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Marano and Grado Lagoon: Narrowing of the Lignano Inlet

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Abstract. The morphological evolution of a lagoon tidal inlet over a medium-long period is a very important research topic since it can greatly affect both the hydrodynamic balance of the coastal environment and all the several human activities related to its proper functioning. The morphodynamic balance, which is the result mainly of the complex interaction of tidal currents and wind waves, can also be deeply influenced by the presence of maritime structures that are required for sea defence. This is the case of the Lignano inlet, which has undergone a progressive narrowing during last decades. In order to investigate the causes of this process and to evaluate possible solutions for the consequent filling of the port access canal, a morphodynamic-spectral coupled model has been applied to this context. Results are presented and discussed confirming that the numerical modelling can be used as a useful engineering tool for the correct management and the integrated planning of coastal zones.

1. Introduction

Coastal lagoons are characterised by a dynamic equilibrium, highly affected by the periodic exchange of waters through the so called “lagoon inlets”, which are considered as breaches of the offshore bar that separates the lagoon from the sea [1]. The proper functioning of the inlets is fundamental because they are important vessel transport routes which are essential for the lagoon ports and for the economic activities involved with them, for example tourism, fishing and industry [2]. Moreover, the efficiency of this water recirculation system can have significant consequences on the entire ecosystem of these fragile transitional environments, one need only think of the salinity and oxygenation values that derive from it [3]. For these reasons, a correct management of the lagoons inlets is required.

The relative importance of tidal currents and wind waves on the hydrodynamics of both lagoon inlets and river mouths has been deeply examined in the literature, as their combined action has also a direct effect on the capacity of entrainment, transporting and deposition of the sediments and hence on the morphodynamic evolution of these estuarine environments [4-15]. Moreover, also maritime structures for sea defence, such as jetties, and dredging activities can significantly influence the hydro-morphological balance of an inlet and in some cases, their effects are evident only at long-term [16-18].

The complexity of the phenomenon inevitably needs a dedicated numerical modelling in order to take into account the mutual interaction between tidal currents and wind waves propagating nearshore from deeper waters. In the literature, several numerical models have been proposed to study this complex interaction and these models consider all the main morphodynamic aspects. Some 3D models have been developed (e.g. [19-20]), but they are still too heavy from a computational point of view to be applied to wide domains. For this reason, 2DH numerical models are still very common to study both hydro- and morphodynamics of a tidal inlet [21-28].



In this study, the Marano and Grado Lagoon, located in the northern Adriatic Sea, has been considered. In particular, the morphodynamic evolution of its largest and westernmost tidal inlet, i.e. Lignano inlet, has been deeply analysed.

As well as allowing the water exchange between the open sea and the lagoon, the inlet is used as access to the internal lagoon ports and docks. In particular, the shape of the Lignano inlet has undergone considerable changes over the recent years, which have caused a partial narrowing of its section [29]. In order to propose an integrated coastal zone planning intended to mitigate the effects of this narrowing, it is necessary to first of all understand and verify the causes which have generated it by means a medium to long-term study. The approach adopted in the present paper is based on a historical reconstruction and on the application of a proper bidimensional numerical model, which considers the actions of both tidal currents and wind waves. Moreover, the numerical model has been also applied as engineering support to the planning of dredging operations of Lignano canal, which must be reshaped every year to guarantee depths compatible with the draught of the vessels.

In section 2 an historical analysis has been presented. The numerical model is briefly described in section 3 and the numerical simulations are conducted and discussed in sections 4 and 5.

2. Field site and historical analysis

The Marano and Grado Lagoon is located in the North-East of Italy, in the northern part of the Adriatic Sea, and it was once part of a system of lagoons which also included the Venice Lagoon. The lagoon covers an area of 16000 hectares bounded by the Tagliamento river mouth on the West and by the Isonzo river on the East (Figure 1). It is connected to the open sea by 6 tidal inlets, from which a network of channels departs, branching toward the inner part of the lagoon, with progressively shallower depth. Among all tidal inlets, Lignano's one is the most western and one of the largest.

