A Tool to Aid the Navigation in La Spezia Harbour (Italy)

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Abstract. The knowledge of sea level in harbours is very important to manage port activities (safety of navigation, prevention of ship stranding, optimization of vessel loading, water quality control). In this article we describe the use of a software tool developed to help local authorities and working organizations to optimize navigation and avoid or manage hazardous situations due to sea level changes in port basins. This prototype application, starting from reading data coming from a monitoring station in La Spezia harbour (in North Western Italy), updates dynamically the port bathymetry based on sea level oscillations (measured in the past or real-time, or expected in the near future). Then, it detects potentially dangerous areas for a given ship moving in the basin at a certain time, by means of the idea of "virtual traffic lights": sea level variations are provided as parameters to the application that performs the updating of the bathymetric map and the subdivision of the harbour in allowed (green)/warning (yellow)/prohibited (red) areas for each ship, based on its draft. The tool can provide a useful support interface to competent authorities to avoid or manage critical situations by detecting hazardous areas for a given vessel at a given time.

Keywords: Coastal maritime transport · Port navigation safety · Harbour water management

1 Introduction

Sea level changes influence significantly the water management in harbours, e.g. ship navigation, maritime transport safety, dock performances, ship loading and mooring, seawater quality and pollution control. Then, being able to monitor and forecast sea level variations should be essential to plan the best time for a vessel to enter or leave a port, to decide its best route, to determine how much it can be loaded or in which dock it can berth, to prevent the risk of accidents, the consequent impact on the surrounding environment and economic damages, or to plan when refloat stranded vessels.

The software prototype application described in the following starts from monitoring or forecasting meteo-mareographic parameters in coastal areas, with the aim of updating port bathymetric maps depending on sea level variations, and then providing to port communities and decision makers a useful tool to optimize harbour water management and port operations or to prevent hazardous situations. In the following, we analyse its

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use in La Spezia harbour (Eastern Ligurian Sea, Italy). It is important to note that the bathymetric map of a port must also be updated (by means of multibeam surveys) after changes in the harbour topography, e.g. as a results of dredging operations.

Sea level oscillations along Italian coastline consist mainly in astronomical tides, first of all the diurnal and semidiurnal components: they are caused by the Earth-Moon-Sun gravitational relationships, so they are periodic and predictable in advance everywhere through the harmonic analysis and tide charts [1].

Nevertheless, sea level changes in harbours also depend on meteorological tides, that are Newtonian adjustment of water mass due to atmospheric pressure unbalances over a sea basin (water level increases when the atmospheric pressure decreases and vice versa): this phenomenon is evaluated by performing a statistical analysis, whose purpose is to estimate the correlation between atmospheric pressure variations (cause inducing) and sea level changes (effect induced) and then to forecast future tides. In particular, a meteorological tide is a geodetic compensation caused by a variation of atmospheric loading over a free water surface: an atmospheric weight rise causes an outgoing seawater flux (low meteorological tide); a lowering of atmospheric loading, on the contrary, causes an incoming seawater flux (high meteorological tide). This phenomenon is influenced by many parameters (the topography of the harbour, the atmosphere dynamics over it, etc.) and then, unlike the astronomical tides, it cannot be described by a deterministic relationship: the change of sea level caused by atmospheric pressure is evaluated by means of the study of the cause - effect events (water level variations following atmospheric pressure changes) that happen in a given basin during a long period of time. After this statistical correlation (represented by the hydro-barometric transfer factor) has been estimated, it will be possible to estimate in advance meteorological tides based on the knowledge of atmospheric pressure changes [2–12].

Meteorological tides can play a fundamental role in contributing to sea level changes in Italian harbours, especially when they add up to the astronomical ones: over the past fifteen years, many unusual tidal fluctuations have been monitored in the Port of La Spezia; the maximum meteorological tide observed in this period was about 53 [cm].

Effects induced by wind or storm surges (not relevant in this place) were not considered in the present work.

2 The Software Application

The starting point of the software tool is the bathymetry of the harbour, also named static map since it has to be considered static until new multibeam surveys are carried out, after changes in the harbour topography (following dredging activities, seabed subsidence, accumulation of sediments, or coastal erosion). Figure 1 represents the georeferenced bathymetric map of the Gulf of La Spezia, that extends over an area of approximately 22 [km^2]. In the north-eastern area of the gulf there are cruise terminal and merchant port; the southern area is bounded by breakwater [13–26].

