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Sedimentation and Erosion in Harbor Estuaries

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Abstract

Harbors, whenever possible, are established in estuaries to take advantage of the existing natural safety and protection conditions. To keep harbors in a safe and usable way, periodic dredging works are carried out. The expansion of harbor's activities and the growth of maritime traffic may lead to changes in the harbor's layout or to improvements of navigation channels and basin depths. Such design adjustments entail changes in estuarine hydrodynamics, and therefore the usual dredging rates are subject to alteration, namely, tending to increase. It is then important to assess the influence of the harbor's new layout on the solid transport pattern and how its effects can be minimized, aiming the reduction of economic and environmental impacts. Within this context, in this chapter estuary hydrodynamics and sedimentation-erosion patterns are summarized. Also, the modeling methodology for planning and management of dredging works which uses geo-processing automatic GIS environment, developed by the Portuguese harbor authority, is presented. Finally, the case study of harbor of Portimão is also described showing the implementation of the referred methodology.

Keywords: erosion, sedimentation, layout, hydrodynamics, dredging

1. Introduction

Sedimentation and erosion patterns and rates in estuaries rely on the interaction of multiple conditions and so are generally complex. However, in a brief and simplified overview, when a system is in equilibrium, there is neither sedimentation nor erosion; when, at local conditions, the flow velocity is not strong enough, there will be accretion; and, if the flow velocity is too strong, there will be erosion. In the case of an environment alteration (e.g. due to natural

causes, as a heavy storm, or due to human intervention, as the construction of a dock), a change in hydrodynamics and, consequently, in the sediment-erosion pattern will occur [1].

Sediment transport processes are subject to the influence of site conditions as the geological and geotechnical characteristics of the estuary basin bed and of the existing suspended sediments. So a good knowledge on sediment geotechnical properties (i.e. granulometry, mineralogy, resistance to erosion,) is important as they define the hydrodynamic velocity for which sedimentation occurs [2] due to the distinct dynamics of transport, and even interactions, between cohesive sediments (mud) and of non-cohesive sediments (sand) [1].

Depending on harbor emplacement, sediment movement is also controlled by the river flow and tidal and wave conditions [3]. When considering harbors located in estuarine areas, particularly in the terminal section where the tide occurs, the tide plays a more important role in solid transport patterns than the river flow itself. Nevertheless, a major factor in this situation is the estuary's tidal prism, which is the volume of water exchanged between mean high tide and mean low tide or the volume of water leaving an estuary at ebb tide. The available tidal prism is so dependent on the geometry of the basin in terms of surface area and mean water depth and also the tidal range, the frictional forces and, to a lesser extent, freshwater inflow. Therefore, the larger the tidal prism related to the river flow, the more determinant for the sedimentation and erosion processes, in the estuary, is the tide and tide flow.

Hence, to better understand estuarine sediment dynamics, it is relevant to study the existing topography, through reliable surveys performed, at adequate detail and scale, for each case location. The obtained data allows hydrographic modeling in order to relate hydrography with hydrodynamics and thus attain the referred knowledge.

Estuarine locations, although provide natural safety and protection conditions to the establishment of harbors and other facilities, are prone to natural filling caused by the settlement of sediments. Consequently, periodic dredging is required to maintain navigation channels and harbors in a safe and usable way. Moreover, given the natural trend of harbor activities expansion, dredging works are also needed to improve the design depth for larger vessels access, to build new wharfs and piers, or to improve existing harbors or other facilities [1]. As stated above, changes to harbor layout entail changes in estuarine hydrodynamics; hence the dredging need rates are subject to alteration, namely, tending to increase. So, it is important, when planning harbor new layout design, to include methods to minimize hydrodynamics changes and to reduce dredging volumes.

Although dredging operations are essential, these have a significant economic impact, not only during the construction phase but also along the operation phase, due to maintenance works. In fact, in small harbors, it corresponds to almost 75% of all maintenance costs [4]. Moreover, dredging activities can also have adverse environmental impacts, either within the dredge area or the deposition site, as fine-grained fraction of sediment resuspension (increasing the turbidity of water), nutrients and pollutants dispersion, water column contamination, or ecosystem degradation (e.g. by burying the biological habitats). So, potential environmental effects and risks are imperative to ascertain and well manage through the implementation of adjusted containing or remedial measures.

The referred economic and environmental impacts of dredging works highlight the importance of an accurate knowledge of sediment transport patterns, namely, the identification of sediment deposition and erosion areas and also of the areas in which there is a balance. Regular hydrographical surveys can allow the determination of the sedimentation rate [4] and are considered as a key procedure for dredging design optimization.

Taking into account the referred goals of efficiency improvement, cost reduction and environment protection, the use of management models is considered a valuable method to support harbor management and design (or new design) decisions. This approach allows to adequately manage the dredged material, in operation phase, with its use (e.g. beach nourishment) or its safe disposal. As well, in design phase, the hydrodynamic modeling enables to achieve a better balance in erosion and sedimentation rates, throughout optimized technical choices. The aimed performance improvement intends to minimize the dredging volumes, keeping the sediments within the system but, at the same time, keeping the waterways of the harbor in a safe mode for the vessels that use it.

This chapter presents a planning and management model of dredging using the geo-processing automatic GIS environment developed by the Portuguese harbor authority, which is intended to be an accessible and efficient tool to support technical options in dredging design. Additionally, the particular case of harbor of Portimão, where the referred methodology was implemented, is discussed. The present hydrodynamic situation of the estuary is characterized, using a tidal model and considering average flows of the river. Then, taking into account the plans for the harbor expansion, the hydrodynamic modeling of the new layout is presented. Using as a reference the current situation, a method to analyze the influence that the planned works will introduce into the estuarine hydrodynamics and, consequently, in the pattern of sediment deposition and erosion is also summarized.

2. Methodology

In estuarine locations, dredging activities are a required procedure both in harbor design and, during operation stage, in harbor management. However, from economic and environmental standpoints, dredging can also cause adverse effects related to the sediment removal from the basin bottom and also related to the management of the dredged material that are important to control. The referred impacts result from changes in local hydrodynamics and as consequence in the existing sedimentation-erosion patterns and rates.

An adequate management system that keeps the harbor in a safe and usable way, but also that controls the dredging impacts, reducing to a minimum the dredged volumes and disposing them, if possible and useful, within the system is so aimed.

In order to achieve those goals, it is essential to have a comprehensive knowledge of the present situation (reference situation) in terms of accretion and erosion areas and the typology (grain size) of the sediments within those areas. This data is attained through the combined analysis of local hydrography and hydrodynamics, as well as local geology and geotechnical

characteristics. As a result, predictive models can be established, and better technical choices concerning harbor design or management are then possible.

Therefore, a set of procedures were established to aid and simplify both the planning of harbor dredging and of the disposal of the dredged materials. Some guidelines are then proposed to be followed [3–5]:

- Analysis of the granulometry of sediments in the harbor area of the estuary
- Analysis of the maximum velocities of tidal flow and its comparison with average tide and living waters flow velocities
- Comparison of the sediment size with the maximum velocities of tide
- The use of automatic geo-processing
- The use of this information in harbor dredging planning, including the definition for dredged material

2.1. Physicochemical model development

Aiming an optimized dredging project management tool, the Portuguese harbor authority has developed and implemented a model of planning and management of dredging using the geo-processing automatic GIS environment which is next presented. Taking into account geo-referenced detailed hydrographical surveys and physicochemical analyses of the sediment, the referred model:

- Identifies the spatial distribution of zones where erosion and sedimentation occur
- Relates them with the existing types and concentrations of contaminants (if any)

allowing then the zoning of the area to be dredged.

The developed analysis system is based on a conceptual model of morph-dynamic and multi-temporal sediment distribution in port areas, automating the production of maps [6].

Through the conversion of different data formats, the proposed model is able to:

- i. Generate surfaces of different particle sizes by using interpolation methods.
- ii. Zone the dredging area.
- iii. Assess the areas and volumes of eroded and deposited sediments considering four distinct particle classes: pebble, sand, silt and clay [4].

This system was implemented by applying Model Builder software ArcGIS® (ESRI), and it consists of a set of tools that operate sequentially in the calculation of the various components of the model.

Firstly, **Figure 1**, five modules (defined as M1–M5) were implemented, each with specific processes to build automatic digital maps with the relevant information allowing [4–7]:

- M1—conversion of CAD entities into vector entities (GIS shapefile).
- M2—development of digital terrain models from bathymetry (DTM), tin and raster.
- M3—interpolation of particle sizes, deterministic method IDW.
- M4—preliminary zoning of sediments of harbor areas.
- M5—calculation of areas and volumes of erosion and deposition for subsequent dredging planning.

So, the integration of the flow field pattern and tides, using finite element method (FEM), with size distributions in estuarine sediments (determined with MAZD), identifying their source, allows then to divide the harbor area in main areas, according to the same sediment typology, for dredging purposes.

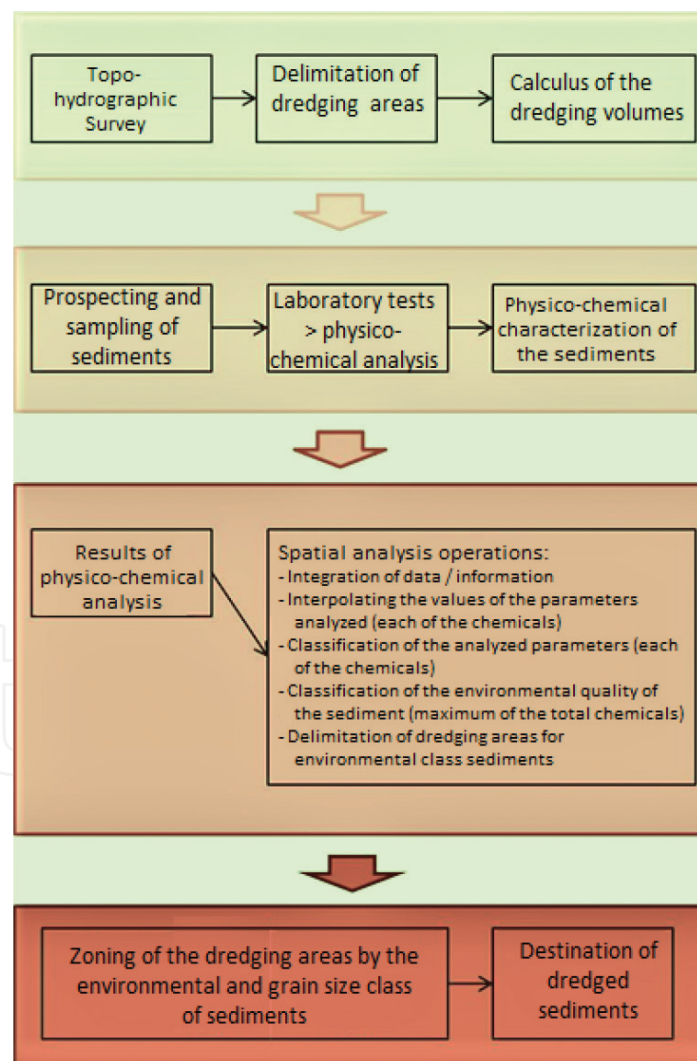


Figure 1. Flow chart of the developed procedure of physicochemical characterization for sediment dredging management in harbors.

