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Numerical Modelling of Orbetello Lagoon Circulation in the XVIII Century

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***Abstract* – This article presents the hindcasts of Orbetello lagoon circulation in different scenarios starting from the XVIII° century. The main objective of this work has been the quantification of water exchanges between lagoon and sea during the centuries. The hindcasts are obtained by means of numerical simulations. The simulations have been conducted by means of a numerical model validated by using field measurements carried out in the present scenario. Once the model has been validated, the bathymetry has been changed according to the morphology of the different past scenarios and the water exchange between lagoon and the sea has been assessed. The comparison of the water exchange in the different scenarios is provided and discussed, providing the necessary background knowledge to support the present management of the lagoon based on the lesson learned from the past.**

I. INTRODUCTION

The Orbetello Lagoon is a partially enclosed coastal basin sited at the southern end of the Tuscan coast (Italy). It is 26 km^2 wide with the mean water depth 1.13 m and the total internal water volume of about 30 Mm^3 (Fig. 1).

At present, water exchange with the Tyrrhenian Sea takes place by means of three narrow channels that are about 20 m wide and from 1 to 2 km long, namely: i) Nassa channel, ii) Fibbia channel and iii) Ansedonia channel (Fig. 1). Inside each channel there is a series of metal grids, each extending along some channel transversal sections, to allow the aquaculture activity in the lagoon and avoiding fishes' escapes. On the other hand, this net of metal grids acts as obstacles thus lowering the sea-lagoon water exchange effectiveness. The poor water renewal is in turns one of the main factors that leads to drastic anoxic crises, the killer of fishes. It seems so that the local communities do not realize properly that their management of the fish activities is one of the main causes, among others, that leads to their problems. To increase the water exchange with the open sea, a system of pumps and gates had to installed in the channels (hereafter, the system of pumps and gates will be referred to as "pumps-gates system").

However, anoxic crises still often occur during summer due to the poor water renewal in conjunction with the presence of abundant organic matter [1]. In fact, the algae species that populate most of the lagoon area [2] act on the lagoon circulation as a high roughness, thus lowering the hydrodynamics, especially at the shallower areas. Moreover, algal bloom often occurs in spring and the algae that die in the summer period fall to the bottom, increasing the amount of organic material. Such phenomenon plays a crucial role for triggering anoxic crises.

Furthermore, since the lagoon is a very shallow water environment, it has a relatively low thermal inertia. In such condition, the energy flux of the sun, especially during the summer months, drastically increases the lagoon water temperature that in turns activates the bio-chemical reactions responsible of the anoxic crises.

Enhancing the water exchange between the sea and the lagoon and promoting a stronger inner water circulation would be certainly beneficial to:

- Increase the oxygen content in the lagoon waters;
- Lower the lagoon water temperature during the summer months;
- Bring out of the lagoon the accumulated organic matter (provided that the hydrodynamic circulation is strong enough for suspending and transporting at least the finer part of it).

The Regione Toscana, the authority in charge of the management of the lagoon environment, is currently developing a project aiming at preventing anoxic crises. Among all the aspects under study (i.e. chemical, biological and environmental aspects [3], [4], [5], [6]), the knowledge of the hydrodynamics of the lagoon is crucial, since it constitutes the base for all the other studies. Quite surprisingly the study of lagoon water circulation has almost not received attention if compared whit the huge among of studies concerning biology and chemical aspects. In each of the latter aspects the water circulation is indeed a fundamental knowledge, but its features have been frequently based on very rough conceptual speculations. Not surprisingly, each group of stakeholders believes that its own specific speculations are the right one.

Starting from this framework, a modelling approach based on a synergic use of both field measurements and numerical simulations has been implemented.

