Razinkovas et al.*, 2008]. The need to manage this part of the coastal zone makes of primary interest to understand processes occurring in these water bodies [*Gonenc and Wolflin*, 2005]. These transitional waters, due to their hydromorphology, respond rapidly to changes in forcing and are therefore characterized by wide temporal and spatial fluctuations in environmental variables [*Newton and Mudge*, 2005; *Perez-Ruzafa et al.*, 2005; *Viaroli et al.*, 2007; *Tagliapietra et al.*, 2009; *Barbone and Basset*, 2010].

In recent years, these areas have become important because they provide the key to understanding the general dynamics of the seas they are connected with [*Gaertner-Mazouni and de Wit*, 2012]. Their existence and their influence on the coastal zones have become a fundamental study topic in many disciplines [*McLusky and Elliott*, 2007; *Viaroli et al.*, 2007; *Basset et al.*, 2012].

Comparisons between lagoons have been already proposed in literature [*Kjerve*, 1986; *Gamito et al.*, 2004; *Basset et al.*, 2006; *Specchiulli et al.*, 2010; *Pérez-Ruzafa et al.*, 2011a, 2011b; *Day et al.*, 2011; *Duck and da Silva*, 2012]. However, an extensive comparison study carried out with numerical modeling has never been applied. This is partly due to the complexity to set up, calibrate, validate, and run a model for more lagoons. It is also a problem of methodology, because using results from applications of different models could bias the results. This is similar to the use of data collected with different sampling strategies and elaboration.

When trying to compare and classify lagoons various parameters were proposed, such as morphological parameters (area, volume, mean depth, cross-section area of the inlets, and openness parameter), physical parameters (salinity, temperature), and various time scales such as flushing time and renewal time. The last parameter deals with the openness of lagoons, and its exchange capabilities with the open sea. It is therefore an important parameter also for other processes, such as ecological evolution and pollution dispersion.

In this work, a comparative study is proposed that uses the numerical shallow water hydrodynamic finite element model (SHYFEM) [*Umgiesser et al*., 2004] applied to 10 Mediterranean lagoons. The applied model is therefore same for all lagoons, assuring uniformity in the model results. The model has previously been applied to and verified for all lagoons. The lagoons intercomparison and classification is carried out using computed parameters such as fluxes, transport time scales, and mixing efficiency. Using the distribution of the water renewal time inside the basins has also allowed distinguishing between different water bodies inside the same lagoon. This approach is important if lagoons cannot be considered homogeneous enough to be treated as a single water body. In this case, numerical studies are needed as the ones presented here.

2. Description of Study Sites

In this work, the 10 Mediterranean lagoons, showed in Figure 1, were studied. The general characteristics of the lagoons in terms of basin surface, mean and maximum water depths, water volume, river runoff, and tidal range are reported in Table 1. Due to tidal dynamics in the Mediterranean Sea, the 10 studied lagoons can be all defined microtidal. In the following, an overview of the study sites is given and their characteristics are presented.

2.1. Marano-Grado Lagoon

The lagoon of Marano-Grado, in the northeastern part of the Adriatic Sea (Italy), is delimited by the rivers Isonzo and Tagliamento (lagoon's surface about 130 km^2, length 32 km, mean width 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). According to a recent bathymetric survey [*Fontolan et al*., 2012], the lagoon is a shallow basin with a mean depth of 1.12 m. The lagoon is separated from the sea by a long shore bar composed by isles and more or less persistent sand banks, identifying six inlets with width from 100 to 400 m and depth ranging between 5 and 10 m.

The lagoon basin is characterized by semidiurnal tidal fluxes (65 and 105 cm mean and spring tidal range, respectively).

The lagoon system of Marano-Grado receives freshwaters from the adjacent rivers in its western sector [*Marocco*, 1995]. The overall amount of average freshwater discharge was estimated to be 70–80 m^3 s^{-1} [*Ferrarin et al*., 2010a].

2.2. Venice Lagoon

Venice lagoon is located in the northwest Adriatic Sea and is the largest Mediterranean lagoon (surface 500 km^2, length 50 km, mean width 15 km). The bathymetry is characterized by the presence of navigable channels, tidal flats, and shoals. The latter ones can either be wet or dry depending on tidal level. Only 5% of the lagoon area is deeper than 5 m and 75% is shallower than 2 m. The mean depth is 1.5 m, but there are some areas deeper than 30 m [*Molinaroli et al*., 2007].

Three inlets connect the lagoon with the open sea (Lido, Malamocco, and Chioggia, from North to South) with length around 2.5 km each, mean depth 10, 16, and 8 m, respectively, and width from 0.5 to 1 km.

The mean tidal range at the inlets of the Venice Lagoon is 50 cm during neap tide and 100 cm during spring tide. Around 415 km^2 are subject to tidal excursion, the other areas are diked to create fish farms with water exchanges limited and regulated artificially [*Guerzoni and Tagliapietra*, 2006]. The mean water volume of the lagoon is around 632 $\times \cdot 10^6$ m^3 and the exchange of water through the inlet in each tidal cycle is about a third of the total volume of the lagoon [*Gacic et al*., 2004].

The input of freshwater into the lagoon is around 30 m^3 s^{-1} from 12 small tributaries. Yearly, the hydrological balance of the lagoon is positive due to the effects of rainfall (rain 800 mm yr^{-1} versus evaporation 200 mm yr^{-1}).

2.3. Lesina Lagoon

Lesina Lagoon, located in the southern Adriatic Sea (Italy), has a surface area of 51 km^2, a catchment area of about 400 km^2, and a mean depth of 0.9 m. Overall, the lagoon is very shallow, the depth never exceeding 1.6 m.

Water exchanges with the Adriatic Sea are provided by two artificial channels, Acquarotta, located at the western end, and Schiapparo at the eastern end of the lagoon (depth 1.4 m; length 1 and 2 km; width 15 and 10 m, respectively). Outside the lagoon the tidal range is about 30 cm.