2.2. Zoning (M4)

Following the physicochemical characterization and analysis of the sediments and taking into account the obtained results, the proposed methodology aims the identification of areas of erosion and deposition of materials.

In the reference situation for the case study, the identification was made using tools of geographic information systems, namely, 3D Analyst and ArcGIS Spatial Analyst. The zoning of the estuary area according to the grain size of the sediments was then established.

2.3. Hydrodynamics

According to the applied methodology, the determination of the maximum velocities of the ebb tide in each of the study zones must be performed, for the reference situation. Later, the determination of the maximum velocities of ebb tide, for the new layout, must also be carried out.

2.4. Sedimentation and erosion (M5)

The following step of the stated method is comprised by the identification of the areas where sedimentation and erosion occur and also where a balance between both states takes place, using the different digital terrain modules obtained from bathymetry in different years.

For each study area, the maximum velocities of the ebb tide are related with the erosion or sedimentation status verified.

2.5. Simulation for layout changes

By the integration of the gathered results from the reference situation and the new layout, it is aimed in this stage to foresee the changes in erosion and sedimentation patterns, comparing the flow changes in both situations. So, the areas in which erosion and sedimentation are likely to increase, or to maintain a probable balance, are then identified, estimating the variation in yearly volume dredging.

Finally, according to the results, an eventual consideration of alternative solutions to dredging can be studied.

3. Case study: harbor of Portimão

In this chapter, the hydrodynamics of the Arade estuary is analyzed considering the area of port interest (Port of Portimão), studying the present situation of deposition and erosion of sediments, relating them, based on the detailed information about the model [8].

The port of Portimão presents the best natural conditions on the southern coast of Portugal. The area under port jurisdiction runs from the mouth of the River Arade to the Roman bridge

in Silves, 13 km upstream. At present, the port area only encompasses the frontier stretch of the city of Portimão, and it can be seen that, upstream of the first Arade Bridge, the river can only be used by small tourist boats and in certain places only at high tide. Two breakwaters protect the entrance to the port, with a minimum of 200 m wide, followed by a 150 m wide navigation channel, which extends to the commercial wharf and the fishing port [9]. The W and E quays have lengths of 820 m and 680 m, respectively. In the wide front, there is a circular and maneuvering basin. On the right bank, from the inlet upstream, first there is Portimão Marina; then the Navy Pier, with a length of about 200 m; and the Terminal of Passengers and General Cargo, about 340 m long; further upstream, in a lower depth zone, there are other docks and berths for recreational craft. The fishing port is located on the left bank, with mooring wharves, a shipyard and a supply pier. The port of Portimão is used for trade, cruising, fishing and recreation. There is a weekly ferry link to Madeira and the Canary Islands.

The modeling of the estuary of the River Arade includes the west coastal zone up to Ponta da Piedade, west of Lagos and the east coastal zone till near Vilamoura. Given the referred coast extension, it was intended to ensure that the tide conditions that were taken into account at the entrance of the bar would be free of undesired influences from the boundary conditions.

Regarding the study area towards the inland, the river Arade was considered as far as the Roman bridge of Silves, in an extension of 13 km, and the Odelouca stream to a section about 14 km upstream from the mouth of the Arade. This way, it was intended to obtain, in the area under study—Arade estuary between the Portimão road bridge and the bar—the most representative situation possible.

It was considered that hydrodynamic conditions are determined almost exclusively by the effect of the tide, since the influence of the river flow is very small, given the regularization imposed by the built dam upstream; it was assumed for the river flow the value of $10 \text{ m}^3/\text{s}$. Upstream of the model limit, the roman bridge of Silves, the volume of the tide prism is very small, due to both the small widths of the channels of the water lines and the high levels of the bottoms.

For the hydrodynamic modeling, the RMA2 model, with the SMS interface, was used. The mesh of finite elements used for the reference situation is presented in **Figures 2** and **3**. For the future layout, the mesh and the boundary conditions were modified considering the future hydrography, according to what each work planned, the respective geometry and the limit of analysis.

To calibrate the model in the reference situation, three points were taken into account, respectively, upstream of the railway bridge in Mexilhoeira Grande, at the junction of the Odelouca River with the Arade River, and downstream of the Roman Bridge in Silves, as referenced in **Figure 4**. The observations available for the calibration of the model, considering the free surface of the flow, took place during a tide cycle. Besides the points used for the calibration of the model, **Figure 4** shows the points used for the overall analysis of the results and also for the detailed analyses.

The variables obtained in the calibration of the model were used in the future layout model, with minor adjustments to eliminate instabilities of convergence of the iterations.

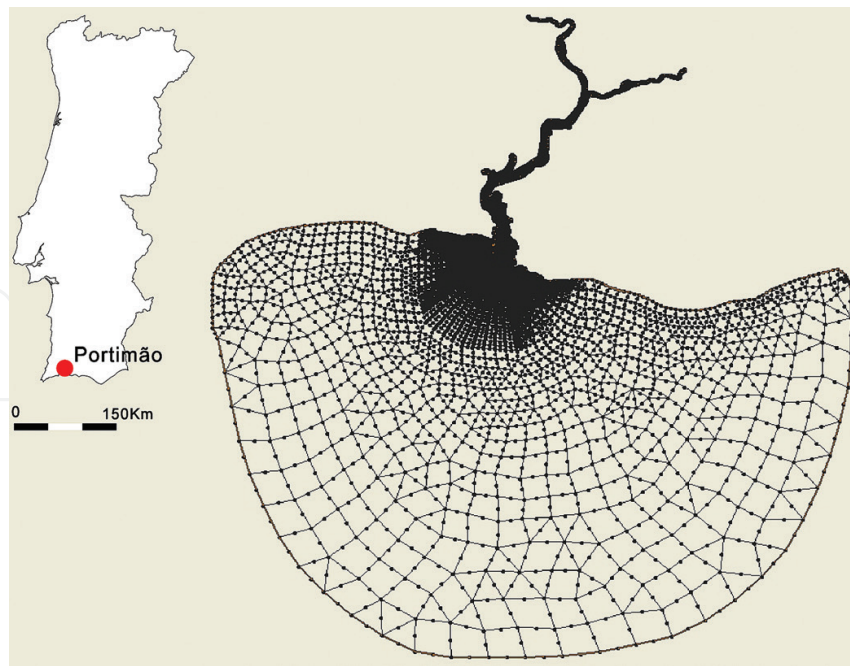


Figure 2. Finite element mesh of the case study and the harbor location.



Figure 3. Details of the mesh in the estuary of the Arade River: the estuary and the zone that comprises the Dock of San Francisco, the fishing port, the commercial wharf and the Navy Pier and the maneuvering basin.

The flow rate considered for both situations (reference situation and future layout) was $5 \text{ m}^3/\text{s}$ in the Arade River and $5 \text{ m}^3/\text{s}$ in the Odelouca stream. In fact, the average current flow rate at the Portimão road bridge is estimated at about $10 \text{ m}^3/\text{s}$. For the calibration, and taking into account the flow rates verified on the day of the field readings, a flow rate of $0.5 \text{ m}^3/\text{s}$ was used for each of the streams.

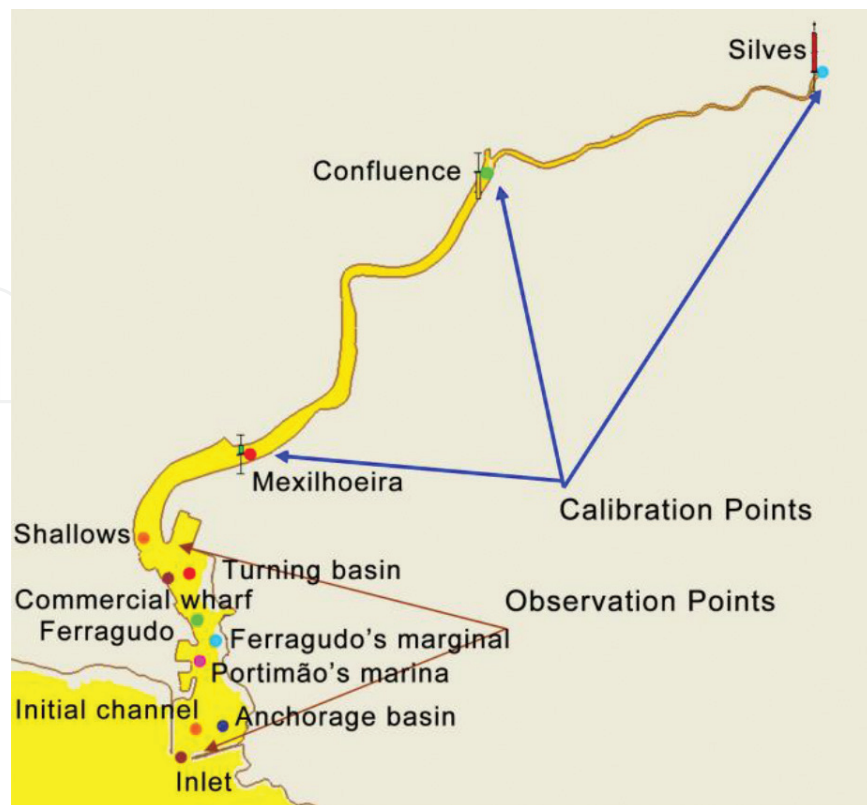


Figure 4. Calibration points and observation points, for comparison of results.

