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Assessing hydrological effects of human interventions on coastal systems: numerical applications to the Venice Lagoon

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Abstract

The hydrological consequences of historical, contemporary and future human activities on a coastal system were investigated by means of numerical models. The changes in the morphology of the Lagoon of Venice during the last century result from the sedimentological response to the combined effects of human interventions on the environment and global changes. This study focuses on changes from 1927 to 2012 and includes the changes planned for the protection of the city of Venice from storm surges and exceptional tides under future sea level rise scenarios. The application of a hydrodynamic model to simulate the circulation of water masses and the transport of a passive tracer enabled the analysis of the morphodynamic effects on the lagoon circulation and the interaction with the sea. The absolute values of the exchange between the lagoon and sea increased from 1927 to 2002 (from 3900 to 4600 $\mathrm{m^3\,s^{-1}}$), while the daily fraction of lagoon water volume exchanged decreased. At the same time, the water renewal time shortened from 11.9 to 10.8 days. Morphological changes during the last decade induced an increase of the basin-wide water renewal time (from 10.8 to 11.3 days). In the future, Venice Lagoon will evolve to a more restricted environment due to sea level rise and periodical closure of the lagoon from the sea during flooding events. Simulated scenarios of sea level rise showed that under fall-winter conditions the water renewal time will increased considerably especially in the central part of the lagoon. Furthermore, some considerations on the impact of the hydromorphological changes on the ecological dynamics are proposed.

1 Introduction

Lagoons are ephemeral environments from an geological point of view and are naturally subjected to rapid morphological changes on a very short time scale. Their evolution depends on the interaction between natural processes, human activities and hydromorphological responses to such activities (Kjerfve and Magill, 1989). Hydrodynamics determine most of the physical and biogeochemical processes affecting coastal and lagoon environments (Viaroli et al., 2007; Pérez-Ruzafa et al., 2011). Man-induced hydromorphological modifications can therefore drastically alter the hydraulic forcing and consequently also the ecological status of such a highly dynamic environment (Tagliapietra et al., 2009).

Investigating hydromorphology of a lagoon requires a large amount of information, which in most cases cannot be easily provided. Only in few cases, i.e. Aveiro Lagoon (Duck and da Silva, 2012), Venice Lagoon (Molinaroli et al., 2007; Sarretta et al., 2010) and San Pablo Bay (Jaffe et al., 2007), the available dataset allows detailed geological and geomorphological investigations. On the other side, numerical models provide a powerful tool for investigating the response of the lagoon hydrodynamics to historical or even future engineering interventions (Gong et al., 2008; Carniello et al., 2009; Ghezzo et al., 2010; Bruneau et al., 2011).

Among the hydrological parameters, the water transport time scale has been widely used in this context since it is an integrative variable providing an overall estimate of the lagoon hydrodynamics. The water transport time scale has been regarded as fundamental parameter in understanding chemical and ecological dynamics in lagoon environments (Gamito et al., 2004; Gong et al., 2008). Several definition of transport time scales exist, referring to different concepts. There are several studies describing and comparing different transport time scales (Takeoka, 1984; Monsen et al., 2002; Jouon et al., 2006; Liu et al., 2008; Cucco et al., 2009; de Brye et al., 2012). Our intent is not to debate this issue, but to provide insight on the applicability of such an indicator.

The aim of this study was to investigate the hydrological regime and renewal capacity of the heavily modified Venice Lagoon via a modelling approach following the morphological changes carried out from 1927 to 2012 and the future sea level rise (SLR) scenarios. The progressive change of the lagoon morphology was represented by adopting four numerical grids, with different coastline and bathymetry, corresponding to the situation of the lagoon in year 1927, 1970, 2002 and 2012. Furthermore, future scenarios were carried out simulating sea level rise and the closure of the mobile barriers at the inlets during flooding events.

As anthropogenic influences on aquatic environments increase, there is considerable scientific and practical interest in understanding how the ecological components will respond to multiple stressors. Therefore, in the last part of this study some hydroecological considerations are presented to improve our understanding of ecological changes happened in the Lagoon of Venice during last decades and to hypothesize some implications in future scenarios.

1.1 Study area

Venice Lagoon, a coastal system located in the Northwest Adriatic Sea (Fig. 1), covers roughly an area of 500 km^2; its major axis is oriented north-east to south-west. It is characterized by a complex network of channels, intertidal flats and shoals. Currently, a few principal deep channels (maximum depth around 15 m) cross an area of very shallow water with an average depth on the order of 1 m. The three inlets are called, from north to south, Lido, Malamocco and Chioggia and are from about 500 to about 900 m wide and up to 17 m deep.

The morphological evolution of the Lagoon of Venice has been strongly influenced by the human presence since remote times. From a few century after its colonisation, the Venetians tried to modify the environment in the attempt to preserve economic interests and for defense purposes (Guerzoni and Tagliapietra, 2006; Solidoro et al., 2010). Priority was given to the management of freshwater and sediment yield of the drainage-basin tributaries to prevent sedimentation in marginal areas, which exposed the city to the threat of invasions from the mainland. The main intervention realized from the second half of the 16th century was the diversion of main rivers (Piave and Brenta) that determined a strong imbalance in the sediment budget of the lagoon. Other important issues were the protection of the barrier islands from storm waves and the accessibility to the port channel. The navigation channel was endangered by the long-shore transport of sand that caused the formation and the SW migration of a large sand bar immediately outside of the lagoon. Several measures were taken throughout the centuries but a definitive solution was found only at the end of the 19th century with the construction of long jetties that joined the flow of three previous inlets in a single self dredging channel which is presently known as Lido Inlet (D'Alpaos, 2010).

In this study we focus on changes occurred from 1927, after the protection of the inlets with jetties, to the present days (2012). For this period detailed bathymetric and morphological data are available (Sarretta et al., 2010). They are:

- Salt marshes destruction from 1927 to 1960 to reclaim land for the construction of the industrial zone (a total of 22 km^2), together with Venice airport and urban development on the lagoon-side of the city of Mestre (S. Giuliano), the latter two occupying a further 5 km^2;
- Dredging of the Malamocco-Marghera ship channel in the central part of the lagoon from 1960 to 1970.
- Restoration activities, which included salt marsh stabilization up to the construction of artificial salt marshes, since the early 1990s.
- Inlet reconfiguration from 2002 to 2012 to construct the mobile barrier system (MoSE, from the Italian acronym for Experimental Electromechanic Module) for defending the city of Venice from floods caused by exceptional tides and storm surges. The main changes are the construction of an artificial island in the middle of the Lido inlet, and the creation of breakwaters and refuge harbours in each inlets. The MoSE project entails building mobile barriers at the bottom of each inlet that, when flood events threaten to become critical, will rise and shut off the lagoon from the sea. The level of 110 cm (above local datum), which conventionally defines the exceptional flooding event (locally called *acqua alta*, *high water*), is the value above which the gates would close to separate the lagoon from the sea (Carbognin et al., 2010). Some hydrodynamic consequences of inlet modification and closure have been previously investigated through numerical models

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by Melaku Canu et al. (2001),Umgiesser and Matticchio (2006) and Ghezzo et al. (2010).