Fig. 1. Aerial view of the Orbetello Lagoon. Left: the yellow markers namely:Marina di Campo (Elba Island) and Civitavecchia, depict the tidal gauges installed by ISPRA, the Rete Idrografica e Mareografica Nazionale. Rigth: the anemometer station (red marker) and the four water level stations (blue markers) installed by CFR, the Centro Funzionale of Regione Toscana.

This model aims to constitute a decision support tool for the management of the lagoon. For instance, it can be used for:

- Hindcasting the hydrodynamics of the lagoon during specific past periods, supporting the understanding of the phenomena that took place;
- Forecasting the lagoon hydrodynamics to actuate an efficient management of the grid-pumps system at the lagoon inlets;
- Verifying the effectiveness of possible strategies, e.g. enhancing water exchange by excavating new inlets connecting the sea and the lagoon or channels on the lagoon bottom.

This work presents the ongoing research activity that aims at the hindcasting, by means of numerical simulations, of the Orbetello lagoon circulation in key scenario over the last two centuries. The difference in the water exchange between the lagoon and the sea due to the different bathymetry of the lagoon in the simulated scenarios is analysed and discussed, with the aim to underline key aspects in the system hydrodynamics.

The knowledge base obtained via this work aims to support the management of the lagoon based on the lesson learned from the past experiences, avoiding the repletion of errors in the lagoon management.

The paper is structured as follows: the field measurements used to force and validate the numerical model are introduced at first (section II), then the numerical model is presented (section III), finally its use to hindcast the circulation in past scenarios is discussed (section IV).

II. FIELD MEASUREMENTS

Field data have been collected by means of different sensors, installed in order to monitor tidal conditions, wind and water levels (Fig. 1).

A. *Tidal stations*

The tidal stations (see Fig. 1) are installed inside the harbour of Marina di Campo (Elba Island) and Civitavecchia. The sensors are maintained by ISPRA (an institute belonging to the Italian Ministry of the Environment). The stations are both equipped by a Radar sensor SIAP+MICROS TLR with an accuracy of about 1 mm.

The Radar sensor measures the water level emitting radar impulses (microwaves) toward the target surface and measuring the related returns echoes. The on-board electronics performs the distance calculation computing time intervals between emission and reception of pulses. The radar sensor is installed in pairs with a second float level sensor based on "shaft-encoder" technology (with the back-up function) and with the ultrasonic hydrometric sensor.

The measurements of these 3 sensors allow ISPRA to obtain an accurate calibration of the radar sensor such as to guarantee perfect continuity of the level data series. Moreover, each level sensor refers to a bracket whose height is determined by referring to the altitude network created by IGM, the Military Geographic Institute.

a) Civitavecchia	b) Marina di Campo
altitude: 2.9765m S.W.L. Lat. 42° 05' 38.25" Lon. 11° 47' 22.73"	altitude: 1.003m S.W.L. Lat. 42° 44' 33.48" Lon. 10° 14' 18.00"

Fig. 2 Tidal station of a) Civitavecchia harbour, and b) Marina di Campo harbour, installed by ISPRA, the Rete Idrografica e Mareografica Nazionale.

B. *Lagoon water level stations*

Field data collected at four measurement stations (see Fig. 1) equipped with ultrasonic surface level sensors SIAP+MICROS ID0710 have been used for monitoring the water level variation in four crucial points inside the lagoon. The surface level gauges sampled 1 measurement every 10 minutes and are installed and maintained by CFR, an office of the Regione Toscana authority.

The ID0710 ultrasonic sensors use an ultrasonic ceramic transducer capable of emitting pulses towards the surface of which the distance must be measured and the return echoes to be detected. The on-board electronics determine the distance to be measured based on the time elapsed between emission and reception. The particularly robust construction, the degree of protection (IP65) and the programmability of numerous functions make the sensor particularly suitable for operation in adverse conditions such as those typical of the marine environment.

To consider the variation in the speed of sound as a function of air density, the sensor is equipped with a transducer for measuring the air temperature; based on the measured temperature value, the measurement is automatically compensated.