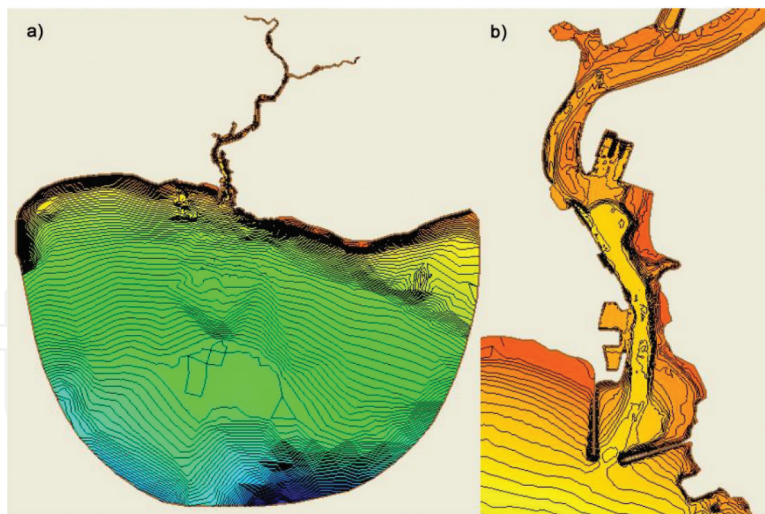


Figure 5. (a) Topo-hydrography considered for the reference situation and (b) detail of the estuary.

In **Figure 5**, the topo-hydrography regarded in the hydrodynamic analysis is presented in a very schematic way, and it was based on the surveys carried out in 2003. For the future layout simulation, this hydrography was modified according to the various reviewed works. This way, the velocity and the water heights at each point were obtained. The interventions planned for the port will not have a significant influence on the hydrodynamics upstream the Portimão road bridge, as there will be no changes in that reach.



Figure 6. Materials (different roughness) considered in the analysis, in the section between the road bridge and immediately downstream of the bar.

Consequently, the “overall” analysis of the results to be achieved will focus only on the section between the Portimão road bridge and the inlet, and so four areas were analyzed in detail: commercial quay and maneuvering basin, Ferragudo channel and Ferragudo bank, the first section of the navigation channel and the inlet. Some considerations are also done about the sandbank channel, upstream the commercial quay. Several zones were considered in the modeling, corresponding to different “materials” and their corresponding roughness, in the RMA2 model, which are represented in **Figure 6**. In fact, the hydrodynamic conditions within the several docks are substantially different from those observed, for example, along the navigation channel.

3.1. Zoning (M4)

Considering the sampling and grain size analysis performed, and considering the fine alternations of thinner and coarser sediments, typical in this type of environment, as well as the various strata, it was decided to divide the estuary into three zones (**Figure 7**):

- Upstream, between the road bridge and the downstream part of the maneuvering basin, as a zone of fine sediments
- Downstream of the former and to the southern end of the Portimão Marina, as an area of medium sediments
- To the south of the previous one, and to the bar, as a zone of coarse sediments

It is considered that the occurrence of erosion and sedimentation in the mooring area, and the coarser sediments, is more related to the swell of SW, than to the currents caused by the tide.

In this zoning, “fine sediments” include materials ranging from fine sand to mud, including silts; in “medium sediments” fine to medium sand, with some silt, are included; the “coarse sediments” include coarse to medium sand.

Figure 7 shows the proposed zoning for sediments, which will serve as a basis for the subsequent analysis of the possible acceleration of erosion or sedimentation trends.

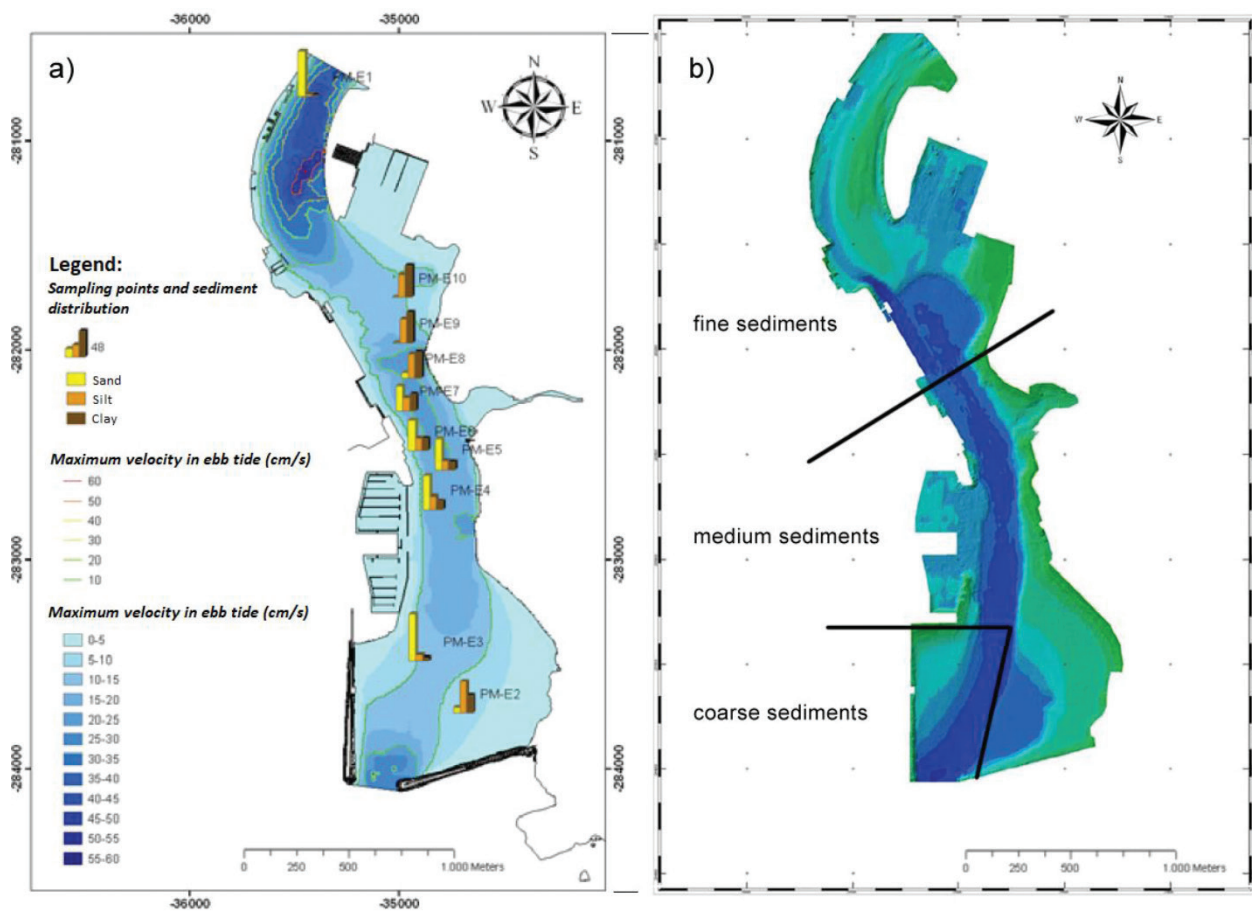


Figure 7. (a) Sampling points and grain size distribution; (b) simplified zoning of the estuary.

3.2. Hydrodynamics

The reference situation corresponds to the current situation of the port of Portimão, as in 2010; however, the hydrography of the survey of 2003 was used since it is still representative.

For performed modeling, and for all subsequent modeling, the tide of 27 February 2002 (Figure 8) was considered for representing a tidal wave, as it corresponds to the obtention of the field values for the calibration of the model. The tide used has a flood level of 3.69 m ZH and a low sea level of 0.30 m ZH.

All the modeling was carried out for a period of 65 hours, i.e. more than five complete cycles of flood and ebb tide. In this way, the aim was to stabilize the obtained results, since, in general, and in the application of the RMA2 model, the two or three first cycles show variations before reaching stabilization. The period considered for analysis, both in this modeling and in the following models, was the between 48 and 62.3 hours of simulation.

Figures 9–11 show some of the results that are considered more relevant for the reference situation. As expected, in this case, there is a delay of almost 1 hour between the peak velocity in the bar and the channel in front of the central zone of Portimão, near the sandbank. There is also a substantial reduction in flow velocity in front of the S. Francisco dock, due to the widening of the flow channel due to the entrance to the fishing port, the S. Francisco dock, and the maneuvering basin. There is also a significant reduction in velocity on the initial section of the channel and in the mooring area, due to the widening of the flow section in that area.

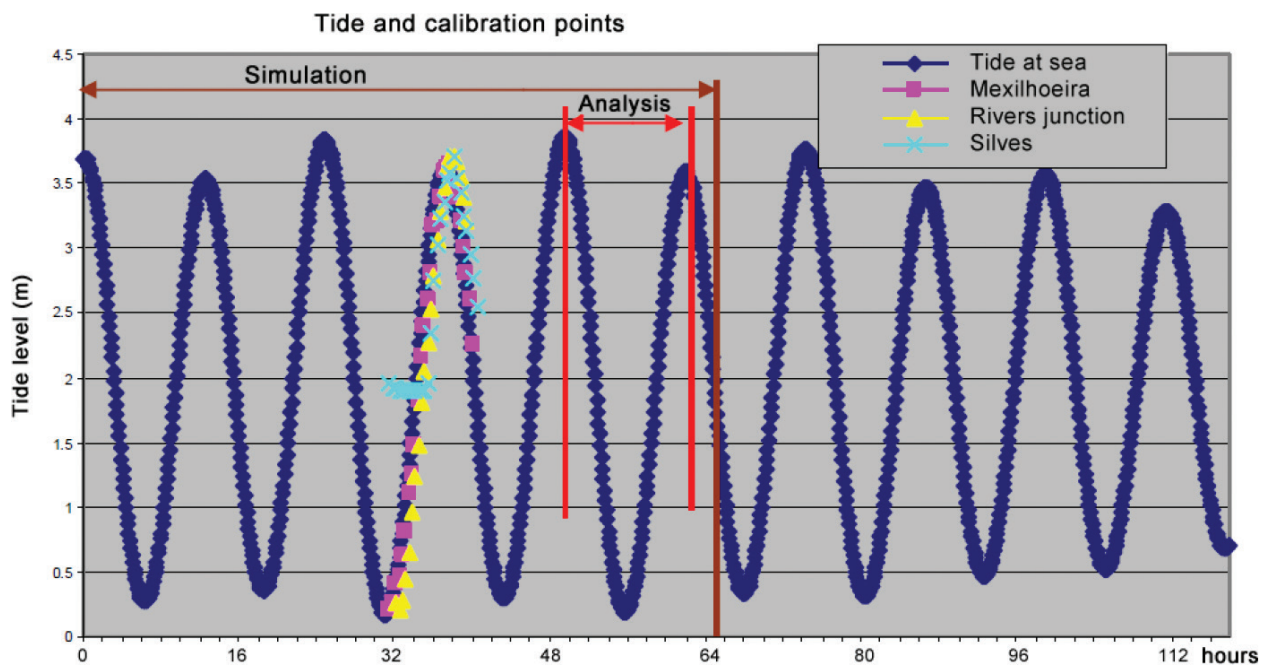


Figure 8. Tide used in the modeling, including the 27th of February (calibration data) and the period used in the analysis.