The main morphological alterations in the period 1970–2002 were an extensive deepening of the lagoon (as a results of subsidence and loss of sediment), and the areal diminution of the salt marshes (Carniello et al., 2009; Sarretta et al., 2010).

2 Materials and methods

A framework of numerical models (SHYFEM, available online at www.ismar.cnr.it/shyfem; Umgiesser et al., 2004) was applied to the surface domain of Venice Lagoon and its adjacent shore. Water renewal times are estimated computing the dispersal and fate of the conservative tracer. The model is especially well suited to very shallow areas and has been successfully applied to several shallow water coastal systems (Umgiesser et al., 2004; Ferrarin and Umgiesser, 2005; Ferrarin et al., 2008, 2010b; De Pascalis et al., 2011).

2.1 Hydrodynamic model description

The 3-D hydrodynamic model SHYFEM here applied uses finite elements for horizontal spatial integration and a semi-implicit algorithm for integration in time (Umgiesser and Bergamasco, 1995; Umgiesser et al., 2004).

The primitive equations, vertically integrated over each layer, are:

$$\frac{\partial U_l}{\partial t} + u_l\frac{\partial U_l}{\partial x} + v_l\frac{\partial U_l}{\partial y} - fV_l = -gh_l\frac{\partial \zeta}{\partial x} - \frac{h_l}{\rho_0}\frac{\partial p_a}{\partial x}$$
$$+\frac{1}{\rho_0}\left(\tau_x^{\mathrm{top}(l)} - \tau_x^{\mathrm{bottom}(l)}\right) + \frac{\partial}{\partial x}\left(A_h\frac{\partial U_l}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_h\frac{\partial U_l}{\partial y}\right)$$

$$\frac{\partial V_l}{\partial t} + u_l \frac{\partial V_l}{\partial x} + v_l \frac{\partial V_l}{\partial y} + fU_l = -gh_l \frac{\partial \zeta}{\partial y} - \frac{h_l}{\rho_0} \frac{\partial p_a}{\partial y} + \frac{1}{\rho_0}\left(\tau_y^{\mathrm{top}(l)} - \tau_y^{\mathrm{bottom}(l)}\right) + \frac{\partial}{\partial x}\left(A_h \frac{\partial V_l}{\partial x}\right) + \frac{\partial}{\partial y}\left(A_h \frac{\partial V_l}{\partial y}\right) \quad (1)$$

$$\frac{\partial \zeta}{\partial t} + \sum_l \frac{\partial U_l}{\partial x} + \sum_l \frac{\partial V_l}{\partial y} = 0$$

with l indicating the vertical layer, (U_l, V_l) the horizontal transport at each layer (integrated velocities), f the Coriolis parameter, p_a the atmospheric pressure, g the gravitational acceleration, ζ the sea level, ρ_0 the average density of sea water, τ the internal stress term at the top and bottom of each layer, h_l the layer thickness. Smagorinsky's formulation (Smagorinsky, 1963; Blumberg and Mellor, 1987) is used to parameterize the horizontal eddy viscosity (A_h). 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).

The model uses a semi-implicit algorithm for integration over time, which has the advantage of being unconditionally stable with respect to gravity waves, bottom friction and Coriolis terms, and allows transport variables to be solved explicitly without solving a linear system (Umgiesser et al., 2004). The Coriolis term and pressure gradient in the momentum equation, and the divergence terms in the continuity equation are treated semi-implicitly. Bottom friction and vertical viscosity are treated fully implicitly for stability reasons due to the shallow nature of the lagoon, while the remaining terms (advective and horizontal diffusion terms in the momentum equation) are treated explicitly (Umgiesser et al., 2004; Umgiesser and Bergamasco, 1995). The maximum allowable time step in the simulation was set to 100 s, and the model adopts automatic sub-stepping over time to enforce numerical stability with respect to advection and diffusion terms.

2.2 Water renewal time and return flow factor

In this study, assuming that advection and diffusion are the main physical processes that influence the cleaning capacity of the lagoon's ecosystem (Rodhe, 1992), the water renewal time was used to compute the transport time of lagoon's waters.

In this study, the water renewal time (WRT) was considered as the time required for each element of the domain to replace the mass of a conservative tracer with new water (Cucco and Umgiesser, 2006; Cucco et al., 2009; Ferrarin et al., 2008). Such a transport time scale can be associated with the renewal time concept and is an adequate indicator related to environmental health of the aquatic system (Abdelrhman, 2005; Plus et al., 2009; Ouillon et al., 2010; Hartnett et al., 2011). The model solves the 3-D advection and diffusion equation to compute the dispersal and fate of the conservative tracer, which is given by:

$$\frac{\partial C_l}{\partial t} + u\frac{\partial C_l}{\partial x} + v\frac{\partial C_l}{\partial y} + w\frac{\partial C_l}{\partial z} = \frac{\partial}{\partial x}\left(K_H\frac{\partial C_l}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_H\frac{\partial C_l}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_V\frac{\partial C_l}{\partial z}\right) \tag{2}$$

where C_l is the concentration of the conservative tracer at layer l, u, v and z are the velocities, K_H and K_V are respectively the horizontal and vertical turbulent diffusion coefficients. The transport and diffusion equation is solved with a first-order explicit scheme based on the total variational diminishing (TVD) method.

To compute the WRT we refer to the mathematical expression given by Takeoka (1984) known as the remnant function. The water renewal time can then be computed for each point of the domain as (Cucco and Umgiesser, 2006):

$$\widetilde{\mathrm{WRT}}(x,y,z) = \int_{t=0}^{\infty} r(t,x,y,z)\mathrm{d}t \tag{3}$$

where $r(t,x,y,z) = C(t,x,y,z)/C(0,x,y,z)$ is the local remnant function, with $C(t,x,y,z)$ the local concentration of a conservative tracer at time t (s) and $C(0,x,y,z)$

its initial value. The integral in the above equation is numerically approximated in accordance with the simulation time step. To account for the residual tracer mass at the end of the simulation, local water renewal time values are subsequently corrected, assuming exponential decay of the tracer, as:

$$\mathrm{WRT}(x,y,z) = \frac{\widetilde{\mathrm{WRT}}(x,y,z)}{1 - r(T,x,y,z)} \tag{4}$$

where $r(T,x,y,z)$ is the local remnant function at the end of the simulation ($t = T$).

The volume-weighted average of local renewal times ($\overline{\mathrm{WRT}}$) 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.