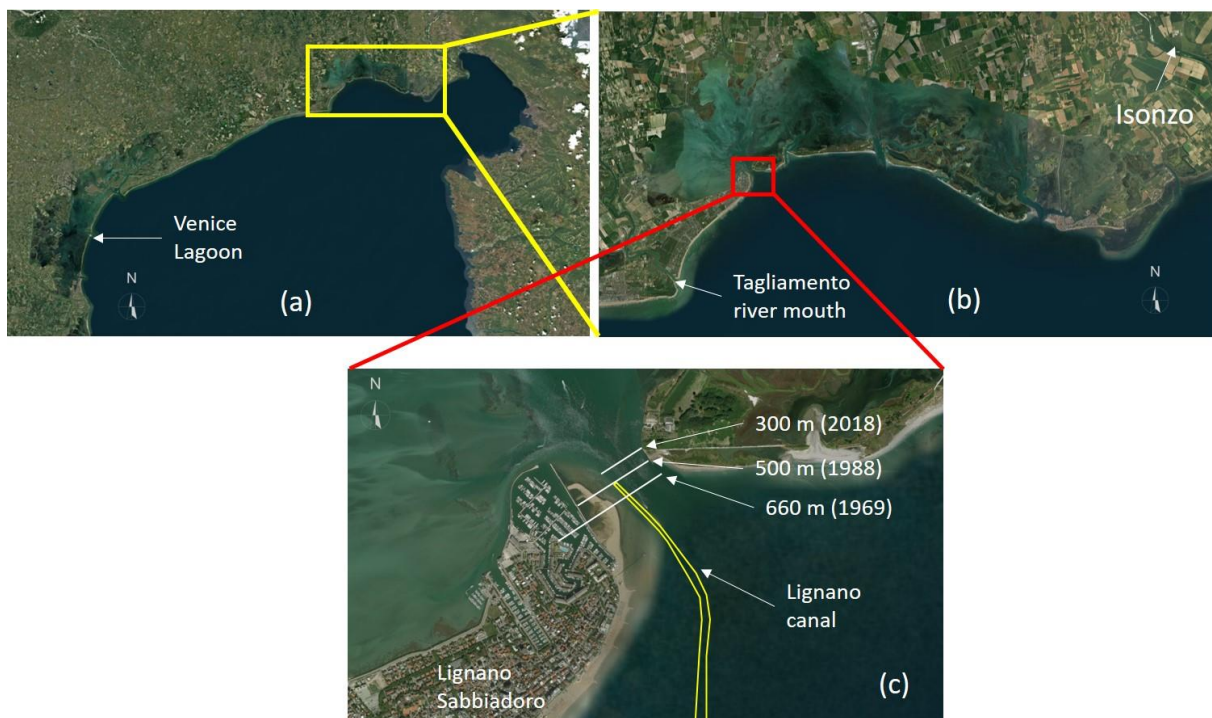


Figure 1. Satellite images of: (a) Northern Adriatic Sea, (b) Marano and Grado Lagoon, (c) Lignano inlet and its width over the years.

Historical images depicted in Figure 2 show that, in the past, the inlet configuration was very different from the present one. A comparison between Figure 2a-c shows that the natural profile of the tip of Lignano peninsula has almost not changed for more than 70 years. In the picture of 1988 (Figure 2d) the

new Marina Punta Faro port can be seen, built close to the inlet. Furthermore, between 1988 and 2017 (Figure 2d-i), a sandy spit can be noticed, developing close to the dock pier from the outside towards the inside of the Lagoon and producing a gradual narrowing of the inlet.