Figure 9. Reference situation. Results obtained during ebb flow: (a) 50, (b) 51, (c) 53 and (d) 55 hours.

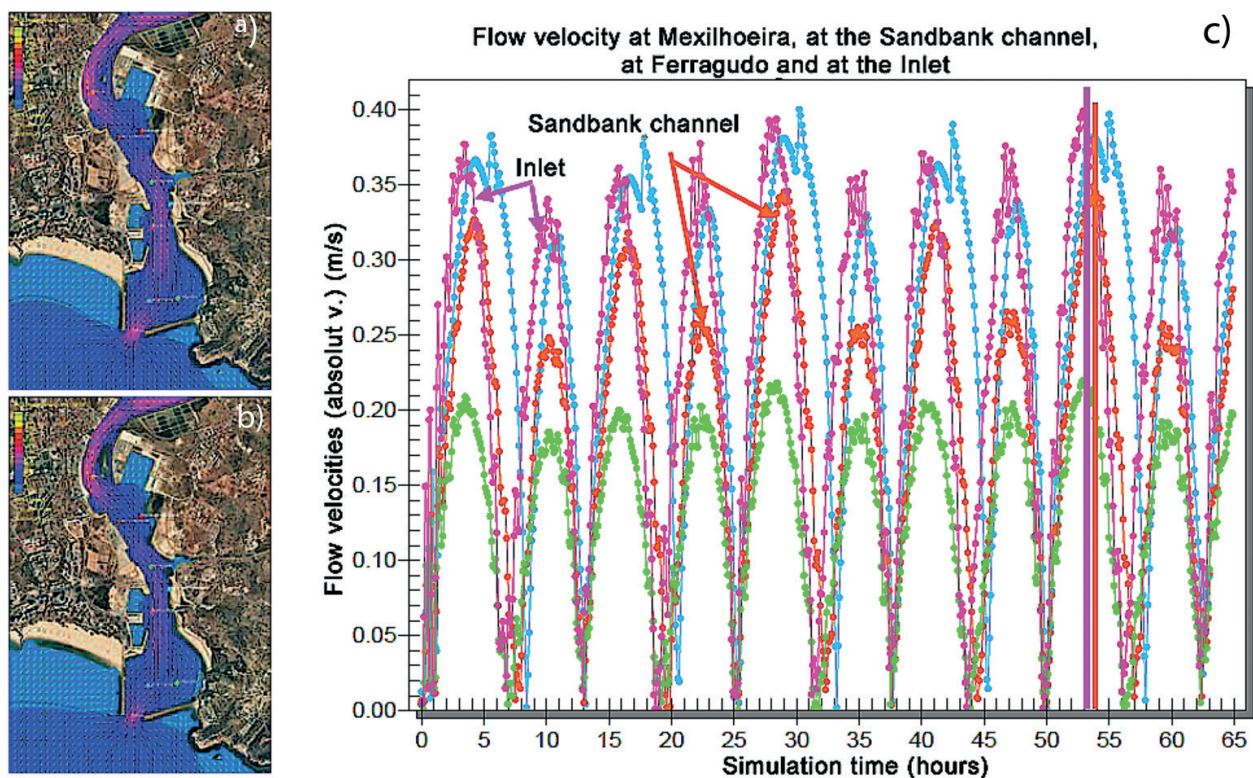


Figure 10. Reference situation. Flow at (a) 53 and (b) 54 hours; (c) delay between the peak of velocity in the ebb tide in the bar and in the channel near the sandbank.

3.3. Sedimentation and erosion

The determination of the areas currently subject to sediment deposition or erosion was done following the methodology explained in Section 2, using the 3D Analyst and the Spatial Analyst tools of ESRI geographic information software. The 2000 and 2003 surveys of the



Figure 11. Reference situation. Results obtained during flood flow: (a) 58, (b) 59, (c) 60 and (d) 61 hours.

entire port of Portimão were used. These two surveys allow a good understanding of the erosion sedimentation procedure, as there were no full dredging works in the meantime, only local dredging works.

The application of this model, simple to apply on geo-referenced surveys, allows to determine the locations where the depth has lowered (deposition of material), or risen (erosion of sediments), and to assess the value of these variations, by analyzing the difference on the assessed depths of two hydrographic surveys separated by a certain time interval.

With the application of 3D Analyst and Spatial Analyst to the two surveys of 2000 and 2003, the results, represented graphically in **Figure 12**, were obtained.

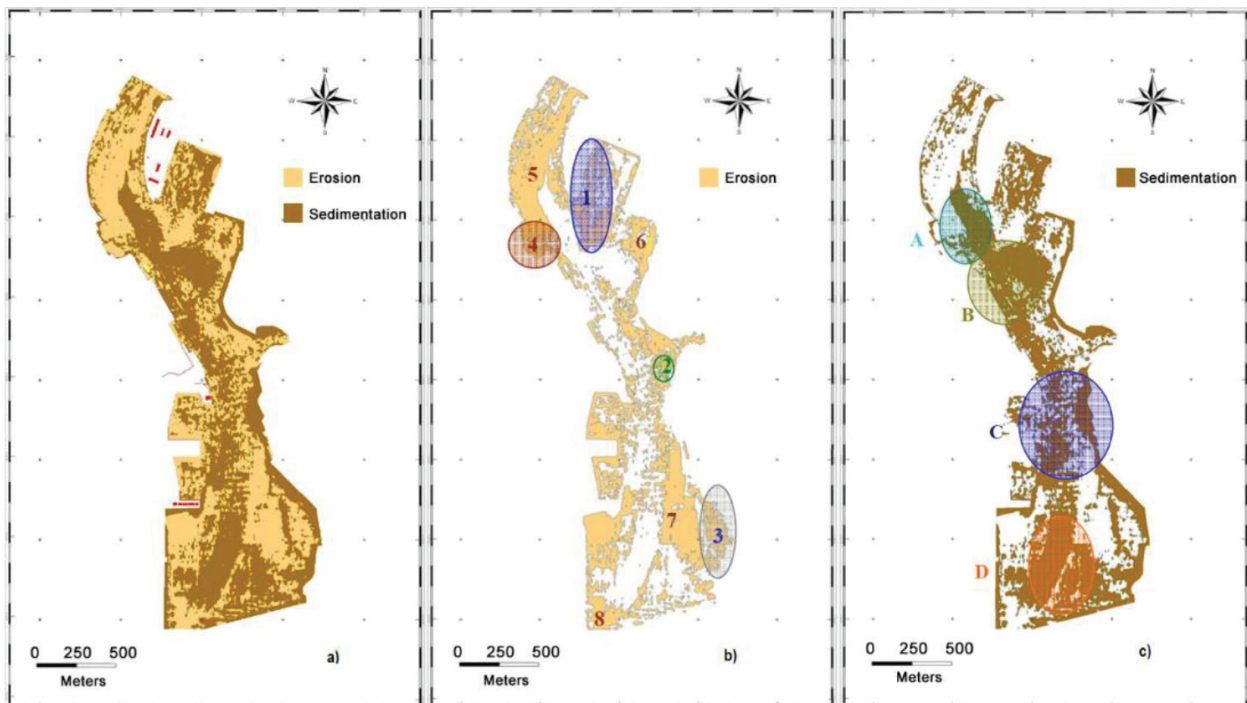


Figure 12. Results of the application of modules M1 to M5 to the surveys of 2000 and 2003: (a) overall results, (b) erosion and (c) sedimentation areas.

The two situations of erosion and sediment deposition will be analyzed separately.

Firstly the areas where erosion occurs (which are presented in **Figure 12b**) will be analyzed. In particular, eight distinct locations deserve careful consideration, as follows.

Starting in zone 1, which corresponds to the fishing port, it is important to notice that a maintenance dredging was carried out in 2001, since this zone, and especially the port entrance and the area next to the haul ramp of the shipyards, was very much silted. Therefore, erosion did really not occur here but rather maintenance dredging. In the remaining areas of this fishing port, the alternation between eroded and silted areas, always of very small values, corresponds to the mooring area of the boats, and to the areas under the piers, and indicates that there was practically no sediment erosion or sedimentation.

The zone 2, which appears in this analysis as strongly eroded, was in fact subject to a local dredging, so, contrary to the obtained results, this is a zone of strong deposition of sediments; on the other hand, the section upstream of this zone, also at the mouth of the Ferragudo River, is, in fact, an area of high erosion. This is, moreover, an area which is important to analyze with particular attention, since it is probable that the planned works will have there an important influence.

In zone 3, the regional departments of environment undertook beach nourishment activities, by placing sands as a coastal reinforcement. According to the empirical experience, confirmed in the present case, the sand that was deposited in this beach was dragged to the mooring area by the effect of the SW waves, so, throughout the tidal range in this zone, there was an erosion of all the material deposited there. Above the level of variation of the tide, there was deposition of sand.

Zone 4 corresponds to São Francisco Dock. In this zone, in the period between the two general surveys, the works of establishment of the referred dock were concluded. Thus, there was no erosion here—it is likely that relatively high silting will occur—but rather a dredging for the establishment of the referred port infrastructure.

The section upstream of the San Francisco Dock and the fishing port and downstream from the road bridge defines the zone 5. Within this area, the erosion is very small, and there is also a small sedimentation under the quay bridges and at the downstream end of the sandbank.

Zone 6 is a muddy, sandy-muddy zone, with a general elevation between low tide and full tide, and is thus under water and out of water in all tide cycles. This zone toggles between erosion and deposition of sediments but always with a very low value, being almost in balance in the current situation.

Zone 7 is usually a zone of erosion, a tendency that was increased after the construction of the Marina of Portimão, on the right bank of the Arade River, with the consequent narrowing of the channel. The sediments eroded in this Zone will generally be deposited in the mooring area.