The water renewal time of a semi-closed basin can be strongly influenced by the properties of the outgoing flow and by the interaction with the coastal currents. In tidally dominated basins, for each tidal cycle, a fraction of the tracer flows out to sea during the ebb tide, but a part of it can flow back into the lagoon again during the next flood tide. Sanford et al. (1992) proposed the definition of *return flow factor* (RFF) as an estimate of the proportion of lagoon water flowing out to sea that returns to the basin. It can be calculated for the whole lagoon domain as:

$$\mathrm{RFF} = \frac{\overline{\mathrm{WRT}} - \overline{\mathrm{WRT}_0}}{\overline{\mathrm{WRT}}} \tag{5}$$

where $\overline{\mathrm{WRT}}$ is the basin-wide average water renewal time and $\overline{\mathrm{WRT}_0}$ is the basin-wide average water renewal time calculated for the situation in which all the tracer that exits the basin vanishes. RFF ranges between 0 (no tracer return) and 1 (the whole tracer mass re-enters) (Cucco and Umgiesser, 2006).

2.3 Simulations set-up

The hydrodynamic numerical computation is performed on a spatial domain that represents the Venice Lagoon and its adjacent shore. The use of elements of variable sizes, typical of finite element methods, is fully exploited, in order to suit the complicated geometry of the basin, the rapidly varying topographic features, and the complex bathymetry. Four numerical grids were constructed representing the morphology of the Venice Lagoon in 1927, 1970, 2002 and 2012. The numerical grid of the 2012 configuration is represented in Fig. 2. The water column is discretized into 17 vertical levels with progressively increasing thickness varying from 1 m for the topmost 10 m to 7 m for the deepest layer of the outer shelf.

The factors affecting the transport process have a high influence on the calculation of the WRT. In the Venice Lagoon, tide (about 1 m tidal range during spring tides) and wind are the most important forcing factors and, in particular, the direction of the wind (Bora and Scirocco), the frequency, duration and intensity of wind events affects strongly the circulation regime of the lagoon and, as consequence, the WRT. In this paper the baroclinic contribution is not considered, therefore the model results take into account only the water exchanges between the lagoon and the sea induced by the tide and wind action.

Four yearly simulations, representing the Venice Lagoon configuration in 1927, 1970, 2002 and 2012, were carried out (named Y_1927, Y_1970, Y_2002 and Y_2012). Considering that we simulate the circulation of the lagoon under realistic tide and wind forcing conditions (the selected year of reference is 2002) and that the results may depend on the initial time of the simulation, we calculated WRT every three months along one year and considered an average values of four repetitions as mean $\overline{\mathrm{WRT}}$ for the year.

In order to investigate effects of morphological modifications during *high water* condition, a set of monthly simulations was carried out (simulation named M_1927, M_1970, M_2002 and M_2012). The period of reference of these simulations is November 2002, during which seven *high water* events occurred. Furthermore, four additional simulations were performed for the 2012 configuration considering the closure of barriers at water level higher than 110 cm (above local datum), and increasing the boundary water level by 0, 10, 30 and 50 cm, to reproduce future sea level rise scenarios (simulations named SLR_00, SLR_10, SLR_30, SLR_50). The absence of water flux through the inlets during the rise of the barriers was simulated by increasing bottom shear stress and viscosity in the inlets area.

All simulations were forced by hourly observations of wind and water level recorded in the open sea in front of the lagoon at the oceanographic tower *Acqua Alta* (up to 15 km offshore). The characteristics of the performed simulations are summarized in Table 1.

The conservative tracer was initially released uniformly throughout the entire lagoon with a concentration corresponding to 1, while a concentration of zero was imposed on the seaward boundary. The horizontal turbulent diffusivity was calculated using the model proposed by Smagorinsky (1963), with a Smagorinsky parameter of 0.3. Vertical diffusivities are calculated by the k-ϵ turbulence closure model.

The model application to the Venice Lagoon has been calibrated in previous works reproducing correctly the flows in the three inlets without and with the MoSE structures (Ghezzo et al., 2010). A full calibration and evaluation of the model capability have been conducted by (Ferrarin et al., 2010a) by the comparison between modelled and measured data of the tidal level inside the lagoon, of the vertical velocity profile over a full tidal cycle at Lido inlets and of the total flux on the three inlets. The numerical procedure for simulating the closure of the barrier has been successfully tested in (Umgiesser and Matticchio, 2006).

3 Results

Modelling results are divided in two sections: the first describes the simulation output of the historical and contemporary layouts (1927–2012), while the second presents the future sea level rise scenarios considering the shut off of the lagoon due to the MoSE barriers.

3.1 1927–2012 evolution

The evolution of the WRTs is linked to the different situation of the bathymetry, of the lagoon perimeter and of the inlets structure, represented by the different grids. The method permits to examine both the $\overline{\text{WRT}}$ value for the whole basin and the local WRT, with a spatial differentiation depending on the local circulation.

Model results for these simulations, as average values for the whole basin, are summarized in Table 2. Fig. 3 shows that the total water exchange with the sea increases from the year 1927 to the year 1970 because of the opening of the Malamocco-Marghera channel and the deepening of the shallow areas, as indicated by the increase of volume and by land reclamation. The variation of the relative importance of the flow through each inlet with respect to the others is not relevant. This means that the increase in the volume of each sub-basin compensates the enhancement in the water flow maintaining the position of the watershed almost unchanged. From 2002 to 2012 the total water flow tends to reduce after the construction of the MoSE infrastructures that slightly decrease the fluxes (Ghezzo et al., 2010). From Fig. 3 it is evident that the flux through some inlets, during ebb and flood phase, does not have a symmetrical behaviour in all the considered situations. For the period 1930–2000, passing from flood to ebb phase, the flow through the Lido inlet increases, and it reduces through the Chioggia inlet, whereas Malamocco inlet maintains a balanced behaviour. With the MoSE structures almost completely in place, as for the present situation (year 2012), even the Malamocco inlet shows a slightly unbalanced behaviour with incoming fluxes greater than the outgoing fluxes.

The basin-wide average water renewal times of the Venice Lagoon are reported in Table 2. The $\overline{\text{WRT}}$ tends to decrease from 1927 (11.9 days), to 1970 (11.0 days), until to 2002 (10.8 days). Only with the last change of the inlet morphology in 2012 (MoSE) it tends to slightly increase (11.3 days).

Qualitatively, the spatial distribution of WRT is heterogeneous, 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 (Fig. 4). The main characteristics of WRT spatial distribution remain similar in the considered scenarios, with a gradient going from the inlets towards the inner margins of the lagoon. Only in 1970 the northern part of the basin appears to have lower WRT than in the other situations.

The comparison between the frequency distribution of the water renewal times and the variations of the elevation of the lagoon (Fig. 5) indicates that:

- From the year 1927 (red continuous line) to 1970 (green dashed line), the frequency of the highest WRT values decreases, whereas the frequency of very low WRT (around 2 days overall) increases significantly. At the same time the bathymetry of the lagoon becomes generally deeper with an overall variation of 0.5 m (from the range $-0.5:0.5$ to the range $-1.5:-0.5$).

- From the year 1970 (green dashed line) to 2002 (blue dotted line) a similar trend is evident: the frequency of WRTs in the range 5–8 days increases. The areas between 0 and −1 m decrease significantly, while deeper areas increase. The areas in the range $0:1$ m increase due to recent construction of artificial salt marshes.