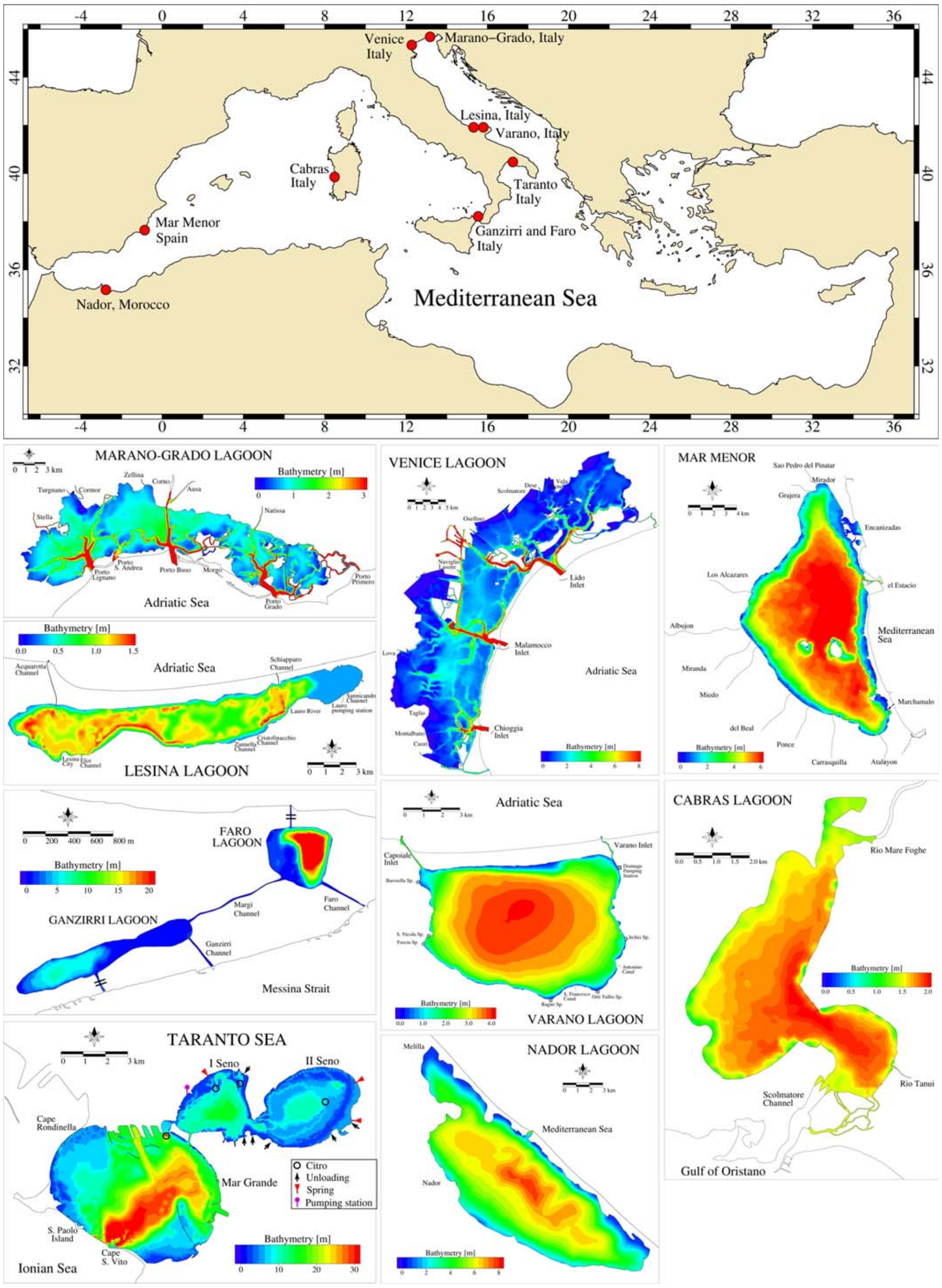

Figure 1. Overview and bathymetry maps of the 10 studied Mediterranean lagoons: Marano-Grado and Venice lagoons in the Northern Adriatic Sea, Lesina and Varano lagoons in the Southern Adriatic Sea, Cabras Lagoon in Sardinia, Taranto Sea in the Ionian Sea, Ganzirri and Faro lagoons in Sicily, Mar Menor in Spain, and Nador Lagoon in Morocco.

The lagoon is influenced both by freshwater and saline water, with strong seasonal variations in salinity (from 10 to 28 psu) [*Roselli et al.*, 2009]. Furthermore, the western region of the lagoon generally exhibits higher salinity than the eastern region. This is due to freshwater input from small tributaries, which flow mostly into the eastern side of the lagoon and drain the majority of the surface and subsurface water coming from the adjacent karstic promontory.

Table 1. General Characteristics of the 10 Mediterranean Lagoons in Terms of Basin Surface, Mean and Maximum Water Depths, Water Volume, River Runoff, and Tidal Range

Lagoon	Surface (km^2)	Mean/Max Depths (m)	Volume (10^6 m^2)	River Runoff (m^3 s^{-1})	Tidal Range (m)
Marano-Grado	131.3	1.12/12.00	147.5	70.0	0.90
Venice	415.1	1.52/39.00	631.5	30.0	0.84
Lesina	50.0	0.91/3.17	45.0	4.5	0.31
Varano	65.2	3.00/4.05	197.3	1.0	0.31
Taranto	56.8	11.85/42.00	672.7	5.4	0.19
Cabras	20.1	1.67/2.10	33.6	5.1	0.28
Ganzirri	0.31	2.90/7.00	0.9	0.0	0.17
Faro	0.26	10.75/30.73	2.7	0.0	0.17
Mar Menor	136.1	4.40/7.00	598.8	0.0	0.13
Nador	110.9	4.84/8.00	536.5	0.0	0.30

2.4. Varano Lagoon

Varano Lagoon, close to the Lesina Lagoon, is the largest brackish basin in southern Italy (65 km^2). The maximum depth of the lagoon (>4 m) is in the central-southern region and the mean depth is about 3 m.

The lagoon is connected to the sea through Capoiale and Varano inlets (depth 2 m; length 2 and 1.3 km; width 30 and 25 m, respectively). Tidal range outside the lagoon is about 30 cm.

Salinity is relatively constant, ranging from 23 to 29 psu [*Specchiulli et al*., 2010] The catchment area is 300 km^2 and Varano Lagoon receives freshwater inputs rich in organic content from urban and agricultural runoff, fish farming, and livestock breeding [*Spagnoli et al*., 2002]. Other freshwater inputs come from groundwater springs in the south-western sector of the lagoon and urban wastewater discharge in the south-eastern zone.