Zone 8 corresponds to the inlet, and the erosion observed there, of the order of 10 cm, is not significant and may be linked to periodic phenomena of storms and, consequently, higher flow speeds in the inlet. It can be considered that this area is almost in equilibrium.

Regarding some of the areas where apparently sedimentation occurs, such as the fishing port, the sediment deposition trend has already been discussed above and related to the observed erosions.

As for the four areas where sedimentation occurs, referred as zones A–D and referenced in **Figure 12c**, these have the greatest interest for port management.

Zone A corresponds to the downstream end of the existing sandbank in front of the central zone of Portimão and is located where the channel widens, with consequent slowing of the flow velocity which results in a reduction of the capacity of solid transport of the river. One of the planned works in the new layout is the dredging of the referred sandbank. There will be an increase of the tide prism, but as the flow section increases, it is not sure if the flow velocity will decrease; as it is possible that there will be a reduction in erosion in the area of the current sandbank, it is important to analyze this area regarding the eventual hydrodynamic change. So, a careful analysis of foreseeable speed variations will be carried out.

Zone B, corresponding to the commercial wharf and the maneuvering basin, is the widest zone in this section of the estuary, where, therefore, the flow velocities decrease, as well as the transportation capacity of the flow, with significant rate of sedimentation.

Zone C is a particularly sensitive zone. In fact, the alternation of the erosion and deposition zones, which are always of small thickness, suggests that the system is close to equilibrium in the navigation channel within this Zone. However, there is a marked deposition both at the entrance to Portimão's marina, on the right bank, and along the left bank of sand, which will be dredged to carry out the planned arrangement of the Ferragudo marginal. Thus, the width of the channel in this section will increase, and it is necessary to carefully analyze what will happen with the flow velocities, especially in the area of the navigation channel.

The zone D, corresponding to the first section of the navigation channel, and the mooring area, is subject to heavy siltation since it is the widest area of the estuary, and that is downstream of areas of substantial erosion, namely, zones 3 and 7.

The histogram (**Figure 13**) shows the distribution of erosion and sedimentation from 2000 to 2003, using ArcGis Space Analyst. Almost all of the values are between -1 m (erosion) and $+1$ m (sedimentation). Values outside this range correspond, in fact, to one-off dredging interventions or landfill works. Even in the -1 to $+1$ m interval, part of the values was caused either by dredging or by land filling.

A more detailed analysis of the results is shown in **Figures 14** and **15**. **Figure 14** presents the same results of **Figure 15b** and **c** but superimposed on the hydrography of 2003.

The direct comparison of the two situations, on the section of the navigation channel between the commercial dock and the Marina de Portimão, shows a mixing of the deposition and sedimentation areas. Considering **Figure 14**, where the section in reference is presented in more detail, both the erosions and the settlements have an absolute value inferior to 0.5 m throughout the zone. The analysis of the right-hand side of this same figure suggests that, in general, this absolute value for erosions and sedimentation is, in fact, less than 0.20 m. It also suggests that an interchange occurs at short distance (distances of the order of the metre) between erosion and sedimentation, with the exception of the river bank areas, where, in fact,

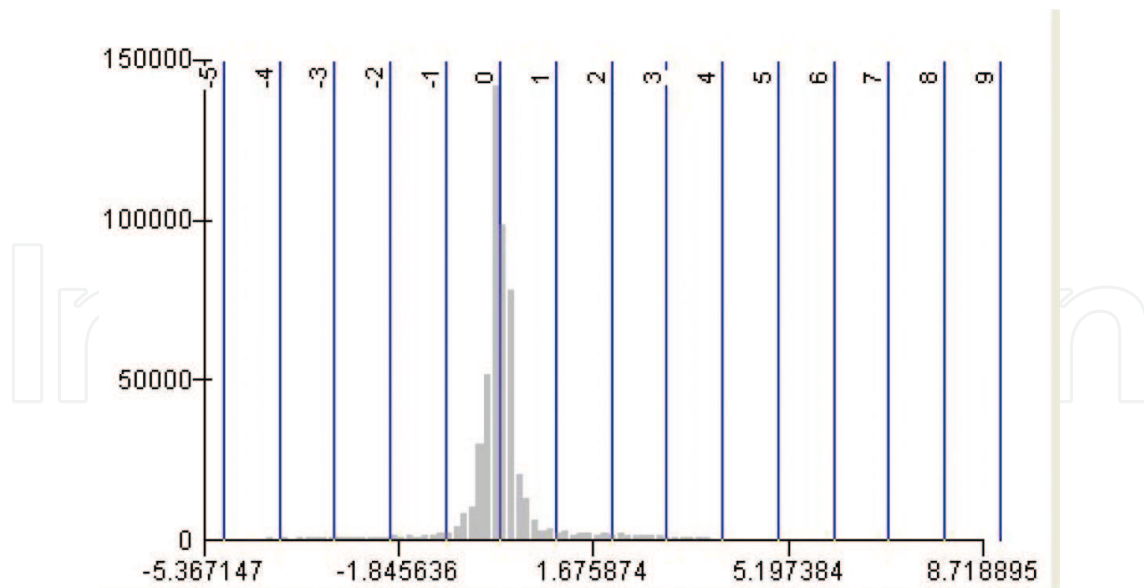


Figure 13. Distribution histogram for the thickness of erosion and sedimentation.

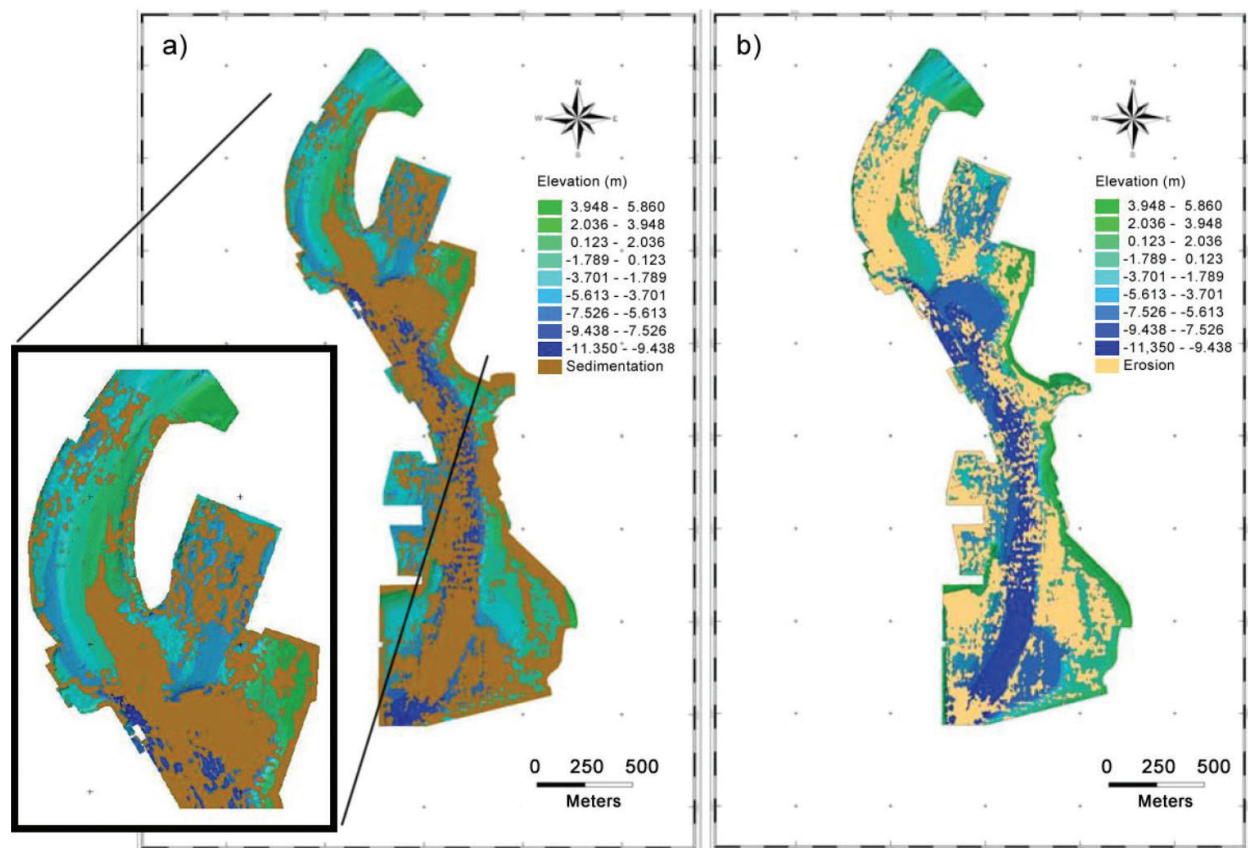


Figure 14. (a) Sedimentation areas on the 2003 hydrography and (b) Erosion.

only sedimentation is observed, with a value between 0.20 and 0.50 m. Thus in this section of the channel, a relative stability is observed, and the described sedimentation and erosion pattern is due to sediment drift in the bottom of the canal, caused by the tide, as well as the propellers of the vessels.

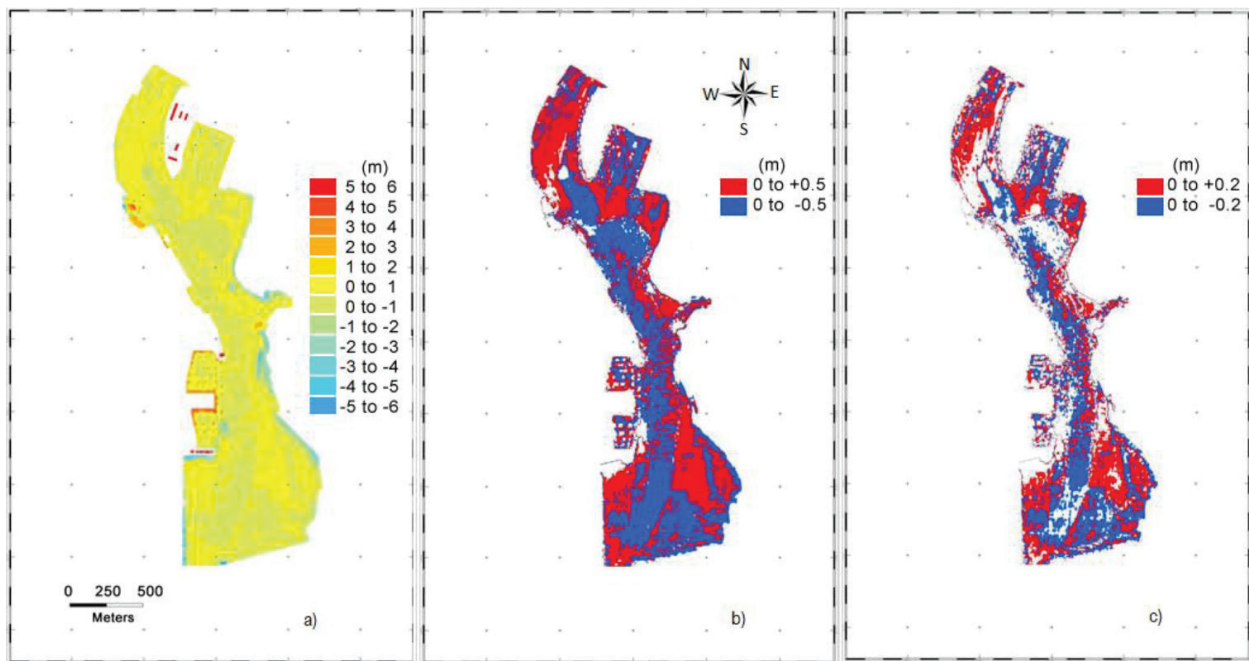


Figure 15. (a) Total erosions and sedimentations, 1 m intervals, (b) erosions from 0 to -0.5 m and sedimentations from 0 to $+0.5$ m, (c) erosions from 0 to -0.20 m and sedimentations from 0 to $+0.20$ m.