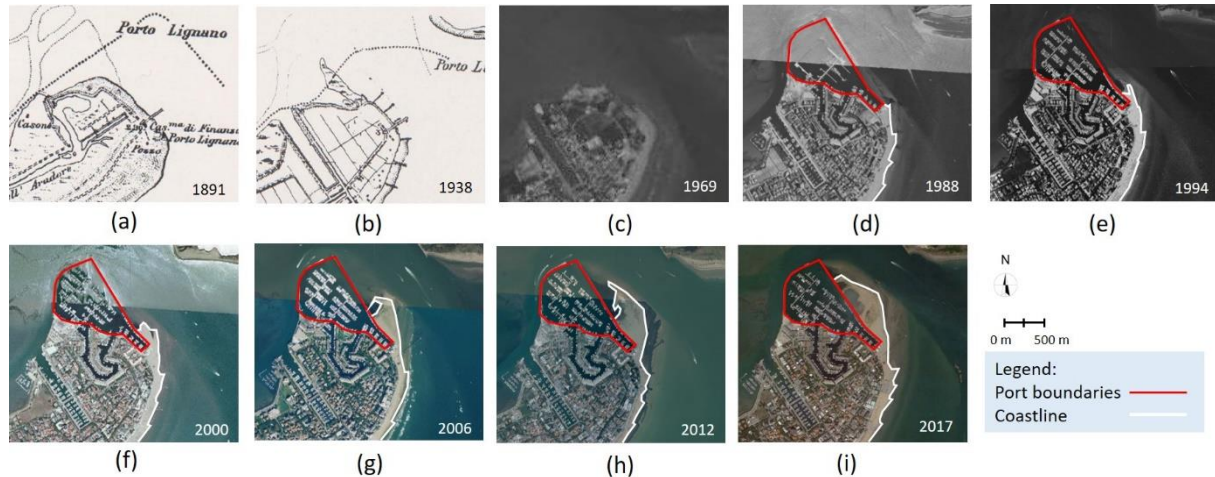


Figure 2. Historical evolution of the Lignano inlet.

The width of the inlet was approximately 660 m until the beginning of the 1980s, when Marina Punta Faro port was built. After that, due to the presence of the pier, the width reduced to around 500 m, as it can be seen in Figure 1c. The formation and subsequent increase of the sand deposit reduced the final width of the inlet to about 300 m. Because of this phenomenon, there are several issues concerning both the water exchange between lagoon and sea, and the navigation, in particular to access Marina Punta Faro port.

In the 31 years between 1938 and 1969 (Figure 3a-b), before the construction of the external pier, the profile of the coastline remained almost unchanged. Instead, considering the 29-years period between 1988 and 2017 (Figure 3c-d), after the pier construction, the coastline profile underwent considerable variations, with a sand deposit close to the structure.

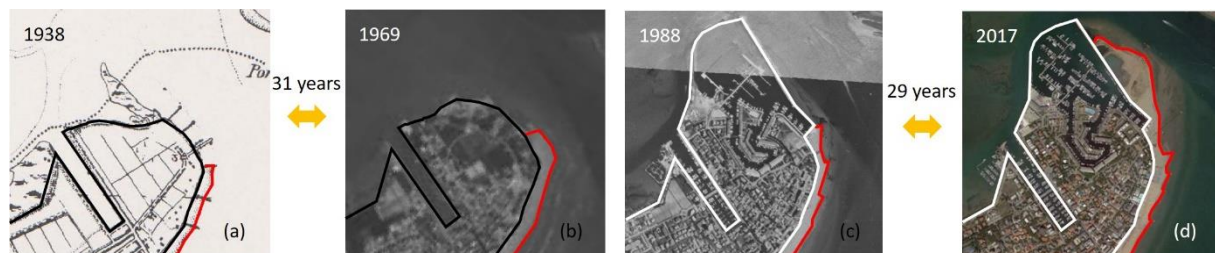


Figure 3. Comparison between 1938 (a) and 1969 (b) and between 1988 (c) and 2017 (d). Red line: coastline; black line: built-up area border until the beginning of 1980s; white line: built-up area border from 1988.

The presence of the deposit caused for example the movement of the fairway from Lignano's coast towards the centre of the inlet. This fact forced the municipal administration to build, in the early 2000s, a new lighthouse, in order to signal the inlet canal access, and to replace the old "red lighthouse", the historical symbol of Lignano Sabbiadoro city. The new lighthouse is positioned at roughly one hundred meters from the previous one, closer to the centre of the canal. Furthermore, periodic dredging operations are required to guarantee canal depths compatible with the draught of the vessels. Moreover, the fairway known as Lignano canal, which departs from the inlet and extends to the offshore, must be dredged to allow the navigation in all tidal conditions also far from the inlet (Figure 1c).

3. Numerical model

The numerical model used in this study couples a morphodynamic model and a wave generation spectral model [30].

The morphodynamic model is based on classic 2DH De Saint-Venant shallow water equations, coupled with the depth-averaged advection-diffusion equation, to describe suspended sediment transport and the sediment continuity equation written on a control volume near the bed, to compute the changes in the bed elevation due to erosion and deposition [31]. The numerical integration of these equations is carried out by means of a shock-capturing finite volume method which is second order accurate both in time and space and which assures a proper propagation also in wet and dry conditions [32-33].