2.5. Taranto Sea

Taranto Sea is situated in the Ionian Sea in southern Italy and it is composed of two parts: the Mar Grande and the Mar Piccolo. The Mar Grande covers an area of 35 km^2 with a maximum depth of about 42 m and an average depth of about 12 m. It connects with the Ionian Sea through two openings. The first one is about 1 km wide, 20 m deep and is situated in the southern part of the basin, between S. Paolo Island and Cape S. Vito. The second one is about 100 m wide, 6 m deep and is located in the northwestern part of the Mar Grande near Cape Rondinella.

The Mar Piccolo of Taranto has a total surface area of 20.72 km^2 structured in two shelves, the "First Seno" and the "Second Seno" connected by a 500 m wide strait. The maximum depth is about 15 m for the First Seno and about 10 m for the Second Seno. The average depth of the two subsystems is about 5 m [*Pastore*, 1993]. The Mar Piccolo is connected to the Mar Grande by two narrow channels, along the island of the old town of Taranto, the Navigabile channel (depth 10 m, length 500 m, width 76 m) and the Porta di Napoli channel (depth 5 m, length 250 m, width 112 m).

The outer inlets of the system experience a tidal excursion of 30 cm in spring tide and 16 cm in neap tide [*Scroccaro et al*., 2004].

The Mar Piccolo is characterized by the presence of about 30 submarine freshwater springs, locally called *Citri*. About 40 m^3 s^{-1} are continuously pumped out of the Mar Piccolo of Taranto and discharged directly into the Gulf of Taranto for industrial purposes. The hydrological balance of the system is generally negative due to the effect of evaporative processes.

2.6. Cabras Lagoon

Cabras Lagoon is a shallow water body (mean depth 1.7 m) located on the west coast of Sardinia, western Mediterranean Sea, and has a surface of 20 km^2. The lagoon of Cabras extends normal to the shoreline and is connected to the Oristano gulf by means of a net of four small creeks, few meters deep, flowing into the main open channel, the Scolmatore channel.

The tidal range in front of the lagoon inlets is about 30 cm. The specific morphology of the inlets and the small tides acting in the area tend to limit the water exchange between the lagoon and the coastal systems [*Ferrarin and Umgiesser*, 2005].

The northern part of the lagoon is connected to a small river, the Rio Mare Foghe, which represents the major source of freshwater. A smaller river, the Rio Tanui, enters in its southern part. River discharge is rather limited due to a low rainfall regime in the region. The lagoon salinity may drop to 10 psu during rainfall periods and rise up to 30 psu, especially in summer [*Cucco et al*., 2012].

2.7. Ganzirri and Faro Lagoons

Ganzirri and Faro lagoons are two interconnected small brackish basins located in Cape Peloro (Sicily, Italy). Ganzirri Lagoon has a surface area of 0.338 km^2, a major axis of 1670 m, and an average width of 200 m. Its maximum depth is 6.5 m and its estimated volume is 0.975×10^6 m^3. Faro Lagoon is a deep coastal basin that extends over 0.26 km^2, has a diameter of about 550 m, and reaches a maximum depth of 30 m [*Cosentino and Giacobbe*, 2011]. With its particular funnel shape, it represents a rare example of a meromictic coastal basin [*Saccà et al*., 2008].

The lagoons receive direct input of Ionian sea water from two main channels (Ganzirri and Faro channels, 300 and 400 m long, 40 and 70 cm deep, respectively, and 10 m wide) and communicate to each other through a small channel (Margi channel, about 40 cm deep, 900 m long, and 8 m wide). Tidal excursion at the inlets is about 17 cm.

There are no direct fluvial inputs into the lagoons and major freshwater inputs derive from nonpoint civil discharges [*Leonardi et al*., 2009].

2.8. Mar Menor

The Mar Menor is an hypersaline coastal lagoon, with a surface area of 136 km^2 located in SE Spain, a semiarid region of the SW Mediterranean coastline. The lagoon has a mean depth of 4.4 m and maximum of about 7 m. It is connected with the sea through three inlets (length 1.5, 1.5, and 0.7 km, width 500, 50, and 20 m, and depth 50 cm, 3.5 m, and 40 cm, from North to South, respectively). The tidal range experienced at the inlets is 20 cm.

Water temperature shows a regular seasonal cycle with a maximum reached in August (30°C) and a minimum in February (11.2°C). Salinity shows heterogeneous spatial and temporal distribution depending on season, rainfall, runoff, and Mediterranean influence through the main inlets, with a minimum of 38.1 and a maximum of 51 psu [*Perez-Ruzafa et al*., 2005].

More than 20 ephemeral watercourses flow into Mar Menor, mostly in its southern part. They are generally inactive, but can carry great quantities of water during torrential rain events [*García-Pintado et al*., 2007]. The mean annual rainfall is less than 300 mm yr^{-1} and potential evapotranspiration is close to 900 mm yr^{-1} [*Perez-Ruzafa et al*., 2005].

2.9. Nador Lagoon

Nador Lagoon is situated in the Mediterranean coast of Morocco. The lagoon basin has a volume of $5.4 \cdot \times 10^8$ m^3 and a surface of 110 km^2. The lagoon has an oval shape, quite regular (major axis length 23 km, minor axis length 7 km). The average depth of the lagoon is 4.8 m, with a maximum depth of 8 m. It is connected to the sea by a single central inlet, 130 m wide, 650 m long, and 2 m deep. At the inlet there is a tidal excursion of around 40 cm.

Small water discharges from some channels exist, but they are not important for the dynamics of the lagoon [*Ruiz et al*., 2006]. The rainfall is of about 300 mm yr^{-1} and the prevalent winds come from W-NW and E, which is about the direction of the major axis of the lagoon.

Along the coast of the lagoon the city of Nador and other smaller settlements are present. The main human activities are iron and steel industry and the Beni Ansar harbor. These activities and the presence of the human settlements cause considerable water pollution [*Ruiz et al*., 2006].

3. Methods

3.1. Model Description

The hydrodynamic model SHYFEM applied here has been developed at ISMAR-CNR (Institute of Marine Science—National Research Council, www.ismar.cnr.it/shyfem) [*Umgiesser et al*., 2004]. SHYFEM resolves the 3-D primitive equations vertically integrated over *z*-layers. It has already been applied successfully to several coastal environments [*Scroccaro et al.*, 2004; *Ferrarin and Umgiesser*, 2005; *Umgiesser et al.*, 2005; *Cucco and Umgiesser*, 2006; *Ferrarin et al.*, 2008; *Bellafiore et al.*, 2008; *Ferrarin et al.*, 2010a; *De Pascalis et al.*, 2011].