C. *Lagoon Wind station*

Field data collected at the station (see Fig.1) equipped with the anemometer (Fig. 3) have been used for monitoring the wind conditions inside the lagoon. The anemometer sampled 1 measurement every 15 minutes, and as the ultrasonic level sensors is installed and maintained by the *CFR*. The anemometer sensor provides the measurement of the horizontal component of the wind speed, within the range 0÷50 m/s. The sensor is constituted by an optoelectronic pulse generator composed by a three-pair impeller attached to the sensor and by an emitting diode which, through a perforated disk, sends its light to an optical sensor. As the wind speed varies, the rotation speed of the disk varies, and consequently the number of pulses generated per time unit.

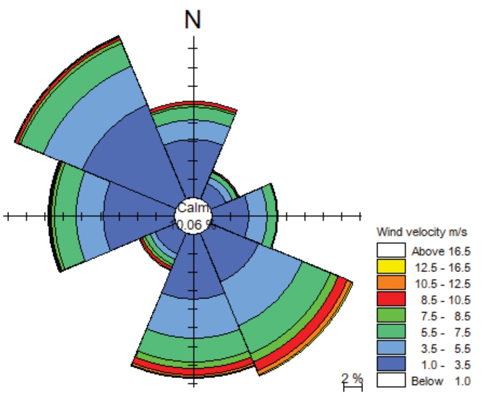

Fig. 3. Annual directional distribution of wind frequency at Orbetello station.

III. THE NUMERICAL MODEL

A. *Description of the model*

A numerical model is used in this work in order to extend the knowledge on the lagoon system process and dynamics as provided just by the available network of sensors. Indeed the field measurements are fundamental, since they represent the real behaviour of the monitored system, but the knowledge arising from this methodology is limited by the low number of points in which the measurements are carried out, i.e. just 4 points in a lagoon that is 26 km^2 wide. By using the numerical modelling in synergy whit field measurements, a huge amount of virtual measuring points inside the lagoon can be added and this enormous quantity of knowledge can be used for a deeper understanding of the spatial and time varying hydrodynamic lagoon processes. This methodology has the potentiality of constituting an Augmented Reality Based Lagoon Management System (ARB-LMS).

The used numerical model is the Hydrodynamic (HD) Flexible Mesh (FM) module of MIKE21 software package [7]. The model is based on the numerical solution of the two-dimensional, incompressible, Navier-Stokes equations under the hypothesis of Bussineseq and that of hydrostatic pressure distribution, which allow to eliminate the vertical dimension from the three-dimensional equations, assuming to neglect the vertical acceleration of the flow (i.e., it solves the so-called Shallow Water Equations, SWEs).

The model consists, therefore, in the equations of continuity and momentum integrated over the vertical, with a turbulence closure scheme based on the eddy viscosity concept approach [7].

The model can handle unstructured grid, which is a particularly useful characteristic for the application at hand, since it provides the degree of flexibility needed to represent the complex geometry of the lagoon, with a smooth representation of its boundaries. Governing equations are discretized with a cell-centered finite volume method.

The spatial scheme uses an approximate Riemann solver to compute convective fluxes, which makes it possible to handle discontinuous solutions [8]. The temporal integration procedure for conservation equations is based on an explicit scheme, thus the time step adopted in the numerical computations must be limited based on the Courant-Friedrichs-Lewy (CFL) criterion.

Since the Orbetello Lagoon is a relatively shallow water environment, with a bathymetry characterized by an almost flat and horizontal bottom, its hydrodynamics is presumably dominated by bi-dimensional, nearly horizontal flows. The use of SWEs to study such a system seems, therefore, appropriate. At the same time, the two-dimensional SWE approach allows a decrease in the computational demands compared to three-dimensional modelling approaches.