The spectral model used in this study is SWAN, an open source third generation model based on the wave action density balance equation. SWAN considers all the energy source terms, from the wind generation to the dissipations caused by wave breaking in deep and shallow waters, and the bottom friction; also the energy transfers resulting from the non-linear interactions between waves components are taken into account [34].

The coupling between morphodynamic and spectral models consists in running them separately one after each other and exchanging the results of one model as input for the other one and vice versa [30]. This means that at every run the results of the morphodynamic model such as water level, current velocities and bottom elevation become the input data for SWAN. Similarly, SWAN results such as gradients of radiation stresses and wave parameters become the input data for the morphodynamic model. In the present study each model runs for 1200 s, before exchanging the results.

4. The simulation set-up

The computational domain of SWAN includes the whole northernmost part of the Adriatic Sea as depicted in Figure 4a and it consists in a structured grid composed by approximately 350000 squared elements with size 250 m x 250 m. This can be regarded as a good compromise between the needed accuracy and a reduced computational time.

The morphodynamic computational domain roughly covers half of the Marano and Grado Lagoon area and a large portion of the open sea nearly up to the Istrian coasts (Figure 4b). This has been discretized with a structured mesh, consisting of about 188000 quadrangular irregular elements of variable size starting from a minimum of 25 m² nearshore to a maximum of 100000 m² offshore.

Bottom elevation of morphodynamic and spectral meshes has been assigned through available surveys [35].

The computational grid of the morphodynamic model has been modified in the Lignano inlet area to obtain three meshes representing different configurations, in order to analyse the evolution of the sand deposit over the time.

“Current configuration” mesh

The current configuration is related to the present state of the area and it includes the Marina Punta Faro port and the sand deposit close to the dock pier as it appears in Figure 3d. In particular, the bed elevation of this area has been accurately redrawn through photographs and georeferenced image data. Furthermore, in this mesh the Lignano canal has been accurately modelled in its current configuration (Figure 1c) through a bathymetric mapping survey carried out in 2017.

Configuration immediately after the pier construction (“post-pier” mesh)

With the purpose of analysing the behaviour of the inlet immediately after the construction of the port, the bottom elevation of the mesh has been modified to represent the configuration depicted in Figure 3c.

Ante-dock construction configuration (“ante pier” mesh)

Finally, a third mesh has been prepared in order to study the behaviour of the inlet before the port was built (Figure 3b) and to highlight any phenomena which could link the construction of the pier to the formation of the sand deposit. Again, the current configuration mesh has been modified, removing the port and assigning the bed elevation deduced from a topographic map dated 1951.

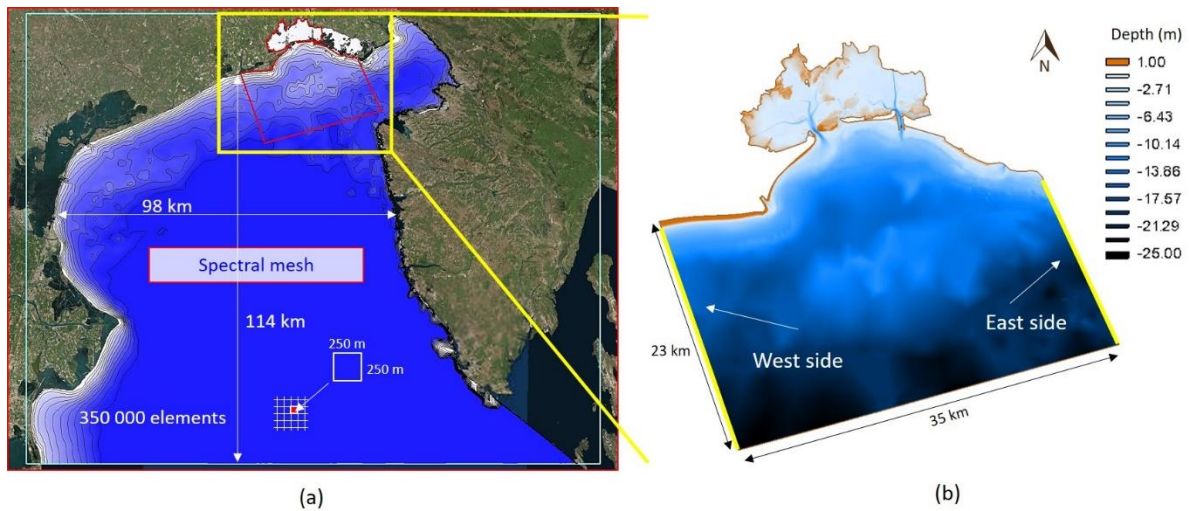


Figure 4. (a) Spectral domain; (b) Morphodynamic domain.