Another area that deserves a careful analysis is the one that constitutes the section, limited upstream by the road bridge and downstream by the south end of the maneuvering basin. The observation of **Figure 14** shows that there is a high erosion rate in the channel, but not in the sandbank, probably due to the small channel width between the shallows in front of the shipyards and the central zone of Portimão, where higher flow speeds are verified.

Downstream, with the widening of the flow section, the velocities decrease, and a strong sedimentation of 0.50 m in the canal and in the maneuver basin is observed. That is to say, the sandbank is moving downstream, which is a serious problem for the management of the port. It is necessary to consider the complete removal of this sandbank or at least a dredging intervention that would establish a balance, without sedimentation or erosion, in the sandbank section.

As can be seen from **Figure 15**, in the navigation channel and the anchoring area at the southern end of the estuary, most of the erosions and sedimentations are of the order of 0.20 m; however, in some localized areas, higher values are observed. But in the navigation channel, throughout this section, the sedimentation is always on the order of 0.50 m.

In the bar itself, erosions reach, for this same period of 3 years, values of 0.50 m.

3.4. Simulation for layout changes

After the calibration of the model for the reference situation, it was applied to the new layout, changing accordingly the topography and hydrography of the harbor. The new layout

includes a new marina, the reshaping of the river bank downstream Ferragudo and the deepening of the navigation channel in order to allow larger ships.

Regarding the sandbank area, a dredging level of -1 m ZH was considered. However this value is not yet final. In the analysis of the obtained results, it will be discussed which would be the most advantageous level for dredging, from the hydrodynamic point of view. **Figures 16–18** present some relevant results obtained for the whole harbor.

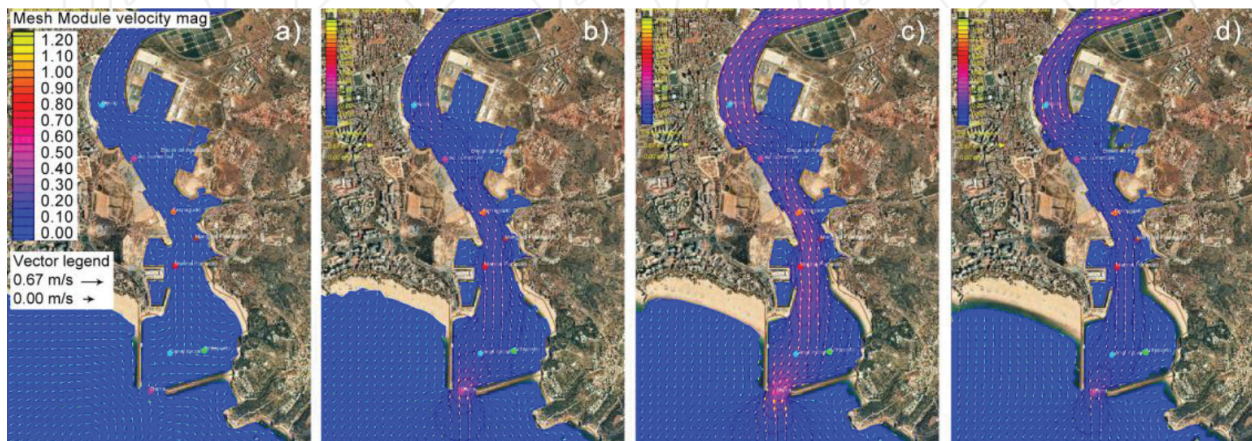


Figure 16. Modeling with the new layout. Results for ebb tide: (a) 50, (b) 51, (c) 53 and (d) 55 hours (see Figure 12).

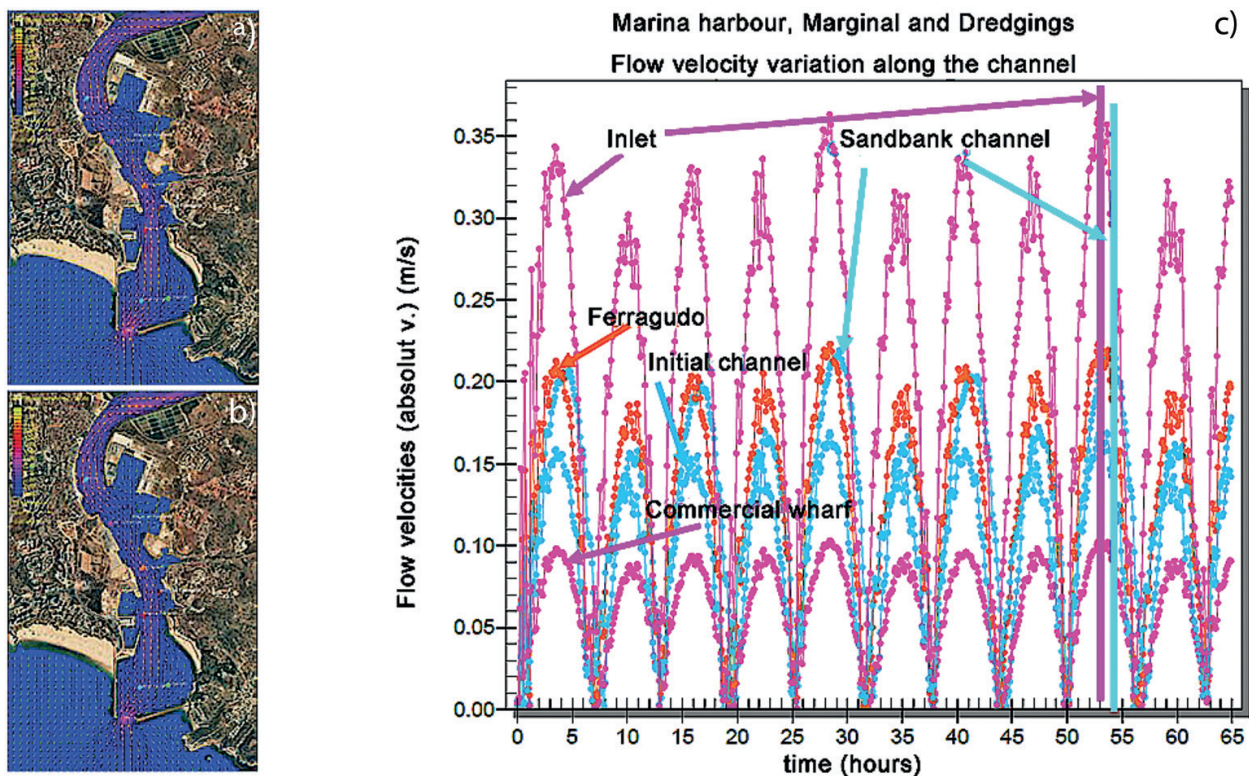


Figure 17. Modeling with the new layout. The delay of the peak velocity in ebb tide (c), between the harbor inlet and the sandbank (a) 53 and (b) 54 hours.

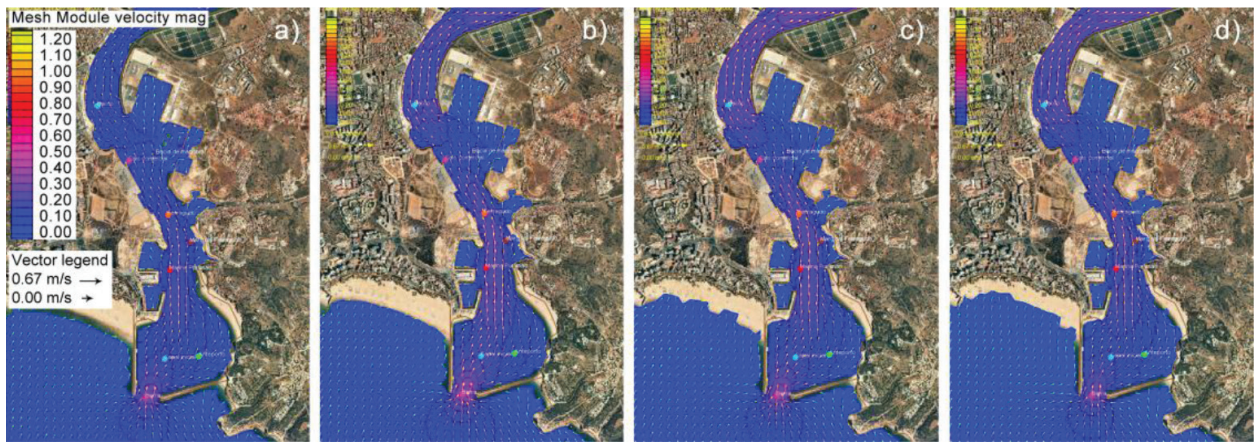


Figure 18. Modeling with the new layout. Results for the flood tide: (a) 58, (b) 59, (c) 60 and (d) 61 hours.