B. Numerical model set up

The domain of the numerical model has an extension of 140 km (in the South-North direction) from Civitavecchia to Marina di Campo (Elba Island). The offshore boundary is almost parallel to the coastline and located about 50 km offshore (Fig. 4). The bathymetry data used in the numerical model derives from bathymetry surveys of the area inside the lagoon performed in 2004, integrated with data obtained by means of digitalization of nautical paper charts for the area outside the lagoon (provided by IIM, Istituto Idrografico Militare [9]). The water depth inside Orbetello Lagoon has an average value 1.3 m above the still water level, with a maximum water depth below 2 m. Interpolated bathymetric data were assigned to the unstructured computational grid. The unstructured computational grid of the model is composed of around 170.000 triangular elements. The size of the elements varies across the computational domain: the greater size of the computational elements is around 2500 m offshore, and it gradually decreases with a nested series of progressive refinements, implementing a dynamical downscaling approach while approaching the lagoon (Fig. 4). The smaller cell length is around 2 m, and is used to discretize the Fibbia, Nassa and Ansedonia in order to have a satisfying salce resolution since each channel is about 20m wide and from 1 to 2 km long. The adopted dynamical downscaling approach allows reproducing all the relevant physical phenomena taking place at the regional scale, as well as the detailed water circulation in the lagoon channels, with an acceptable computational effort. In fact, this specific implementation of the model has been intentionally developed balancing the necessary resolution and the related computational efforts in order to also allow the use of numerical modelling as a real-time forecast system. In this work, the time series of hourly data of water level recorded at the tidal gauges during the year 2016 have been used as North, South and West offshore boundary conditions. An integration whit numerical models that simulate the hydrodynamic of the whole Mediterranean Sea is going-on at present aiming at a better implementation of the boundary conditions in terms of both time-varying fluxes and water levels. The wind time series recorded by Orbetello anemometer station has been imposed as a source term acting uniformly over the numerical domain, to allow the simulation of the storm surge and the inherent effects on the lagoon water exchange. As for the numerical set-up of the model, a uniform and constant value of the Manning coefficient equal to 32 $m^{1/3}/s$ have been imposed in the computational domain to determine bottom friction.

The turbulence closure approach adopted is based on the use of a constant eddy viscosity value, imposed equal to 0.001 m^2/s. The time step used in the simulation is dynamically adapted in order to maintain a CFL number lower than 0.8. For both time and space integration, first order upwind schemes are adopted [7].

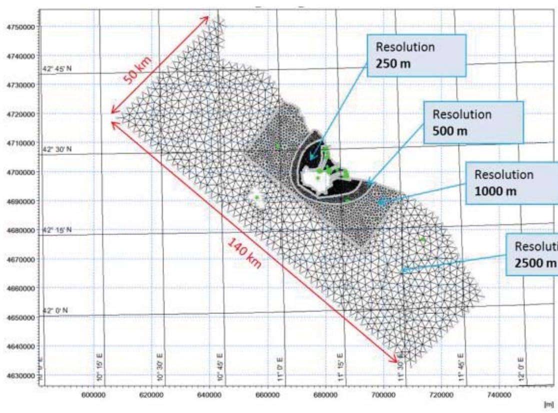

Fig. 4. Computational domain of the numerical model of Orbetello Lagoon.

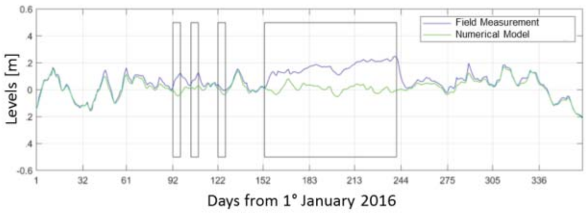

Fig. 5 Comparison of the time series of the daily mean lagoon water levels for the year 2016 measured by the water level station in the center of the lagoon (blue) and numerically simulated (green).