A reflective boundary condition has been applied to all morphodynamic mesh boundaries, with the only exception of the East and West sides represented as a yellow line in Figure 4b, where a tidal boundary condition has been used. In the Adriatic Sea the tide moves counter clockwise [36], hence on the West side a water level sequence has been assigned, which has the same amplitude as in the East side, but a phase shift of about 50 minutes.

The purpose of this study is to represent the morphological evolution of the Lignano inlet and of its neighbouring areas over an average year. Preliminary simulations showed that the tide alone is responsible for a limited amount of sediment movement and only inside the lagoon inlets. For this reason, it is necessary to evaluate the effects of both tides and waves generated by winds. More preliminary simulations in this sense showed that only winds with intensities higher than 10 m/s are able to move sediments and trigger sediment transport. Thus, wind speeds higher than 10 m/s have been considered in association with their direction and mean annual duration as described in Petti et al. [37]. Finally, the simulated winds have an intensity of 12 m/s and 17 m/s and directions of 75°N (Bora/Levante) and 165°N (Scirocco), which are the ones that mainly affect the study area.

The tidal oscillation adopted is depicted in Figure 5 and it derives from an analysis of tidal levels measured during particular wind events with the same speeds and directions described above.

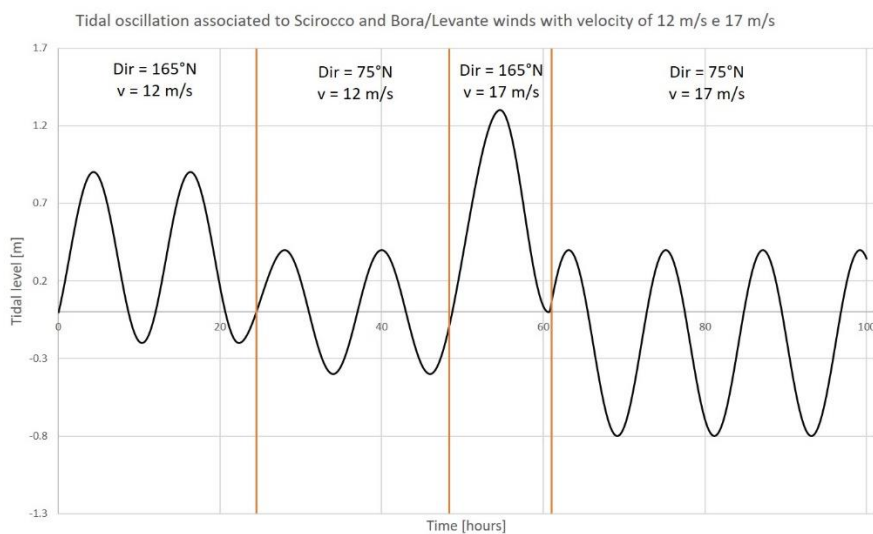


Figure 5. Tidal oscillation adopted for the simulations.

It can be observed that the tidal oscillations have an increased maximum level when the blowing wind direction is 165° N; on the other hand, there is a reduced minimum level concurrently with 75° N direction winds.

Current bed shear stress has been assigned through the Manning coefficient [30].

Focusing on the morphodynamics of the tidal inlet, where the fraction of granular sediments is predominant, a single type of bed material has been set, i.e. granular sediments with mean diameter of $200\ \mu\text{m}$.

The SWAN spectral model parameters were set as in Petti et al. [30] with the only exception of the equivalent roughness length scale of the bottom, which has been set as $0.02\ \text{m}$ to evaluate the wave decay due to bottom friction following Madsen formulation [38]. This parameter is consistent with that proposed by Pascolo et al. [39-40].

The overall simulation lasts 100 hours and follows a time sequence as the one described in [37].