- From the year 2002 (blue dotted line) to 2012 (gray dot-dashed line) there is a general shift of water renewal time toward higher values. In particular the frequency of WRTs below 6 days decreases, whereas WRTs between 6 to 10 days increases. This variation is related to the recent changes in the circulation at the three inlets induced by the realisation of the MoSE structures at the inlets. In this period a single dataset of bathymetry is available and elevation differences cannot be estimated.

The average value of the return flow factor for the basin slightly increases (from 0.082 to 0.086) from 1927 to the year 1970. This indicates that the opening of Malamocco-Marghera channel intensifies the current velocities, but retains the symmetry of the flow and therefore the amount of tracer that may come back increases. From 1970 to 2002 it maintains the same value and finally in the year 2012 reaches the maximum value of 0.112. From these results we can argue that the new structures at the inlets modify the local circulation and determine a longer retention of water masses in the areas around the inlets.

3.2 Future scenarios of sea level rise

From the statistics of the local climatology, winter months, particularly November, are more frequently characterised by meteo-marine conditions favourable to the onset of storm surges (*high water*). Typically, southeasterly winds (Scirocco), associated to storm surges in the Northern Adriatic sea, induce an energetic circulation in the Lagoon of Venice (Umgiesser, 2000) and consequently lower water renewal time of the lagoon with respect to calm conditions (Cucco and Umgiesser, 2006).

Modelled water renewal time and the daily fraction of lagoon water volume exchanged with the open sea (FVE), the number of *over threshold* events and the overall time of closure of the mobile barriers at the inlets for the considered scenarios are reported in Table 3. From 1927 to 2012 the WRT for the whole basin calculated by the monthly simulations has similar values: from 8.1 to 8.3 days. On the other hand, closing the gates during *high water* events (for a total of 39 h of closure) increases the water renewal time to 9.4 days. The operating time of the MoSE barriers under the different sea-level rise scenarios extends the modelled WRTs. The computed average water renewal time is 10.6, 12.2 and 15.2 days for a SLR of 10, 30 and 50 cm respectively.

In 1927 more than half (54 %) of the lagoon water volume was daily exchanged with the sea during strong Scirocco events. Morphological modifications so far introduced changed both the lagoon water volume and the flux through the inlets, reducing the daily fraction of water volume exchanged with the open sea (FVE = 0.49 in 2012).

Model results show that sea level rise and the closure of the MoSE gates increase the lagoon volume and reduce water fluxes through the inlets. During autumn, a SLR of 50 cm, and the associated closure of the MoSE barriers, limit the daily water exchange with the sea to about one-sixth of the overall lagoon water volume.

The distribution of the WRTs in the lagoon is presented in Fig. 6. The effects of Scirocco winds on the water renewal capacity of the lagoon are spatially diversified with more efficiency in the southern areas than in the northern ones, where the highest WRT values are found (Fig. 6a). With increasing SLR, the WRT in the northern part of the lagoon decreases, whereas it increases in the central and in the southern sub-basins. In these future scenarios, the spatial distribution of water renewal time seems less related to the distance from the inlets, but rather resembles a radial gradient with higher values in the central part of the lagoon (close to the city of Venice) and lower values in its southern and northern areas. The decrease of the WRT with increasing SLR in the northern parts of the lagoon is due to the inflow from the Porto di Piave Vecchia channel which is not planned to be closed during *high water* events. With a SLR of 50 cm (Fig. 6d) the central basin is expected to have WRT values that are found in the present situation only in the more confined inner lagoon areas (Fig. 4d).

4 Discussion

4.1 Hydromorphological evolution

The evolution of the Venice Lagoon from the recent historical period to the future is summarized in Fig. 7 in terms of basin-wide average water renewal time computed for the monthly simulation. The morphological evolution from 1927 to 2002 implies a slow decrease in the $\overline{\mathrm{WRT}}$, while the fixed MoSE structures bring back the $\overline{\mathrm{WRT}}$ to the values obtained in the 1927 simulation. With increasing sea level rise, the number of *high water* events and closure period increase. While in the present situation the closures are only related to storm surges, in the future scenarios of SLR the barriers are expected to operate also for very high tides related to purely astronomical forcings. The Venice Lagoon will then become progressively more isolated and, as a consequence, the average renewal time of the lagoon's water will increase.

In the present configuration (2012), the value of water renewal time during strong Scirocco winds is three days lower than the average value computed in the yearly simulation. Figure 7 shows that a sea level rise between 10 and 30 cm leads to a $\overline{\mathrm{WRT}}$ higher than the present (2012) yearly averaged value (red dotted line). The obtained results indicate that the closure of the inlets during storm surges and very high tides to prevent flooding in Venice makes Scirocco winds less effective in mixing the lagoon. Consequently, the internal circulation redistributes the tracer and has more influence on the spatial distribution of the water renewal time than the exchange with the sea.

Model results could also be used to investigate the historical and future hydromorphological evolution of Venice Lagoon. According to 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. Even if no clear and sharp distinction among hydromorphological types exists, according to this classification, Venice Lagoon may be defined between leaky and restricted.

Lagoon type classification was archived in this study according to $\overline{\mathrm{WRT}}$ and to daily fraction of lagoon water volume exchanged with the open sea (Fig. 8). The inverse of FVE represents the flushing time (in days) as defined by Monsen et al. (2002) (gray line in Fig. 8). Water renewal time computed by the model as volume-weighted average of local values is always higher than the flushing time, since this last time scale considers an homogeneous fully mixed system and does not take into account internal physical processes and their spatial distribution.

Fig. 8 shows that Venice Lagoon in the last century did undergo slightly changes in hydromorphological type, with a shift towards a more restricted system. From 1930 to 2002, the water renewal time decreases slightly, as well as the daily fraction of water volume exchanged with the coastal sea. This was mostly due to the deepening of the lagoon and loss of marsh areas in the inner lagoon. The MoSE structures reduce the exchange with the sea and slightly increase the overall water renewal time. Simulations of future scenarios indicate an evolution towards a more restricted environment. The fraction of water volume exchanged daily with the open sea decreases from 0.49 of the present situation (M_2012) to 0.17 in the case of a SLR of 50 cm. Such a marked decrease depends on two factors: first, the closure of barriers during *high tide* events limits mechanically the water flow between the lagoon and the sea; second, SLR induces a water volume increase in the basin that is only partially compensated by the increase in water exchange through the inlets.

4.2 Hydroecological implications

The spatial distribution of WRT can be used to improve our understanding of the links between physics, hydrology and ecosystem conditions. The rate of accumulation of nutrients, organic matter and pollutants in semi-closed systems can be proportional to water transport time scale (Dettmann, 2001). This process depends on the accumulation rate of substances in respect to the auto-depurative capacity of the system. The balance of these two processes can means a shift of environmental conditions and consequentially a different habitat typology, community composition and distribution (Guelorget and Perthuisot, 1989).