C. Validation with field measurements

The daily mean water level time series measured at the level station located at the centre of the lagoon, with the corresponding results of the numerical model, are plotted in Fig. 5. Rectangles highlight the time windows during which the pumps-gates system was turned on to promote the water exchange.

It has to be highlighted that the pumps-gates system was not simulated in the numerical model. Excluding the time windows in which the pumps were active, the agreement between measurements and numerical results is very good. Moreover, the numerical model has also permitted to know the lagoon water level that would have been present if the pumps-gates system had turned off. In this respect, the Fig. 5 shows that the pumps-gates system is effective in setting the lagoon water level much higher than in natural condition.

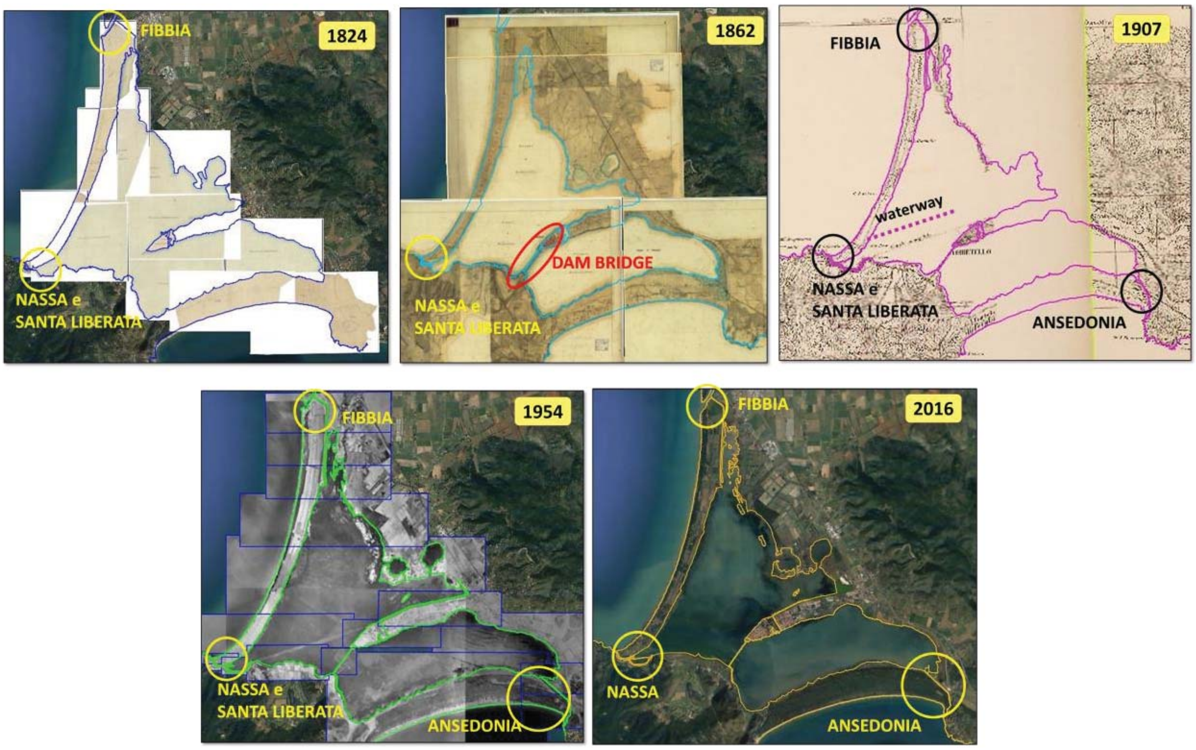

Fig. 7 Basic morphological features of the different scenario considered: 1824 (source: cadastral maps), 1862, 1907, 1952 (source: Italian national mapping agency, IGM), 2016 (source: CTR cartography).