5. Model results and discussion

First of all, a simulation of an average year has been carried out on the “current configuration”, to evaluate the source of the sand deposit close to the pier. To this end, 10 cross sections placed along the inlet have been considered (Figure 6a). The qualitative estimate of the net average sediment flux which crosses these sections every year has been made. As it can be seen, the cross sections arranged along the littoral are relatively short, because for this analysis only the surf zone has been considered, where the sediment transport is also affected by longshore currents induced by the breaking wind waves. Sections 1 to 8 are divided in 3 subsections while sections 9 and 10 are divided into 4 portions. In Figure 6b the net fluxes are represented with red arrows if directed toward the lagoon, on the contrary with yellow arrows if they are exiting from the lagoon.



Figure 6. (a) Sections considered); (b) representation of the sediment flux through the sections.

The sediment fluxes in the subsections closest to the coast move from South-West to North-East, i.e. entering the lagoon, with varying values; instead, in the deepest part of the Lignano inlet the sediment fluxes head from the lagoon to the open sea. From these results, it is possible to assume that the sand which is progressively accumulating in the area close to the pier, comes from outside the lagoon, most likely from the northernmost part of the Lignano Sabbiadoro beach, as it is constantly subject, during recent years, to an erosive phenomenon and consequent sand nourishment operations. This trend is also confirmed by the comparison among the historical images reported in Figure 2.

The same analysis has been carried out on the “post-pier” configuration. The Figure 7 helps to better understand the pattern of the sediments. In particular, sections 7 to 10 have been analysed, which are the closest to the pier. The net yearly average sediment flux through sections 7, 8, 9 and 10 are respectively equal to about $26000\ \text{m}^3$, $20000\ \text{m}^3$, $10000\ \text{m}^3$ and $14000\ \text{m}^3$. As a consequence, it is possible to conclude that between sections 7 and 8 about $6000\ \text{m}^3$ of granular sediments have a tendency to be deposited every year, while between sections 8 and 9 the average annual deposit is approximately

10000 m³. This is a further confirmation that the sediments feeding the deposit come from the coastal area outside the lagoon, in accordance with the satellite images reported in Figure 2.

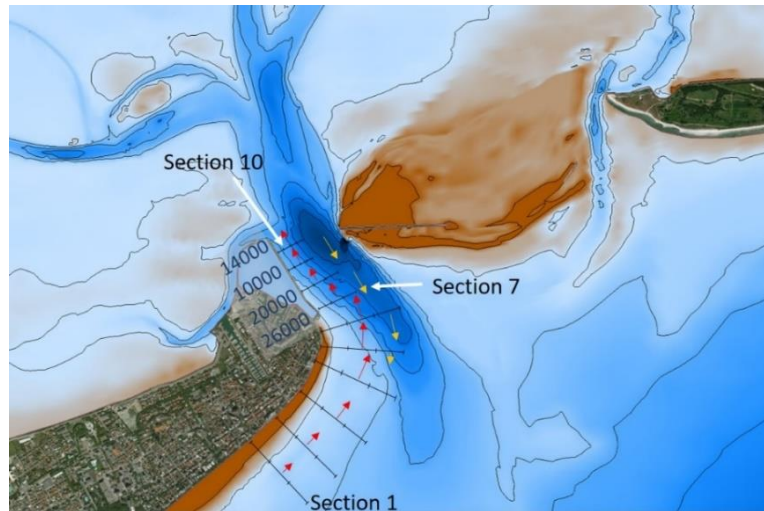


Figure 7. Representation of the sediment flux through the sections on the “post-pier” mesh.

In order to make a comprehensive analysis, the previously described simulation has been carried out also on the “ante-pier” mesh. With the aim of verify if this configuration was in equilibrium, the morphodynamic effects of 5 average years have been simulated. At this purpose, after the first year, four more years have been repeated assuming the results of one year as the initial conditions of the following one. In particular, the changes in the cross section depicted in Figure 8 have been analysed.