The model uses a semi-implicit algorithm for integration in time, which combines the advantages of the explicit and the implicit scheme. The spatial discretization of the unknowns is carried out with the finite element method, partially modified with respect to the classic formulation. This results in a grid that resembles a staggered grid often used in finite difference discretization.

The boundary conditions for stress terms (wind stress and bottom drag) follow the classic quadratic parametrization. Heat fluxes are computed at the water surface and water fluxes between air and sea consist in the prescribed precipitation minus evaporation computed by the SHYFEM model.

Smagorinsky's formulation [*Smagorinsky*, 1963; *Blumberg and Mellor*, 1987] is used to parameterize the horizontal eddy viscosity. For the computation of the vertical viscosities, a turbulence closure scheme was used. This scheme is an adaptation of the k-ϵ module of GOTM (General Ocean Turbulence Model) described in *Burchard and Petersen* [1999]. A more detailed description of the 3-D model equations is given in *Bellafiore and Umgiesser* [2010] and *Ferrarin et al.* [2013a].

3.2. The Transport Time Scales

The water transport time scale has been used as fundamental parameter for the understanding of the hydroecological dynamics in lagoon environments [*Gong et al.*, 2008; *Ferrarin et al.*, 2008, 2013b; *Wan et al.*, 2013]. Hydrodynamic time parameters in semiclosed basins can be defined in many different ways depending on the numerical technique used [*Takeoka*, 1984; *Monsen et al.*, 2002; *Delhez et al.*, 2004; *Jouon et al.*, 2006; *Liu et al.*, 2008; *de Brye et al.*, 2012; *Melaku Canu et al.*, 2012], but there is no unique agreed method of determination.

In this work, assuming that advection and diffusion can be reasonably considered, the main physical processes that influence the cleaning capacity of a lagoon, two parameters are used to compute the water transport time, the Water Renewal Time (WRT) and the Water Flushing Time (WFT).

WRT is computed by simulating the transport and diffusion of a Eulerian conservative tracer released uniformly throughout the entire lagoon with a concentration corresponding to 1, while a concentration of zero is imposed on the seaward and freshwater boundaries. The local WRT is considered as the time required for each cell of the domain to replace the mass of the conservative tracer, originally released, with new water [*Cucco and Umgiesser*, 2006; *Cucco et al.*, 2009; *Wan et al.*, 2013]. The average of local renewal times equals the overall water renewal time of the basin computed as the time integral of the total concentration over the model domain, divided by the initial amount of material in the water body. To compute the spreading and the fate of the tracer, a solute transport model is used, which solves the advection and diffusion equation using a high-order explicit scheme based on the total variational diminishing (TVD) method [*Cucco et al.*, 2009].

The basin-wide water flushing time is defined as the theoretical time necessary to replace the complete volume of the lagoon V with new water coming from the sea and from the rivers, assuming an hypothetical fully mixed basin. If the volumetric water flux flowing out of the system is Q, then the flushing time can be computed as [*Monsen et al.*, 2002]:

$$WFT = \frac{V}{Q} \tag{1}$$

The mean water outflow Q in this study is computed by the numerical model.

Another way to look at the WFT is comparing it to a stirred tank. In this analogy, all water masses entering the water basin, and characterized by tracer concentration equal zero, are immediately mixed with the water inside the basin. Therefore, the change in mass of the tracer C over one tidal cycle is:

$$\frac{d(CV)}{dt} = -QC \tag{2}$$

Using the fact that V is constant over one tidal cycle, this can be solved to give:

$$C(t) = C_0 e^{-t/\tau} \tag{3}$$

where C_0 is the initial tracer concentration and τ is the WFT as defined in equation (1). Therefore, in this idealized case WFT can be considered as WRT if the whole basin waters completely mix with the incoming waters.

The ratio between WFT and WRT can be interpreted as an index of the mixing behavior of the basin (i.e., mixing efficiency, ME). ME ranges between 0 and 1 and is equal to 1 in case of a fully mixed system (WRT becomes equal to WFT). In the theoretical case of ME = 0, the water masses entering the lagoon do not mix at all with the inner waters, and the renewal time goes to infinity.

3.3. Model Setup

A common model setup was chosen for the simulations in the 10 Mediterranean lagoons. The use of elements of variable sizes, typical of finite element methods, is fully exploited, in order to suit the complicated geometry of the different basins. The horizontal resolution of the numerical grids is site specific and reaches few meters in the small channels. The model runs in a 3-D baroclinic mode, with the water column discretized into vertical layers with variable thickness ranging from 1 m, in the topmost 10 m, to 5 m for the deepest layer.

In order to investigate the seasonal evolution of the renewal time and account for the effects of the initial time of the computation on its estimation, for each lagoon, more than one simulation was carried out. Typical renewal times computed for most of the studied lagoons are fractions of 1 year and this gave a possibility to repeat computations of renewal times during the year. It also gives a possibility to compute the temporal variation and a statistical average of the renewal time. The number of replicas was also limited by the availability of the forcing data. Two repetitions were performed for Lesina and Varano lagoons, four for Taranto Sea, Nador Lagoon and Venice Lagoon, eight for Cabras Lagoon (four per year), and twelve for Marano-Grado, Ganzirri (four per year), and Faro (four per year) lagoons. In the case of Mar Menor, only one replica was computed.

The applied forcing for each simulation are wind, heat fluxes, precipitation, total sea level, and freshwater river runoff. Forcing, initial (IC), and boundary conditions (BC) were derived from observations, where available, or obtained from other sources (literature, climatology, numerical models). Sea level measured outside the lagoon was used as BC in most of the case, except for Mar Menor and Nador Lagoon were astronomical tide derived from harmonic constants is applied. Measured water temperature (T) and salinity (S) boundary conditions were used in all cases, except for Nador Lagoon where monthly means climatology values derived from the World Ocean Atlas provided by the National Oceanographic Data Center (NOAA-NODC) are assigned. Meteorological forcing is imposed in all cases as single point observed time series, except for Nador Lagoon in which the data are extracted from ECMWF analysis fields. For river runoff values, where observations were not available, regression techniques from precipitation data (Cabras Lagoon) or runoff coefficients for each river, knowing the total basin freshwater input (Mar Menor), were used. For Nador Lagoon, no river discharges were considered, since they give negligible contribution to the dynamics of the system. All forcings, initial and boundary conditions, year of simulation, and number of model runs for each lagoon are summarized in Table 2.