IV. HINDCASTED SCENARIOS & PRELIMINARY RESULTS

The validated model has been used as an hindcast tool, with the aim to evaluate the role of the anthropic action and management strategies on the lagoon circulation. For this purpose, the lagoon morphology (e.g. in terms of bathymetry, number and shape of the channels connecting the lagoon to the open sea, presence of significant artificial structures) in five key scenarios over the last two centuries has been characterized by analysing the available documentation and cartography. The lagoon hydrodynamics, resulting as a response to the same external forcing in the different scenarios, was then simulated.

The key features of the five scenarios considered can be summarized as follows (Fig. 7):

(i) The 1824 scenario was characterized having as main source the available cadastral maps. In this scenario, 3 inlets connected the lagoon with the open sea: Nassa and a parallel channel named S. Liberata (with a length of around 750 m, and a width of 10-15 m), Fibbia (with a length of 1400 m, a width of 7 m). The inlet of S. Liberata was located in the west side of the lagoon, next to Nassa inlet (see Fig. 1 for reference). The lagoon had an average water depth of around 1.3 m.

(ii) In the 1862 scenarios, only 2 inlets were present, since also Fibbia had been closed. Moreover, an artificial dam bridge at the centre of lagoon was built (still present now day), with a length of 980 m and only three openings, 13 m wide each, to allow for the water circulation between the northern and the southern part of the lagoon.

(iii) In 1907 scenario, 4 inlets connected the lagoon and the sea, since Fibbia was reopened and operating again (with an increased width, up to about 20 m) and a new channel named the Ansedonia channel was excavated in the south (1500 m long, 20 m wide). Moreover, 5 more openings were realized on the dam bridge. Furthermore, a waterway was excavated on the lagoon bottom, connecting Nassa to Orbetello. The average water depth was about 1.4 m.

(iv) In 1954, all the 4 inlets were still open, but with a reduced width of the sections of Nassa and S. Liberata.

(v) In the 2016 scenario, S. Liberata channel was closed and a touristic harbour is now day present inside it. The lagoon average water depth is around 1.3 m.As an index of the hydrodynamic activity of the lagoon in the 5 scenarios, the total volume of water entering the lagoon in a tidal cycle has been analysed (Fig. 8). The maximum values, around 540.000 m3/12h, are obtained in the scenario of 1907, where all the 4 lagoon inlets were open. The lowest values are obtained in the 1862 scenarios, when only 2 channels were present, and are around 80% lower than those obtained in 1907. In the present scenario (2016), the water exchange is almost 40% lower than the maximum one (i.e. the 1907 scenario).

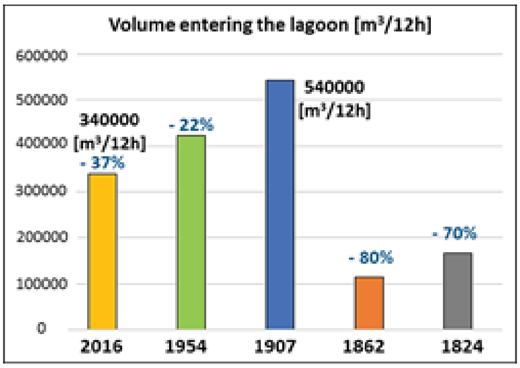

Fig. 8 Volume of water entering the lagoon in a tidal cycle: comparison of the scenarios of 1824, 1862, 1907 and 1952. Percentage changes expressed as relative to values of 1907 scenario.

The opening of Ansedonia was also crucial, since 20-30% of the water enters the lagoon through this inlet. Fibbia inlet contributes to around 20% of the water inflow. The extent of the areas inside the lagoon reached by the inflow discharge during a tidal cycle can be visualized by considering the contour map of the velocity at the same instant in time for different scenarios. In the 1824 scenario (Fig. 9, top), the one with the lower hydrodynamic activity, the extent of the areas characterized by very low velocities (lower than 0.1 mm/s) increases significantly compared to the scenario of 1907. In such areas, velocities are so low that there is practically no water renewal during a tidal cycle. Even if to a lower extent, the same observation applies to the present scenario (2016, Fig. 9 bottom), in which the only relevant morphological change respect to the 1907 scenario is the closure of S. Liberata channel.