To hydrological changes have overlapped in the last century significant changes in water chemistry, producing toxic and trophic effects. While the toxic effects are still under discussion (Guerzoni and Raccanelli, 2004), there has been a well documented trophic effects on vegetal and animal benthic communities due to the input of phosphates and fertilizers of agricultural and urban origin (Sfriso et al., 1992; Tagliapietra et al., 1998; Solidoro et al., 2010). Therefore, the occurred modifications of communities due to trophic changes have often masked the effect of hydrological changes.

To understand the combined effects of these changes we must remember the peculiar ecological structure of lagoons, which are characterised by progressive changes in the main environmental variables, such as salinity, water renewal, nutrients, turbidity and sediment structure that generate composite gradients. The direction of the gradient is generally oriented perpendicularly to the coastline or along the river mouth axis, depending mainly on hydrological energy. In different basins and sub-basins the shape of the gradient can change, depending on the relative importance of the environmental variables within the gradient, but it is roughly sea-land oriented (Tagliapietra et al., 2009). These environmental gradients influence directly the structure of benthic assemblages selecting sensitive species (Peasron and Rosenberg, 1978; Guelorget and Perthuisot, 1983, 1989).

Increasing eutrophication caused a succession of aquatic vegetation from seagrasses to fast growing macroalgae, phytoplankton and finally to picoplankton and cyanobacteria (Sfriso et al., 2003; Sfriso and Facca, 2007; Viaroli et al., 2010). The increased production of macroalgae, due to eutrophication, and the consequent degradation of organic matter, has resulted in an increase of saprobity, seen as the state of the environment resulting from the input and decomposition of organic matter and the removal of its catabolites. These processes dependent on hydrodynamics, which govern water renewal and generate land-sea gradient (Tagliapietra et al., 2012b). During the eutrophication period of the 80 s–90 s, the disproportionate increase of catabolites generated by the degradation of organic matter was not balanced by an adequate water exchange producing an accumulation of toxic catabolites and an increase of the reducing conditions, flowing finally in dystrophic crisis.

Populations of benthic macroinvertebrates evolve progressively generating a succession of biocoenoses ranging from communities classically attributed to the Well Calibrated Fine Sands Biocoenoses (SFBC, Biocoenoses de Sables Fins Bien Calibrés) typical of the sandy coast but protruding into the tidal delta; the Superficial Fine Sands Biocoenoses (SFS Biocoenoses de Sables Fins Superficiels) and the Superficial Muddy Sand in Sheltered Area Biocoenoses (SVMC Biocoenoses de Sables Vaseux Superficiels en Mode Calme) in the most dynamic areas of the central basin; different facies of the Biocoenoses of Euryhaline and Euritherm Lagoon (LEE, Biocoenose Lagunaire Euryhaline et Eurytherme) on the inner parts and the fluvial delta. Within each biocoenoses, it can be recognized the associations related to changes in habitat at a smaller scale (Pérès and Picard, 1964; Michez et al., 2011). In the presence of a large central basin, as in the lagoon of Venice, the most common associations are therefore the SVMC with its various facies in the more flushed areas and the LEE in confined areas (Tagliapietra and Minelli, 2009).

With the increase of salinisation due to excavation of large waterways and the reduction of inputs of fresh water, the biocenosis LEE has then undergone to a shift to mainland with the loss of *Potamogeton* associations, and associations of Ruppia (Michez et al., 2011) and an expansion towards the inside of the biocoenoses SVMC, if not the biocenosis more sandy sediments (Pérès and Picard, 1964).

At a functional level, the sequence from the sea towards more and more confined areas provides a succession of species from "sensitive species", K-strategists (Pianka, 1970) characteristics of the less confined habitats to "opportunistic species" (Grassle and Grassle, 1974) characterized by type "r" reproductive strategy (r-strategists) that dominate under conditions of intense disturbance. This is accompanied by a progressive decrease in the number of species. The K-strategists species are typically represented by large animals, long-lived, including many bivalve while the r-strategists opportunistic species have short life cycle, small size, rapid growth, reproduction throughout the course of year, between the latter prevails the trophic group of detritivores, in particular polychaetes. In practice going from the less the more confined areas communities switch from community strongly characterized by bivalve/filter feeders to communities characterized by polychaetes/detritivores. Together with the variation of salinity, one of the main mechanisms responsible for this seriation of species and reduction of biodiversity along the gradient is the increase of saprobity. The inner areas of the lagoons are therefore naturally the most saprobic and host communities more tolerant towards the accumulation of organic matter, towards catabolites arising from degradation, and to hypoxic and reducing conditions.

Zooplankton studies in the Lagoon of Venice have shown that hydrological aspects such as lunar cycle, river inflows and exchanges with the sea influence zooplankton dynamics (Bandelj et al., 2008) and determine the dominance of some species such as small crustaceans, primarily copepods, over other taxa. From 1970 to the present, changes have been observed in the mesozooplankton community structure (Acri et al., 2004; Solidoro et al., 2010). The shift in zooplankton composition, with occurrence of the copepod *Acartia tonsa* Dana mainly in the inner area of the Venice Lagoon, can be regarded as an indicator of euphotic conditions (Solidoro et al., 2010), but also as an indicator of the hydrological changes here described.

Scenarios with a SLR from 0 to 50 cm (Fig. 6) propose a lagoon in which the hydrology of the various habitat is profoundly changed: the banded zonation with increasing confinement from sea to land, shift to a lagoon characterized by a more concentric confinement gradient, in which the circulation is more influenced by the wind and that looks more like to choked Mediterranean lagoons (coastal ponds). In the most extreme simulation (SLR 50 cm), the area with higher water renewal time moves from the edge of the lagoon towards central parts of the lagoon, coinciding with the watershed (divide) between the basins of Lido and Malamocco, spreading up to and including the city of Venice. There is a reduction of the land-sea gradient of confinement resulting in a homogenization of communities in many parts of the lagoon. The higher the level of the sea, and the frequency of closures, the lagoon will be increasingly confined with a reduction of water exchange, resulting in a possible reduction of species with marine affinities, more sensitive to saprobic conditions.

Numerical simulation of future scenarios focus on the period of maximum closure of the inlets (autumn) which coincide with the highest load of sediments, nutrients and pollutants. If these inputs from the hinterland and the City of Venice will not change there will be a possible entrapment of toxic substances in the central areas of the lagoon with increased eutrophication and saprobity and risk of anoxia that would also involve the historical city. The lagoon will have to rely almost exclusively on the internal metabolic processes for the assimilation and mineralization of the nutrient inputs. If nutrients and pollutants are not biologically, chemically or geologically retained in the system, they may be flushed during the following winter, otherwise in spring they will trigger the growth of algae (Tagliapietra et al., 2012a). The eutrophic conditions may also lead to the reduction of seagrass, currently in the recovery phase, with drastic effects on biodiversity. Among others, the zone with lower water renewal time is situated in the area where there is now a higher harvesting of Manila clams which might suffer a considerable reduction.