SHYFEM model has been already applied to each lagoon and a detailed description of the site-specific model setup can be find in *Ferrarin et al*. [2010a] (Marano-Grado Lagoon), *Ferrarin et al*. [2010b] (Venice Lagoon), *Ferrarin et al*. [2013c] (Lesina Lagoon), *Molinaroli et al*. [2014] (Varano Lagoon), *Scroccaro et al*. [2004] (Taranto Sea), *Ferrarin and Umgiesser* [2005] (Cabras Lagoon), *Ferrarin et al*. [2013a] (Ganzirri and Faro lagoons), *De Pascalis et al*. [2011] (Mar Menor), and *Umgiesser et al*. [2005] (Nador Lagoon).

The numerical model has been validated in each site using available time series of measured water level (Venice, Marano-Grado, Lesina, Varano), water temperature and salinity (Venice, Marano-Grado, Lesina, Varano, Cabras, Mar Menor), and current velocity (Venice). Observed vertical profiles of salinity and water temperature were used to validate the model for the Faro, Ganzirri, and Taranto lagoons. Transport time scale model intercomparison was carried out for Nador Lagoon. A remarkable overall correlation between WRT as computed by the hydrodynamic model and apparent age from radium isotope was found for Venice Lagoon [*Rapaglia et al*., 2010].

Table 2. Simulations Details in Terms of Year of Reference, Number of Model Runs, Meteorological Forcings, River Runoff, Initial (IC), and Boundary Conditions (BC) for Sea Level and Water Temperature and Salinity (T-S)

Lagoon	Year	Number of Runs	Meteo	River Runoff	T-S IC	Sea Level BC	T-S BC
Marano-Grado	2005	12	Hourly	Daily	Spatially var.	Hourly	Monthly
Venice	2005	4	Hourly	Monthly	Spatially var.	Hourly	Monthly
Lesina	2010–2011	2	Hourly	Monthly	Spatially hom.	Hourly	Monthly
Varano	2000–2011	2	Hourly	Monthly	Spatially hom.	Hourly	Monthly
Taranto	2005	4	Hourly	Literature	Spatially hom.	Hourly	Monthly
Cabras	2006–2007	8	Hourly	Monthly	Spatially hom.	Hourly	Monthly
Ganzirri	2006–2008	12	3 hourly	Literature	Spatially hom.	Hourly	Monthly
Faro	2006–2008	12	3 hourly	Literature	Spatially hom.	Hourly	Monthly
Mar Menor	1997	1	Hourly	Literature	Spatially hom.	Harmonic const.	Monthly
Nador	2005	4	ECMWF data	No	Spatially hom.	Harmonic const.	Climatology

The numerical model was proved (see cited references) to correctly reproduce the main physical processes occurring in the investigated basins, e.g., tidal propagation, wind-induced currents and setup, seasonal heat and salt fluxes, thermohaline stratification, and vertical mixing in the deep Faro and Taranto basins. The deviation of the modeling results with respect to reality may be due to small spatial-scale and temporal-scale processes which are not resolved by the model. The high uncertainly on the freshwater inputs and the low resolution of the T/S boundary conditions may be partially responsible for this.

4. Results and Discussion

4.1. Transport Time Scale Variability

In this section, we present and discuss the temporal and spatial variability of the water renewal time in each considered lagoon, which is crucial for understanding the system's renewal capacity and the dispersion patterns of pollutants [*Cucco et al.*, 2006; *Ferrarin et al.*, 2008; *Sámano et al.*, 2012].

More than one value of renewal time was computed to be able to provide a sort of seasonality, in the cases where WRT are fractions of the year. This kind of analysis was not possible in the case of Mar Menor, where WRT is longer than 1 year. As shown in Figure 2, Venice, Cabras, Lesina, and Varano lagoons have longer renewal times during the summer season, probably due to the main action of evaporation, with low precipitation and limited injections of freshwater from rivers, and a calmer situation of the wind regimes. Faro Lagoon has the shortest WRT in the winter period, when vertical mixing is higher [*Ferrarin et al.*, 2013a]. A different behavior can be seen for Marano-Grado Lagoon where renewal time is strongly dependent on local meteo-marine conditions. In fact, even a short storm can reduce the water renewal time over the whole lagoon. This decrease is caused by enhanced water exchange due to water level fluctuations outside the lagoon and to enhanced mixing because of higher wind forcing inside the lagoon. Variations are of the order of few days for Marano-Grado Lagoon, while bigger differences during the year are registered for the other lagoons (tens of days). Ganzirri, Taranto, and Nador lagoons do not show a remarkable seasonal WRT evolution.

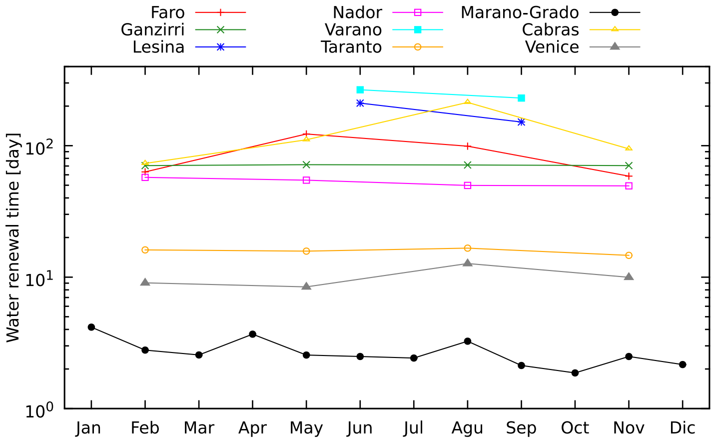

Figure 2. Temporal variation of the water renewal times for the Mediterranean lagoons, computed for each repetition. Mar Menor is not shown since only one run was carried out.