V. CONCLUSIONS

The circulation in the Orbetello lagoon in different key scenarios over the last two centuries has been compared by using a numerical model validated with field measurements. This allows the acquisition of the necessary background knowledge to support the management of the Lagoon, avoiding repeating errors on the basis of the lesson learned from the past. From the historical notices acquired by reviewing original ancient documents and from the comparison of the lagoon circulation in the different scenarios, the following main conclusions can be drawn:

- In the studied period, the lagoon system has always shown anoxic crisis at least since the XVIII° century (i.e. the starting period for the present study).
- To cope with anoxic crisis, several different strategies were tested in the past: opening/closing or reshaping of lagoon inlets, excavation of channel on the lagoon bottom to promote water circulation.
- The level of water renewal is strongly related to the number of lagoon inlets, as expected, i.e. closing inlets decreases the volume of water entering the lagoon and the water renewal and vice-versa;
- The closure of Fibbia inlet, that was already tested in 1862, led to a drastic increase of the anoxic crisis in the northern part of the lagoon, leading to the decision of reopening this inlet just few years later;
- The best scenario resulted that of 1907, when all the inlets were open (Fibbia, Nassa, S. Liberata, Ansedonia).

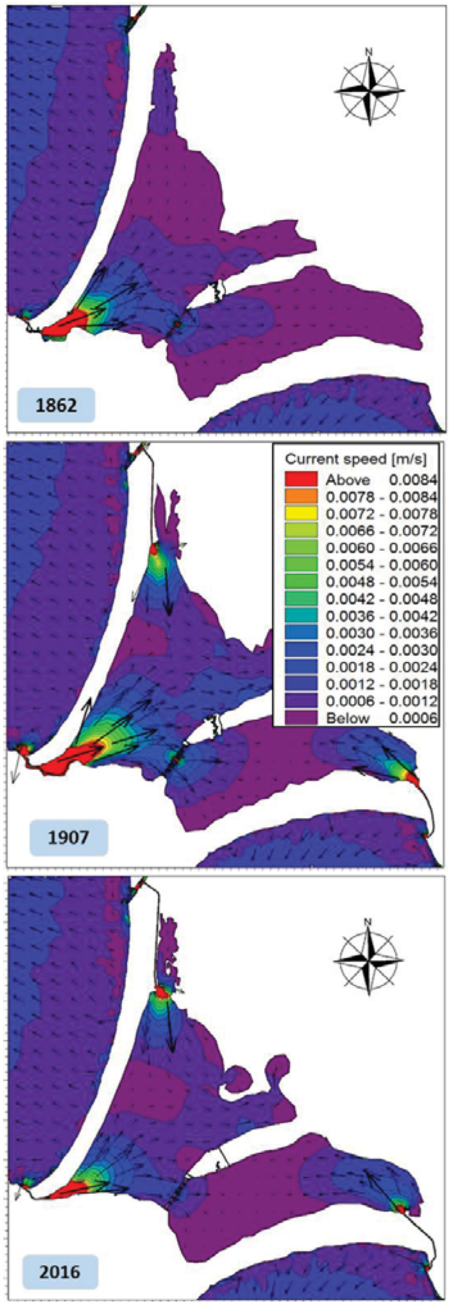

Fig. 9 Velocity contour plot in the Orbetello lagoon: comparison of the circulation resulting under the same external forcing in 1862, 1907 and 2016 scenarios.

The model also allowed to estimate that, now day, opening S. Liberata inlet would increase the water renewal of almost 40%, significantly improving the water quality in the lagoon. Furthermore, on the base of the lesson learned from the past, it can be said that closing the Fibbia inlet, if actuated exactly as in the past, would lead to an increment of the frequency of anoxic crisis.

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