The benthic community could assume a structure more similar to that of the communities currently present in the peripheral areas of the central basin close to the salt marsh fringe. The hypothesized conditions will affect the most sensitive species needing oxygenated waters, including many species of molluscs, and favouring resistant species, tolerant and opportunistic, among them mainly small polychaetes. The communities will therefore be less different, composed of more tolerant species, and in which the *vigor* is expressed in increasing the number of individuals of small dimensions rather than in increased biomass as, conversely, happens in less impacted situations. So, it could occur a general increase in polychaetes, and a reduction in bivalves, but also face a less favorable environment for many species of fish including the prized sea bream and bass and more favorable to mullets.

In future scenarios the connectivity with the sea will be reduced, limiting the incoming passive particles and migratory organisms, and increasing the relevance of the recirculation and redistribution inside the lagoon. Since Venice Lagoon plays a nursery role for several species, the larval colonisation and the fish migration can be disturbed by the limited connectivity and this could have some consequences on the recruitment (Cowen et al., 2005).

5 Conclusions

In the recent morphological history of the Venice Lagoon (1927–2012) several steps can be recognized as important interventions affecting hydromorphological structures and processes. Human activities in the period 1927–2002, and hydromorphological responses to such activities caused a reduction of the lagoon's water renewal time (from 11.9 to 10.8 days), while MoSE structures induced a loss of flushing capacity.

From 1927 to the present the lagoon slowly moved towards a more restricted coastal system. These major environmental changes have had inevitable effects on biological communities.

The future scenario of SLR and operation of mobile barriers at the inlets makes the Venice Lagoon similar to an artificially semi-closed basin and the limited sea-lagoon water exchange, most in the fall-winter months, implies that in these conditions the dynamic of the ecosystem becomes a recirculation. Simulated basin-wide average water renewal time under winter conditions increased from 8.3 days in the present situation to 15.2 days in the scenario with a sea level rise of 50 cm. It has to be noted that the future increase in water renewal time is more evident in the central part of the lagoon, where most of the pollutant sources are located. This implies that the area close to the city of Venice and close to the industrial zone will experience the most intense ecological consequences of the human induced, locally and globally, modifications.

The maximum sea level rise considered in this study was 50 cm, but recent prediction suggested an end-of-century scenario of more than 60 cm, not excluding the chance of a 100 cm increase (Umgiesser et al., 2012). Such a SLR will worsen the ecological implications of a further decrease of sea-lagoon water exchange and of the increasing water renewal time discussed in this study. Moreover, the expected increase in temperature during this century will makes the situation worse (Tagliapietra et al., 2011).

In an increasingly confined lagoon the management of nutrients, pollutants and organic matter inputs from the drainage basins, but also from population centers, will become vital.

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Table 1. Simulations description and set-up.

Sim. name	Layout	Duration	MoSE Closure	SLR (cm)
Y_1927/M_1927	1927	Yearly/Monthly	NO	0
Y_1970/M_1970	1970	Yearly/Monthly	NO	0
Y_2002/M_2002	2002	Yearly/Monthly	NO	0
Y_2012/M_2012	2012	Yearly/Monthly	NO	0
SLR_00	2012	Monthly	YES	0
SLR_10	2012	Monthly	YES	10
SLR_30	2012	Monthly	YES	30
SLR_50	2012	Monthly	YES	50

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Table 2. Simulation results for the 1927–2012 scenarios. Results are given in terms of lagoon volume, average sea-lagoon water fluxes, basin-wide average water renewal time and return flow factor. The last two parameters were calculated as average of four replicas.

Sim. name	Volume (10^8 m^3)	Sea-lagoon fluxes (m^3 s^{-1})	$\overline{\text{WRT}}$ (days)	RFF (adim)
Y_1927	5.45	3881	11.9	0.082
Y_1970	6.77	4688	11.0	0.086
Y_2002	6.95	4641	10.8	0.086
Y_2012	6.92	4570	11.3	0.112

Table 3. Model results of monthly simulations in terms of basin-wide average water renewal time ($\overline{\text{WRT}}$) and daily fraction of water lagoon volume exchanged with the open sea (FVE). Table reports also the number of *high water* events and the overall closure time of barriers.

Sim. name	Number of *high water* events	Closure period (hours)	$\overline{\text{WRT}}$ (days)	FVE (adim)
M_1927	7	0	8.3	0.54
M_1970	7	0	8.2	0.52
M_2002	7	0	8.1	0.50
M_2012	7	0	8.3	0.49
SLR_00	7	39	9.4	0.43
SLR_10	10	60	10.6	0.41
SLR_30	25	183	12.2	0.28
SLR_50	42	372	15.2	0.17

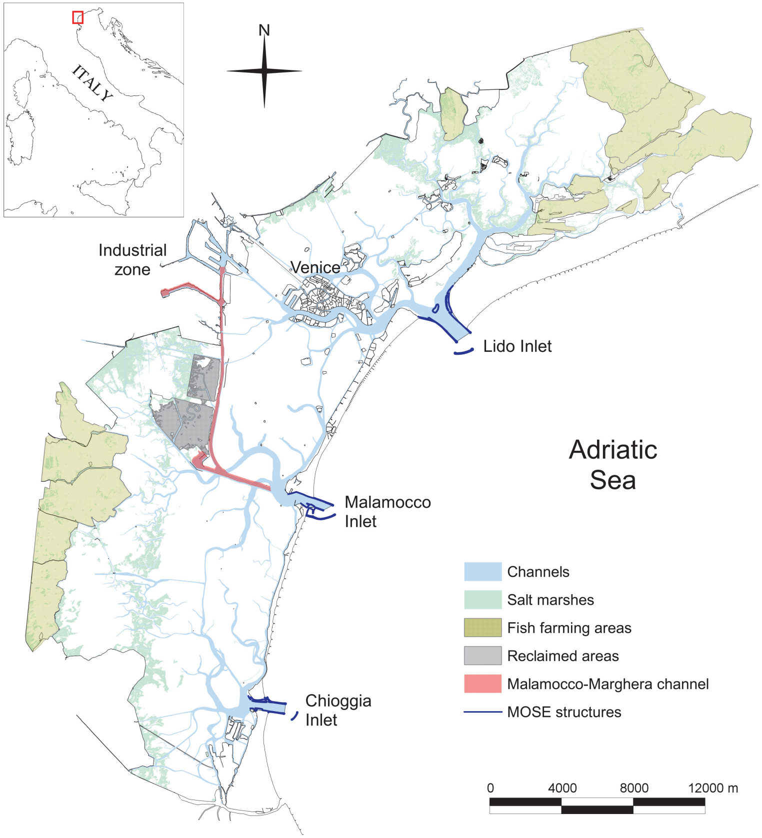

Fig. 1. The Lagoon of Venice in its present configuration (2012). Major morphological types (channels, salt marshes and fish farming areas) and modifications (reclaimed area, Malamocco-Marghera channel and MoSE structures at the inlets) are illustrated.