Coastal systems with complex morphology exhibit a highly heterogeneous spatial distribution of the water renewal time. Therefore, WRT maps can also clearly identify areas where waters are either well mixed or poorly mixed [*Hartnett et al.*, 2012]. Examples of vertically integrated WRT distribution are shown in Figure 3 for Marano-Grado, Varano, and Cabras lagoons. In many

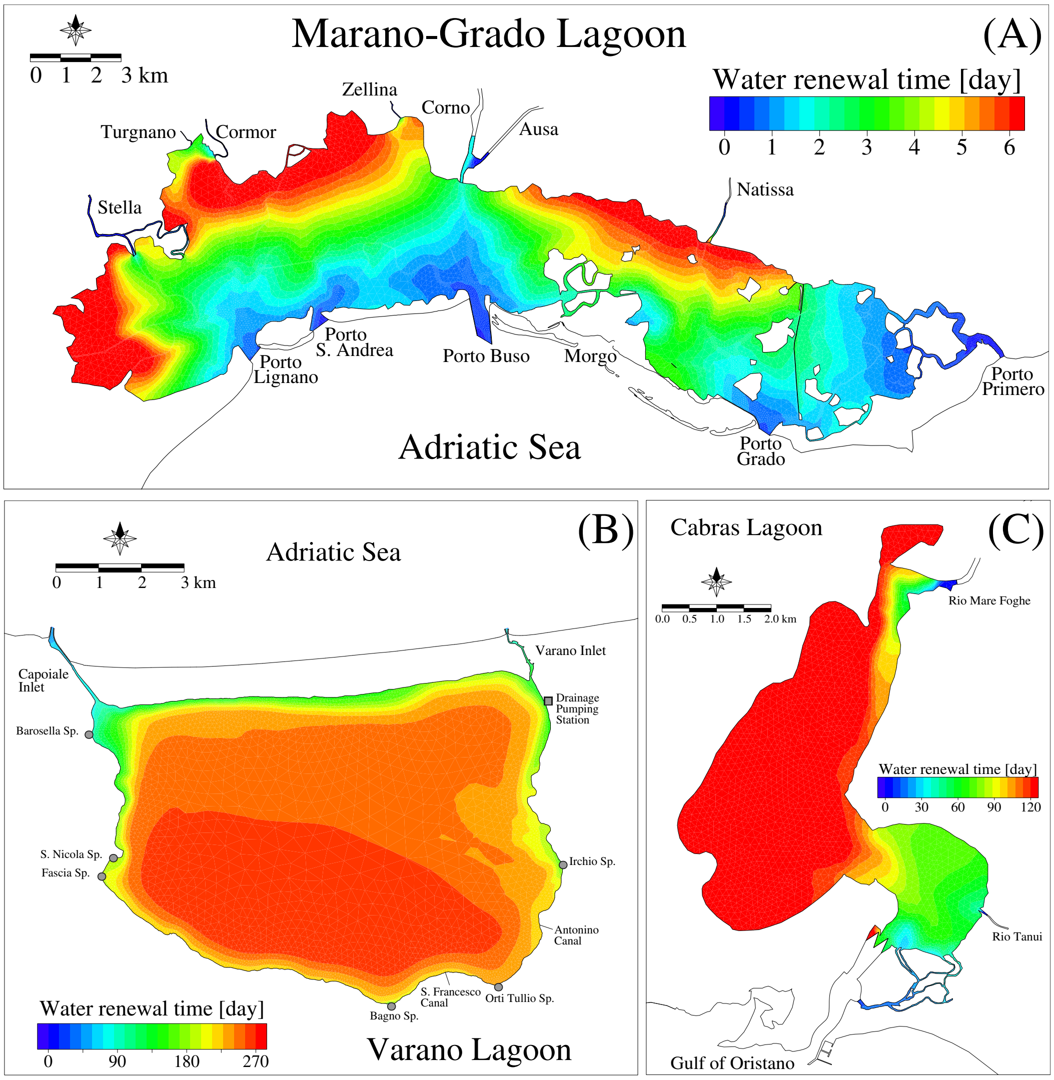

Figure 3. Vertically integrated water renewal time maps for (a) Marano-Grado Lagoon, (b) Varano Lagoon, and (c) Cabras Lagoon.

cases (Venice, Marano-Grado, Taranto, Nador, Varano, Ganzirri, and Mar Menor), WRT is mainly dependent on the relative distance from the inlets and on the presence of channels. The areas connected to these channels are directly influenced by the sea and consequently their water renewal times are lower. In other basins (Lesina and Cabras), the river runoff plays also a role in determining the water renewal heterogeneity.

Of particular interest is the meromictic Faro Lagoon, which, with its particular deep funnel shape and due to the permanent stratification, is characterized by strong vertical WRT variability. The warm upper layer (mixolimnion) exchanges water with the open sea and has an average WRT of 23 days, while in the hypolimnion, the stagnant deep layer dominated by diffusive mixing, the water renewal time reaches more than 200 days [*Ferrarin et al*., 2013a].

Moreover, the renewal time frequency distribution was analyzed for each lagoon for the identification of subbasins having different physical characteristics. This analysis, shown in Figure 4, consists in defining the percentage of the lagoon volume characterized by a certain water renewal time.

For the Venice and Marano-Grado lagoons, a typical frequency curve for a tidal lagoon, as given in *Rodhe* [1992] can be seen. It shows a unimodal distribution with one maximum close to, but lower than the

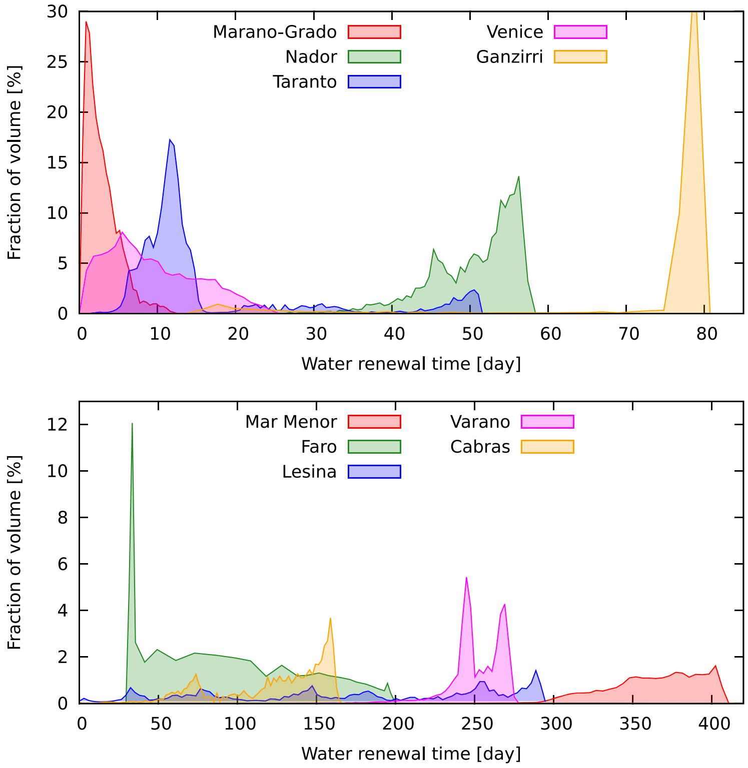

Figure 4. Water renewal time frequency graphs for all lagoons.

average WRT of the lagoon (see Table 3 for reference). Other unimodal distributions can be found for the Mar Menor and Nador lagoons, but now the maximum has been shifted to much higher values, with very low frequency values for low renewal times. This is due to an internal recirculation cell that shows a spatially homogeneous high renewal time, but that is very little participating in the exchange with the sea. Varano Lagoon shows a similar behavior, but has two peaks close to the average values.