4. Results

According to the mineralogy and grain size of sediments, the longshore transport of sediments only affects this estuary near the inlet, more precisely in the mooring area, due to SW waves. In this particular case study, the longshore transport and the waves have no significant

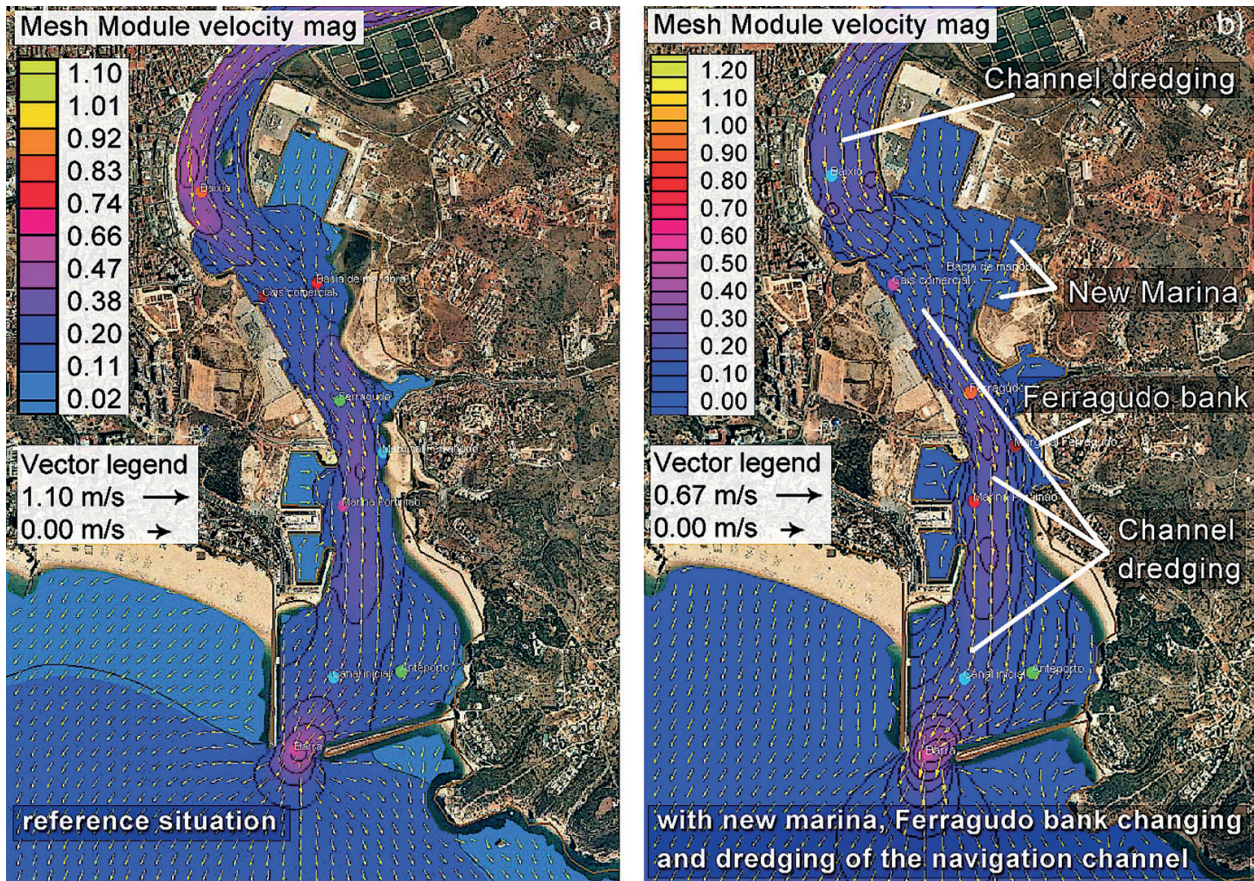


Figure 19. The estuary, in the peak of ebb tide (53 hours), (a) for the reference situation and (b) for the new layout simulation.

effect in the main part of the estuary, and so the referred influences were not considered in this analysis. However, taking into account the new layout, **Figure 19**, it can be observed that the construction of the new marina affects the main flow in the channel leading it to the right bank, downstream of the commercial wharf.

The new shape for the Ferragudo river bank will increase the flow velocity near the left margin. Also the flow, as being diverted by the promontory of the castle of S. João towards the right bank, will increase the velocity near the entrance of the Marina of Portimão; moreover, there is an flow velocity increase, upstream of the São Francisco dock, in the area of the sandbank, due to its dredging to -1 m. The planned dredging will have a significant influence on the flow in the sandbank area, where the flow will be more evenly distributed over the whole width, with a significant reduction of the maximum speed that occurred in the reference situation in the channel near the right bank of the river (**Figure 20**).

In front of the commercial wharf, and the new marina, is located the maneuvering basin of the harbor; as a consequence of the increase in the ships draft that is aimed, and also due to the construction of the new marina, this area will be dredged, and so it will present a larger water section. As it can be seen from the velocity variation from the reference situation, there will be a still significant decrease in the velocity in this area.

As for the maneuvering basin, **Figure 21**, there is also a clear reduction of the velocity; the peak velocity values obtained for the ebb tide were 0.076 m/s and for the flood tide 0.063 m/s.

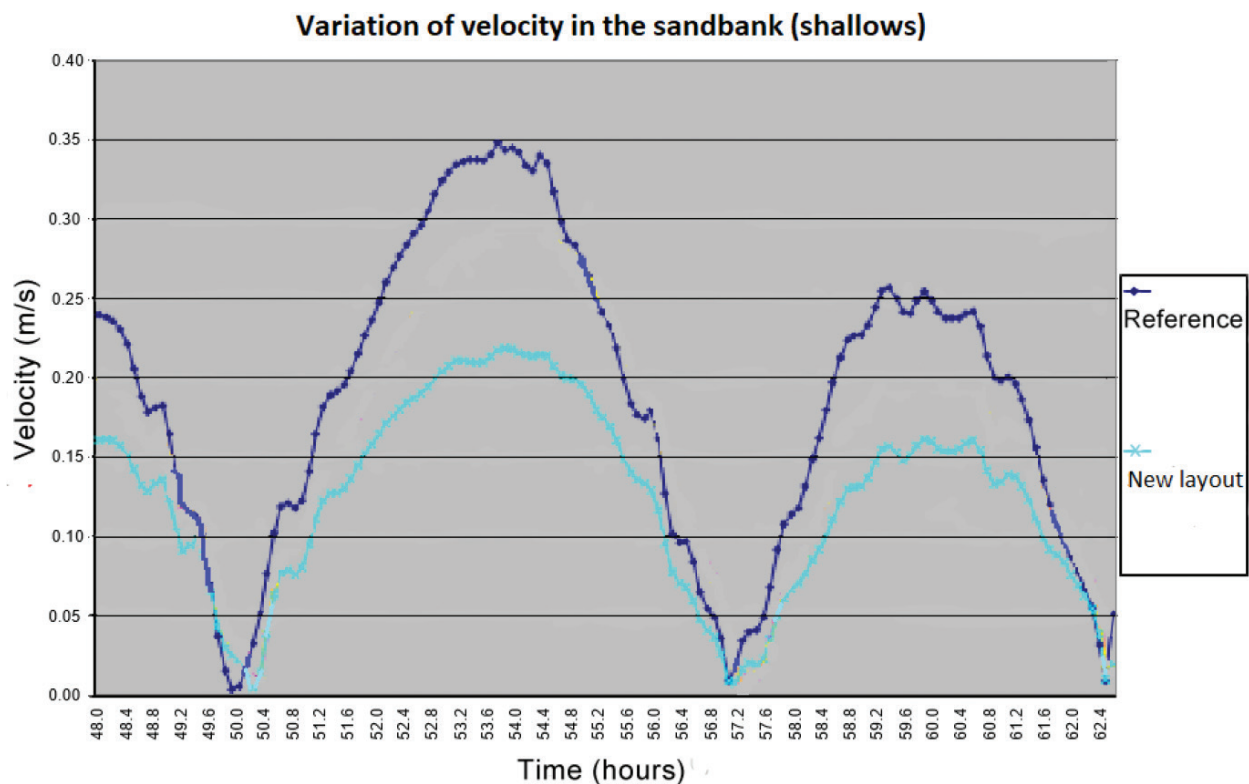


Figure 20. Upstream of the study area, in the sandbank in front of the town, the dredging of that sandbank will reduce significantly the velocities (velocity in absolute value).

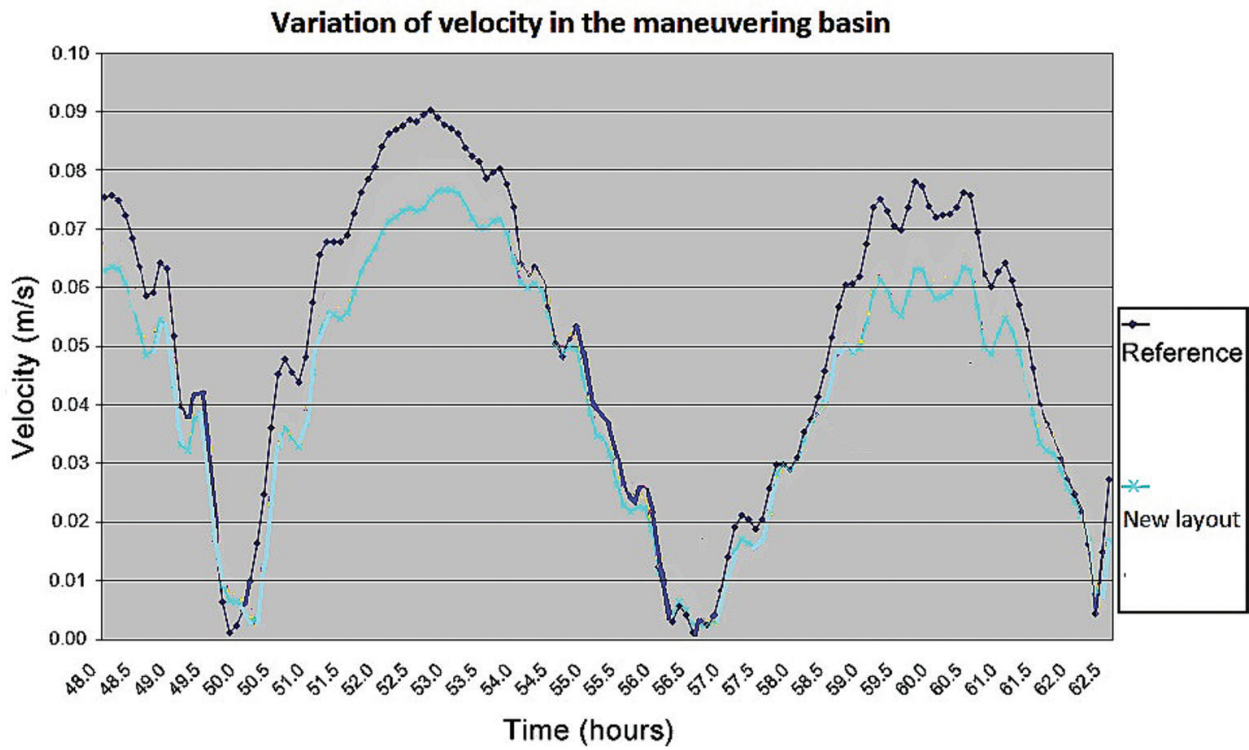


Figure 21. It can be seen from the velocity variation that there will be a still significant decrease in the velocity in this area (velocity in absolute value) and so an increased sedimentation.