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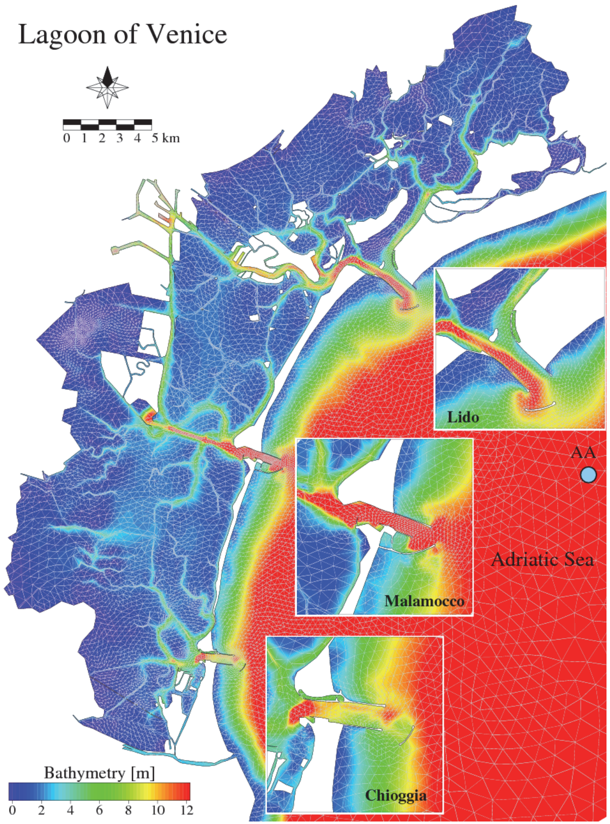

Fig. 2. Bathymetry of Venice Lagoon in the present situation (2012) and adjacent shore obtained by using finite element model grid (superimposed). The circle indicates the location of oceanographic tower *Acqua Alta* (AA).

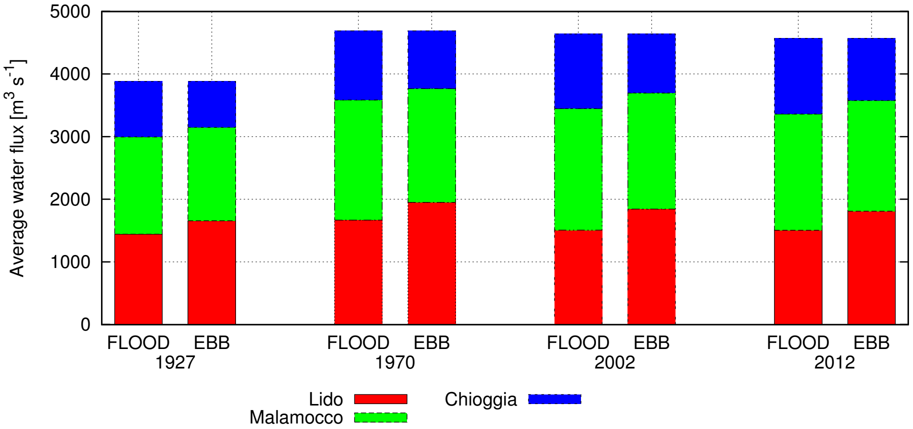

Fig. 3. Average water fluxes between the lagoon and the sea during ebb and flood tide for the four past and present situations (1927, 1970, 2002, 2012).

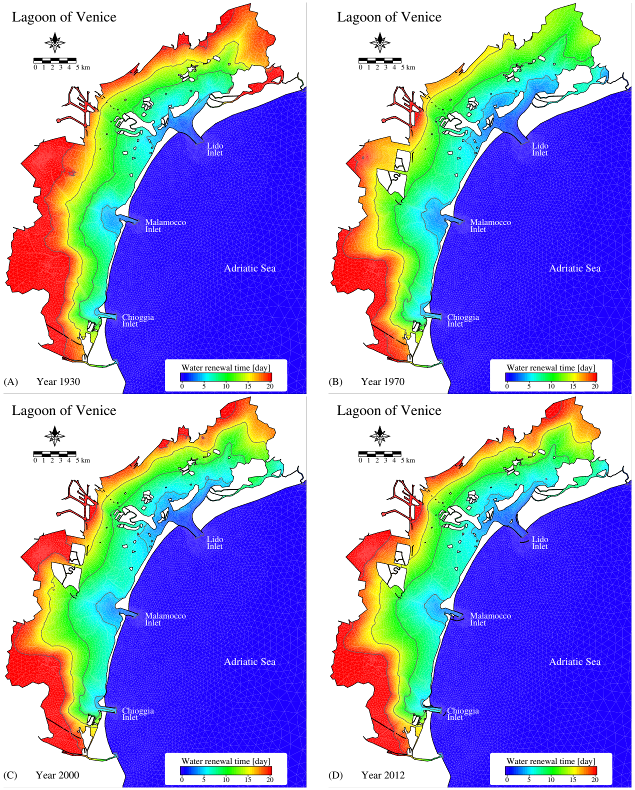

Fig. 4. Maps of water renewal time computed by the model for the 1927 **(A)**, 1970 **(B)**, 2002 **(C)**, 2012 **(D)** situations. Values were computed as average of four replicas obtained by forcing the model with water level and wind observations of year 2002.

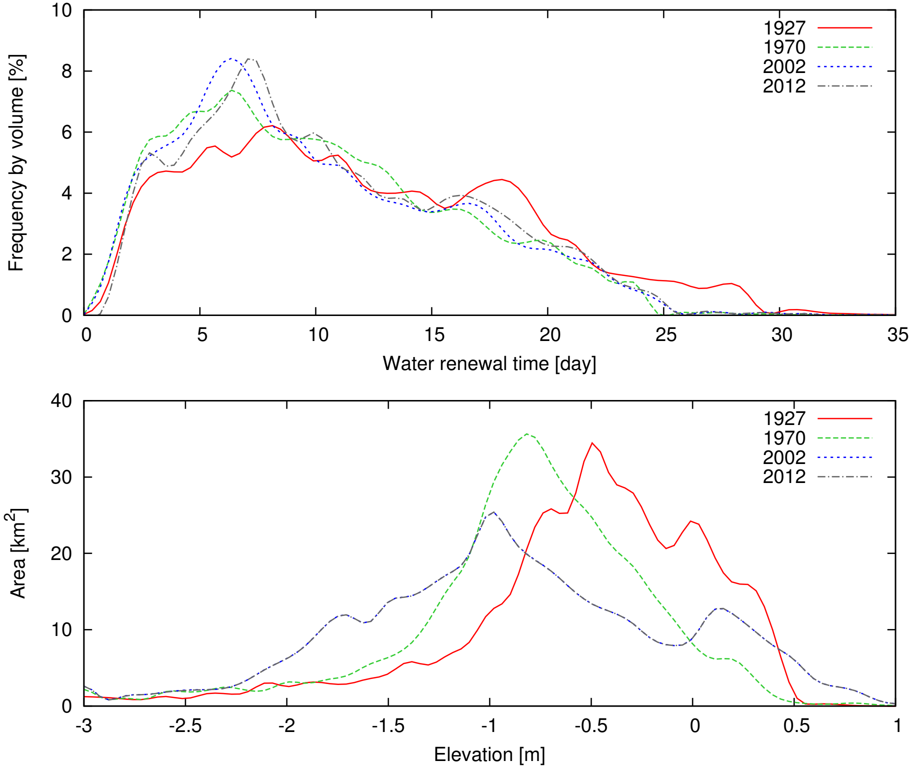

Fig. 5. Frequency distribution of water renewal time and bathymetry for the 1927 (red continuous line), 1970 (green dashed line), 2002 (blue dotted line) and 2012 (gray dot-dashed line) scenarios.