The other cases differ from the unimodal curves seen before. The Taranto Sea case shows a peculiar curve with three distinct peaks, corresponding to 12, 30, and 50 days. Each of these values can be connected with one of the subbasins (Mar Grande, I Seno, II Seno). Ganzirri Lagoon shows a curve with two distinct peaks, a small one (at 18 days), which represents the shallow eastern subbasin close to the Ganzirri seaward channel, and a second big maximum with WRT of 78 days, which represents the western deep subbasin characterized by the internal recirculation cell. Faro Lagoon shows a distribution with a peak around 30 days, which identifies the well-mixed mixolimnion (about 5 m thick) and a long tail of the curve which represents the part of the basin below the mixolimnion that has very little participation in the exchange with the sea

Table 3. Model Simulation Results for Each Lagoon in Terms of Average Water Flux Through the Inlets, Fraction of Basin Volume Exchanged Daily With the Open Sea (FVE), Water Renewal Time (WRT), Water Flushing Time (WFT), and Mixing Efficiency (ME)

Lagoon	Flux (m^3 s^{-1})	FVE (adim)	WRT (days)	WFT (days)	ME (adim)
Marano-Grado	4029.6	1.15	3.0	0.9	0.30
Venice	9509.0	0.65	10.4	1.5	0.15
Lesina	7.8	0.01	181.0	87.1	0.52
Varano	33.2	<0.01	248.2	133.4	0.54
Taranto	853.3	0.09	16.2	11.1	0.68
Cabras	22.5	0.03	122.5	30.1	0.25
Ganzirri	1.7	0.09	71.0	10.8	0.15
Faro	2.1	0.04	86.0	28.3	0.33
Mar Menor	70.6	<0.01	384.0	196.2	0.51
Nador	351.6	0.03	52.8	35.3	0.67

[*Ferrarin et al*., 2013a]. The WRT frequency distribution for the Cabras Lagoon shows two peaks and therefore, from the hydrological standpoint, the lagoon can be subdivided into two subbasins, a southern one close to the connection channels, having WRT in the order of 60–80 days, and a northern one with WRT between 120 and 160 days. Finally, Lesina Lagoon shows a relatively homogeneous distribution which represents the smooth west-east WRT gradient [*Ferrarin et al*., 2013c].

It has to be noted that most of the Mediterranean lagoons considered in this study have limited freshwater input. Anyway in some cases (Marano-Grado, Lesina, and Cabras lagoons) low values of the renewal time can be found close to the inlet and to the river mouth and therefore a proper spatial zonation should also account for other parameters, as salinity and bottom sediment characteristics [*Ferrarin et al*., 2008].

4.2. Lagoon Intercomparison and Classification

The results of the numerical simulations in terms of fluxes at the inlets, fraction of lagoon water volume exchanged daily with the sea (FVE), average water renewal time (WRT), flushing time (WFT), and mixing efficiency (ME), for each lagoon, are provided in Table 3.

The presented results highlight the wide hydrodynamical variability of the Mediterranean lagoons. The openness with the sea and therefore the water exchange with the open sea is positively correlated with the tidal range. The lagoons located in the Northern Adriatic Sea, Marano-Grado, and Venice, are the ones with the most active exchange with the open sea, driven by the tidal action. Each day more than half of the basin volume is renewed through the inlets. On the other side, most of the investigated basins have limited connection with the sea and less than one-tenth of the basin volume is exchanged daily through the inlets.

Numerical results show that the basin-wide average water renewal time ranges from few days in the Marano-Grado lagoon to more than 1 year in the case of the Mar Menor. The transport time scales in the investigated lagoons are mostly influenced by the exchange with the open sea, but also other factors (wind and stratification) influence the renewal processes.

In lagoons with only one inlet (Nador and Cabras) or close-by inlets (Taranto), the wind is not contributing to the flushing with the sea, but is only mixing internally the lagoon water. As has been shown by *Umgiesser et al*. [2005], in Nador Lagoon, increasing the wind speed does not enhance the exchanges with the sea, but creates a well-mixed condition within the basin. Therefore, during this situation the renewal time is very close to the flushing time.

In lagoons with more inlets, the wind can create a setup inside the lagoon which then enhances the exchange with the sea. For example, in Venice, the Bora wind, which is blowing from NE, creates a setup in the southern area and a set-down in the northern area. In this way, a part from the tidal exchange, a steady circulation is created where water enters the northern inlet and leaves the southern one, enhancing effectively the water exchange. Similar exchange mechanisms can be found in the other lagoons here presented with more than one inlet.

However, even in the presence of strong winds the lagoon may be not well mixed. This happens if a strong and stable stratification is present. An example here is the Faro Lagoon, where during summer time a warm water body covers a cold one and where winds can mix only the upper part of the lagoon. In this case, the mixing efficiency is lower than expected.

According to *Kjerve* [1986] and *Kjerfve and Magill* [1989], coastal lagoons can conveniently be subdivided into choked, restricted, and leaky systems based on the degree of water exchange between lagoon and ocean. Lagoon type classification was archived in this study according to WRT and to the fraction of lagoon water volume exchanged daily with the open sea (Figure 5). Even if no sharp distinction among hydromorphological types exists, the results of this study identify the Marano-Grado Lagoons as examples of leaky lagoon, the Taranto Sea, Ganzirri, Faro, Nador, and Cabras as restricted lagoon, while the Mar Menor is a good example of a chocked lagoon. Venice Lagoon may be defined between leaky and restricted and Lesina and Varano lagoons may be identified as between restricted and choked systems. It must be stressed that the term choked is only referring to the exchange characteristics of lagoons as used in *Kjerve* [1986], and is not indicating the phenomenon of tidal choking, which is the reduction of tidal range inside a (confined) water body.