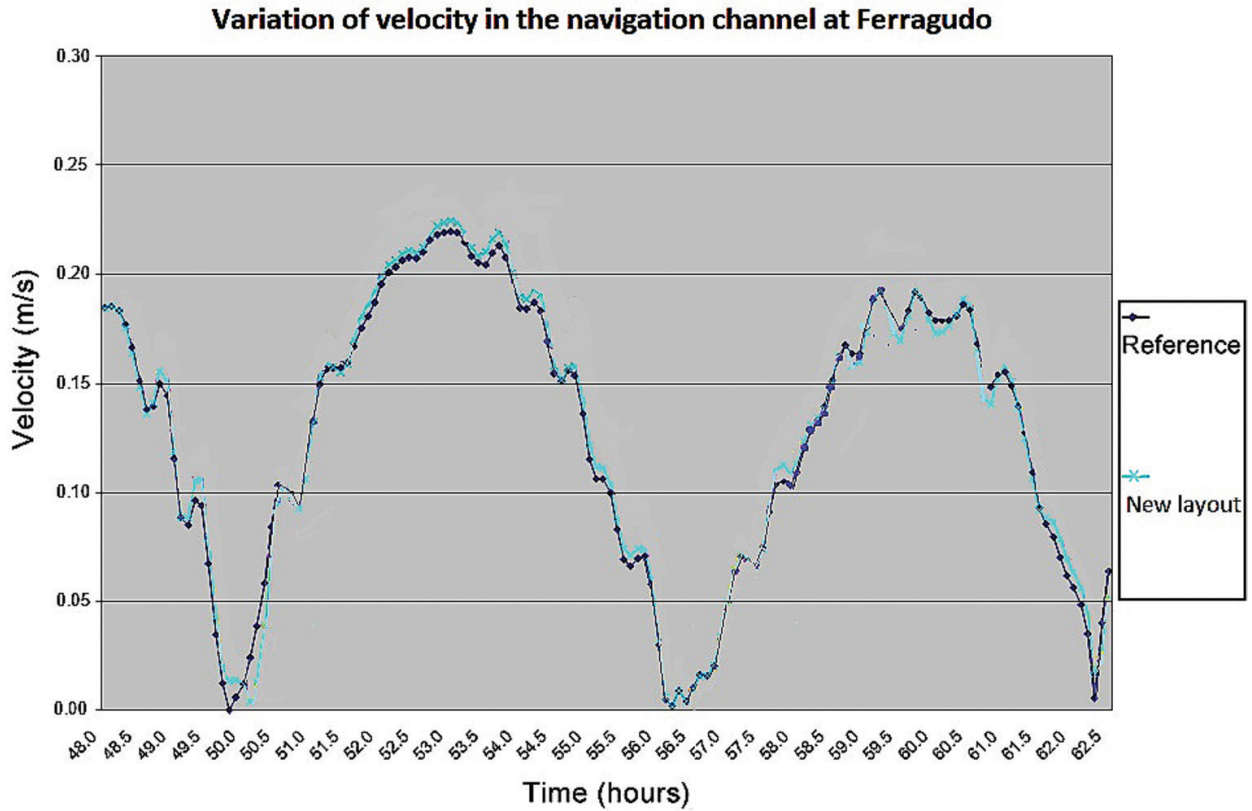


Figure 22. In front of Ferragudo, the velocity is almost unchanged (velocity in absolute value).

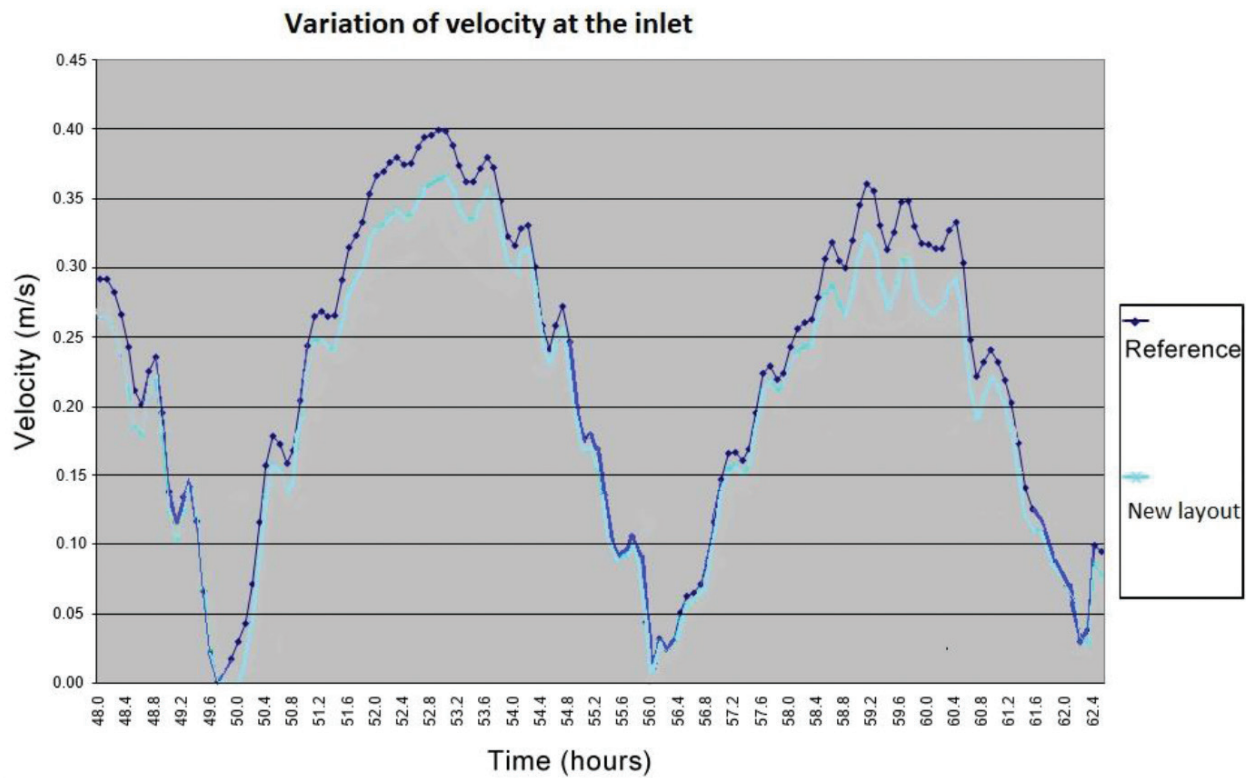


Figure 23. At the inlet the velocity will decrease slightly (velocity in absolute value).

The navigation channel, in front of Ferragudo, Figure 22, presents almost no velocity variation from the reference situation to the final layout situation. This is due to contrary effects of the various interventions planned for the harbor: on one hand, the dredging of the channel will increase the section flow and, so, decrease the velocity, and on the other hand, the works upstream, marina, sandbank, by example, will increase the tide prism upstream this analysis point and so increase the velocity. The referred effects, opposite to each other, cause almost no variation in velocity.

After the planned work completion, the predicted peak velocity of the ebb in the inlet is 0.36 m/s. In the flood, the peak velocity, which in the reference situation was 0.36 m/s, will then change, with the three interventions performed, to 0.32 m/s (Figure 23). So, at the inlet the velocity will decrease slightly, and so an increase in sedimentation and consequently of dredging should be expected.

Analyzed situation	Ebb maximum velocity (m/s)			
	Sandbank	Maneuvering Basin	Ferragudo	Inlet
Reference situation	0.350	0.090	0.220	0.400
New layout	0.220	0.077	0.225	0.365

Notes: ■ Ref. situation erosion zone; ■ Ref. situation limited erosion zone; ■ Ref. situation equilibrium zone; ■ Ref. situation sedimentation zone.

Table 1. Result summary.

Table 1 presents, for the four reference sections above mentioned, the ebb maximum velocity in the reference situation and in the simulation considering the new layout. It presents also, for the reference situation, if each zone presents erosion and sedimentation or is in equilibrium.

5. Conclusions

As stated, harbors are, whenever possible, established in estuaries to take advantage of the existing natural safety and protection conditions. But to keep harbors in a safe and usable way, periodic dredging works are carried out. The expansion of harbor's activities and the growth of maritime traffic may lead to changes in the harbor's layout or to improvements of navigation channels and basins depths. Such adjustments entail changes in estuarine hydrodynamics, and therefore the usual dredging rates are subject to alteration, namely, tending to increase. It is then important to assess the influence of a harbor's new layout on the solid transport pattern and how its effects can be minimized, aiming the reduction of economic and environmental impacts. Within this context, in this chapter estuary hydrodynamics and sedimentation-erosion patterns were summarized. Also, the modeling methodology for planning and management of dredging works which uses geo-processing automatic GIS environment, developed by the Portuguese harbor authority, was presented. Finally, the case study of harbor of Portimão was also described showing the implementation of the referred methodology.

The method presented to estimate erosion and deposition ratings, and so allowing to plan dredging works, has proven its usefulness and proved to be of easy implementation. In the case study presented, it allowed to identify the areas where the hydrodynamic changes will likely increase sedimentation and also where no change or an increase of erosion should be expected. Lower velocities will mean higher depositions and, accordingly, a greater volume to dredge. Anyway its application must be careful, as it is important, besides the use of adequate topographic surveys, to know where, in the time period of those topographic surveys, dredging works were carried on, as well as the volumes dredged.

Also the hydrodynamic pattern of the harbor is of the uttermost importance, mainly when a changing in the harbor layout is planned, in order to forecast the changing in the erosion deposition rates in the different harbor zones.

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