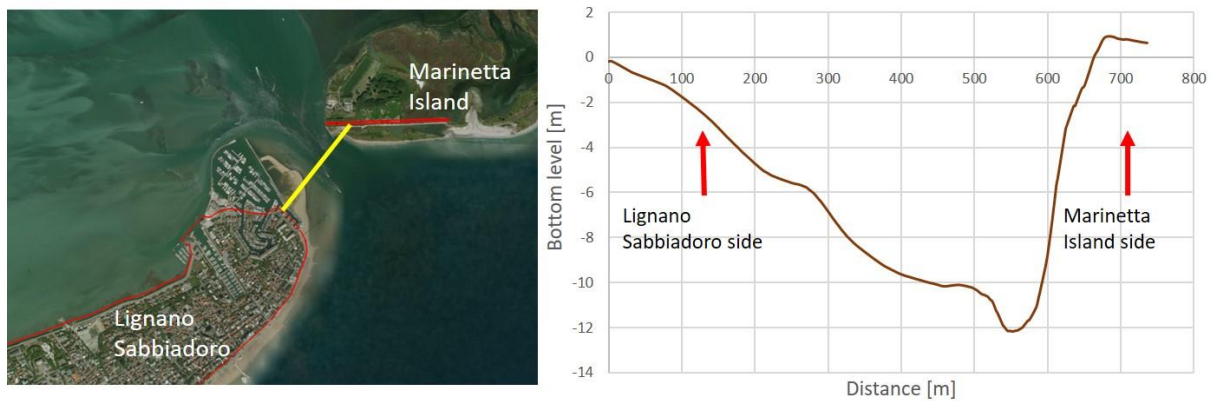


Figure 8. (a) Position of the section analysed; (b) and representation of the section shape.

In Table 1 the submerged area under 0-level is shown, as it changes over the simulated years. It can be seen that this parameter has a tendency to remain constant, attesting the morphological equilibrium of this configuration. This seems to confirm that the pier is the prevalent cause of the deposition, which is bringing to the progressive narrowing of the inlet.

Table 1. Variation of the submerged area of the section over the 5 simulate years.

Submerged area of the section [m ²]					
Year 0	Year 1	Year 2	Year 3	Year 4	Year 5
4147	3825	3770	3770	3745	3710

5.1 Lignano canal

The Lignano canal, whose complete path is reported in Figure 9a, is the route used by vessels to move between open sea and the docks inside the Lagoon. As such, it is subject to constant and repeated maintenance works in order to permit the access to the Marina Punta Faro port, which, with its 1200 berths, represents one of the major realities of its kind in the North Adriatic area.

Every year this canal is subject to expensive dredging operations deriving from the filling phenomena due to the stronger autumn and winter storm tides.



Figure 9. Lignano inlet traces: (a) current configuration, (b) straightening proposed.

The evaluation of the sand volume deposited inside the canal has been deduced from the simulation on the "current configuration", which has provided an annual deposit of about 37400 m³. Considering the whole canal area, this means an overall increase in the bottom elevation of about 27 cm, even if the area mostly subject to deposition is located in the central part of the canal.

In order to evaluate a possible solution for the Lignano canal filling issue, which could improve the planning and the management of this area, an attempt has been made to verify if a modification of the existing trace could have an advantage compared to the present state. This change is the straightening of the canal trace, as reported in Figure 9b.

The "current configuration" mesh has been modified to describe this new arrangement and the simulation has been carried out once again. At the end of the simulation, in the straightened canal there is a deposit of about 32700 m³. In general, the area subject to deposition is located in the outer more part toward the open sea while closer to the Lignano inlet there is some areas subject to erosion.

From these observations it is possible to say that this solution, with a straightening trace of the Lignano canal, cannot substantially reduce the volumes of sediment deposit and consequently the burdens of the dredging operations.

6. Conclusions

The morphological evolution over recent decades of the Lignano lagoon inlet has been studied by means of the comparison of some satellite images, referring to different years, showing that the human action can highly interfere with the natural functioning of the inlet. The construction of the Marina Punta Faro dock determined a narrowing of the section of the inlet which has been further restricted due to the formation of a sand deposit close to the pier dock. Moreover, it has been shown that the sediments forming the sand deposit come from the outside of the lagoon.

The same issue has been studied through a 2DH morphological model coupled to a spectral model, in order to consider the effect of both tidal ebbs and flows and the wind waves. The numerical modelling has allowed to study different historical phases of the lagoon inlet to better understand the effects of the port construction.

The simulations seem to confirm that the sand of the deposit close to the pier comes from the outside of the lagoon, in particular from the northernmost part of the Lignano Sabbiadoro beach which is every year subject to sand nourishment interventions.

The numerical modelling has been also applied for the study of the canal which connects the lagoon with the open sea with the aim to evaluate the advantage of a possible change in its trace. This is another important confirm of the utility of the numerical modelling to plan and manage the operations involving a lagoon inlet area.

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