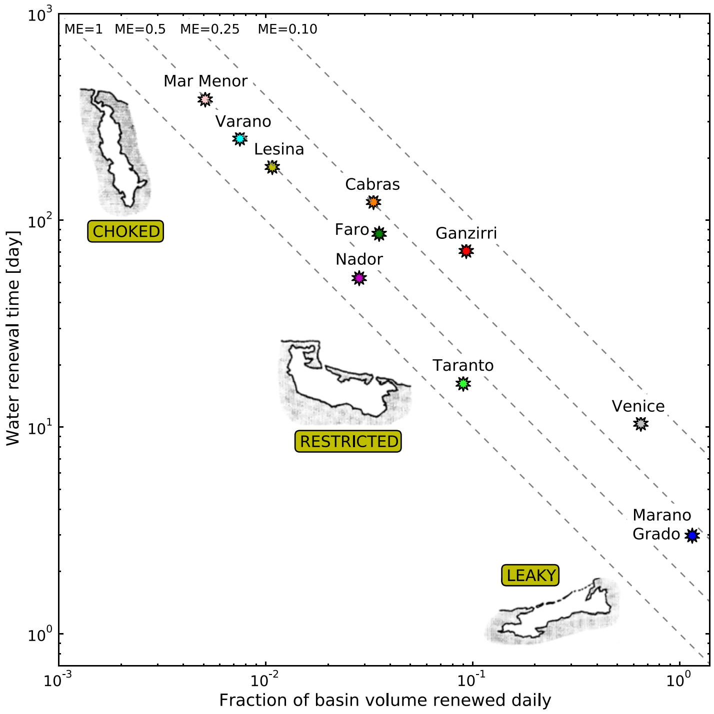

Figure 5. Classification of the 10 Mediterranean lagoons based on simulated water renewal time and daily fraction of water volume exchanged with the coastal sea. The four gray dashed lines represent mixing efficiency (ME) values equal to 1, 0.5, 0.25, and 0.1. Leaky, restricted, and choked water body sketches are from *Kjerfve and Magill* [1989].

In Figure 5, the four gray dashed lines represent mixing efficiency values equal to 1, 0.5, 0.25, and 0.1 (see Table 3 for reference). As explained above, WFT and WRT values tend to be equal only if the lagoon is well mixed and consequently all the points lie to the right of the ME = 1 line. The closer the point is to this line, the more the system is well mixed. Therefore, our results could also be used to describe the different hydrodynamic behavior that characterizes the spatial heterogeneity inside the lagoons.

Lowest ME can be found in Venice Lagoon (ME = 0.15) due to its complicated morphology composed by channels, tidal flats, and salt marshes and in Ganzirri (ME = 0.15) and Cabras (ME = 0.25) lagoons, which have a particular shape and internal circulation dynamic [*Ferrarin and Umgiesser*, 2005; *Ferrarin et al*., 2013a]. In Venice, the whole northern part and most of the western part are semisheltered by a belt of salt marshes from the central lagoon, effectively lowering the mixing efficiency. In Ganzirri, the whole western part is hardly influenced by the circulation close to the inlet and is not participating in the water exchange. Finally, in Cabras there are two basins, a big one in the west that is exposed to the Mistral winds, and a smaller one, close to the inlets, that is separated from the general circulation of the main lagoon.

High values of ME (greater than 0.5) can be found in chocked basins (Mar Menor, Lesina, and Varano), where the exchange with the open sea is very low and the wind has enough time to mix the basins well. All three lagoons mentioned also show a high level of morphological homogeneity in their inside, which makes it easy for the wind to mix the waters. The other two systems with high mixing efficiency are slightly different. Taranto Sea (ME = 0.68) has a deep inlet that allows a two-layer dynamics, which enhances the mixing of the outer basin. Moreover, the submarine freshwater springs inhibit thermal stratification and favor the vertical mixing in the two inner shelves. In Nador Lagoon (ME = 0.67), due the fact that there is only one central inlet, the wind is strongly contributing to mixing and not influencing the exchange with the open sea [*Umgiesser et al*., 2005].

An intermediate situation (ME = 0.30) can be found for Marano-Grado where the exchange is driven mostly by tides. Even if the tidal forcing is very similar to the Venice lagoon, some differences exist. One is the relative openness of the Marano-Grado lagoon with its six inlets, which allows a homogeneous flushing of the lagoon. Moreover, contrary to the Venice lagoon, the inside of the Marano-Grado lagoon is not obstacled by salt marshes and presents itself as a much more homogeneous environment. This all contributes to a higher mixing efficiency of the system.

Finally, judging from the inlet characteristics, Faro Lagoon should really be a well-mixed system, because water exchange is very limited. However, as already mentioned, during summer time, the wind can mix only the upper part of the basin, whereas the part below the thermocline does not take part in the mixing, lowering the ME to a value of 0.33.

5. Conclusions

A first attempt to use modeling as a suitable tool to classify and study the basic hydrodynamic characteristics of a number of Mediterranean lagoons has been presented. The studied parameters concern the hydrodynamics of lagoons, identifying renewal time, interaction with the open sea they are connected with and internal mixing processes.

We demonstrated that the analysis of the frequency distribution of WRTs allows in some cases (Ganzirri, Faro, Cabras lagoons, and Taranto Sea) the identification of well defined subbasins having different physical characteristics. Other systems, as Venice, Marano-Grado, Nador, and Lesina lagoons, have a smooth spatial gradient of the water renewal time, while some others (Varano Lagoon and Mar Menor) show a rather homogeneous WRT distribution.

Water renewal time and fraction of water volume exchanged daily with the coastal sea were used to classify10 lagoons in leaky lagoons (Marano-Grado), restricted lagoons (Taranto Sea, Cabras, Nador, Faro and Ganzirri), choked lagoons (Mar Menor), and intermediate types (Lesina, Varano and Venice). The analysis of renewal time frequency and seasonal variation permitted to spatially and temporally characterize different water bodies inside each lagoon.

Tidal action and wind setup are the main processes controlling water exchange and thereby the flushing time, while mixing efficiency is controlled by the internal circulation dynamics which is a function of morphological complexity and wind action in shallow water basins, and stratification in the deep systems.

In the next future, the influence of climate change on these coastal environments will be investigated, studying also the evolution of the temperature and salinity fields.

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