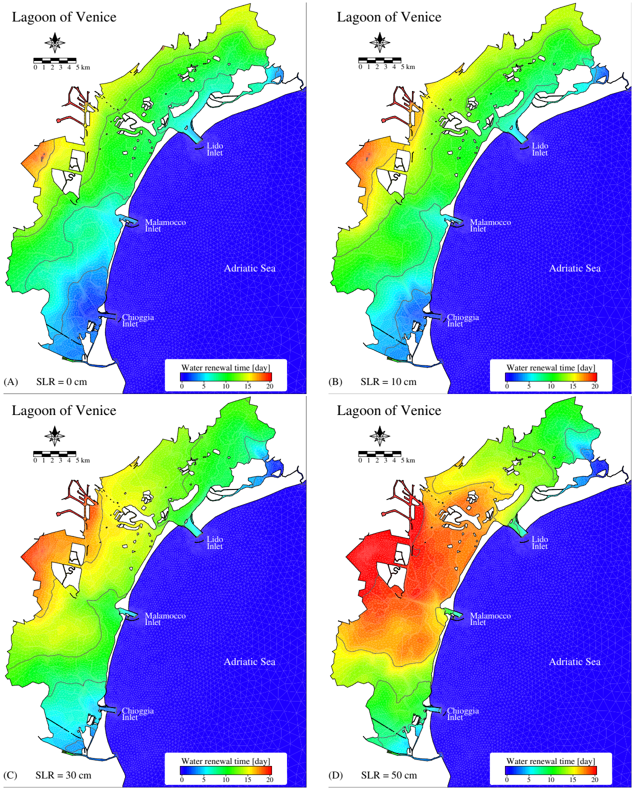

Fig. 6. Maps of water renewal time computed by the model for the SLR scenarios considering the closure of the inlets during *high water* events. The period of reference is November 2002.

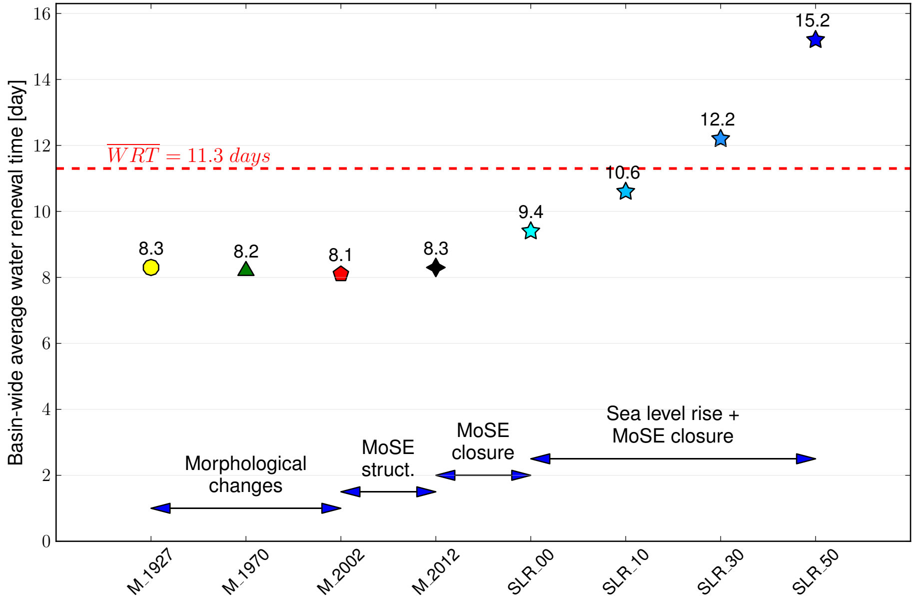

Fig. 7. Evolution of average water renewal time in the Venice Lagoon under fall-winter conditions considering: morphological changes, the MoSE structures, the closure of MoSE barriers during *high tide* events and the sea level rise of 10, 30 and 50 cm. The red dashed line at WRT = 11.3 indicates the average value of the present situation (2012, simulation Y_2012).

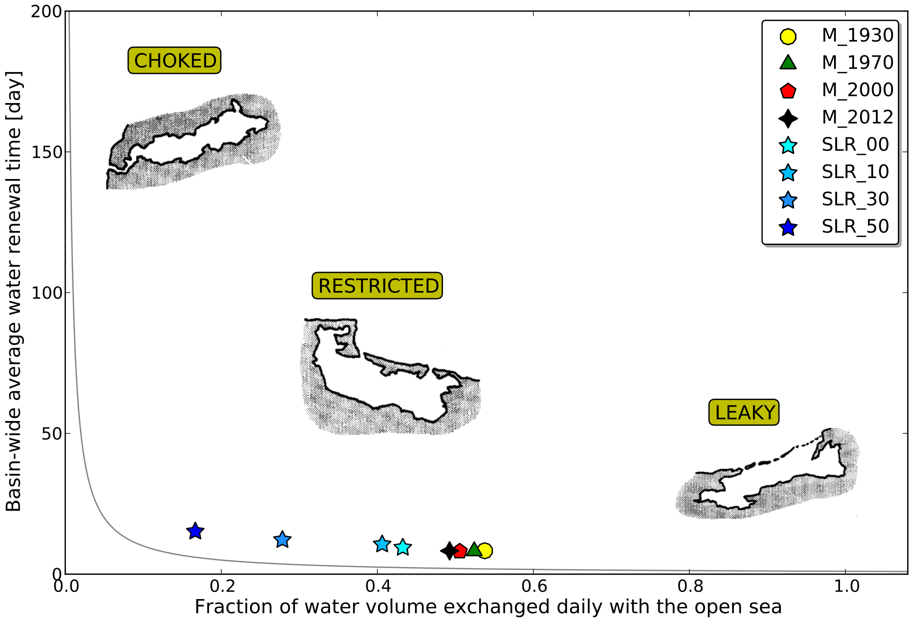

Fig. 8. Evolution of lagoon type in the different scenarios under fall-winter conditions. Gray line represents the flushing time defined as 1/FVE, with FVE the daily fraction of lagoon volume exchanged with the open sea.