The harbour can be classified in three zones, by setting two depth levels, a lower and an upper threshold, that vary vessel by vessel based on their draft; the three areas are identified by as many colours: the red identifies zones forbidden for that ship (bottom depth less than the lower threshold, typically chosen equal to the ship draft), whereas the green represents deep or permitted areas for that vessel (bottom depth more than the upper threshold, in its turn greater than vessel draft: there is a great space between the vessel keel and the seafloor); lastly, the yellow represents shallow or warning areas (bottom depth between the lower and upper threshold: there is a small space between the ship keel and the sea bottom). This subdivision implements the idea of virtual traffic lights customized vessel by vessel, a useful interface to support decision makers to mitigate the risk arising from potentially dangerous circumstances:

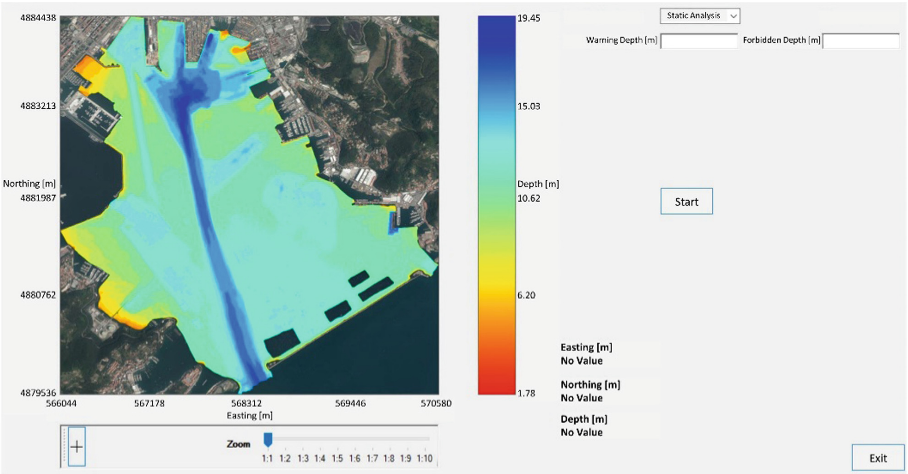

Fig. 1. Bathymetric map of the Gulf of La Spezia, in UTM coordinates (Universal Transverse of Mercator, Zone 32T); the sea depth is referred to IGM's 0 sea level (Italian Military Geographic Institute); data are kindly provided by Port Authority of La Spezia (now named Port System Authority of the Eastern Ligurian Sea).

For a vessel characterized by a draft of 11 [m], for instance, we can choose thresholds equal to 11 and 12.5 [m] respectively; the result is the partition of the bathymetric map reported in Fig. 2: so, for that vessel the zones with bottom depth values smaller than 11 [m] are considered prohibited (red), those where bottom depth values are between 11 and 12.5 [m] are classified warning areas (yellow), and those in which bottom depth values are more than 12.5 [m] are permitted areas (green). This represents the static analysis (the map remains the same as the time changes). Figure 3 shows the same bathymetry but partitioned by setting other threshold levels, for a vessel having a deeper draft than the earlier example (e.g. a Panamax cargo ship, whose draft is nearly 12 m): thresholds fixed at 12 and 13.5 [m] respectively cause the enlargement of the red (forbidden) areas and the reduction of the green (permitted) ones: the tool classifies as prohibited the areas with bottom depth less than 12 [m], warning zones those characterized by bottom depth values between 12 and 13.5 [m], and permitted zones those with bottom deeper than 12 [m]; of course, the greater the draft of the vessel, the wider the zone prohibited to it.

The software application is able to automatically update in real time the bathymetric map of the harbour by using sea level data acquired and transmitted by a meteo-mareographic station working in the port area. Moreover, as explained below, the software tool can start from atmospheric pressure values to evaluate expected sea level variations known as meteorological tides, that will be summed to the astronomical ones, periodic and known by means of tide charts, to estimate the forecasted sea level and finally the expected bathymetric map of the harbour.

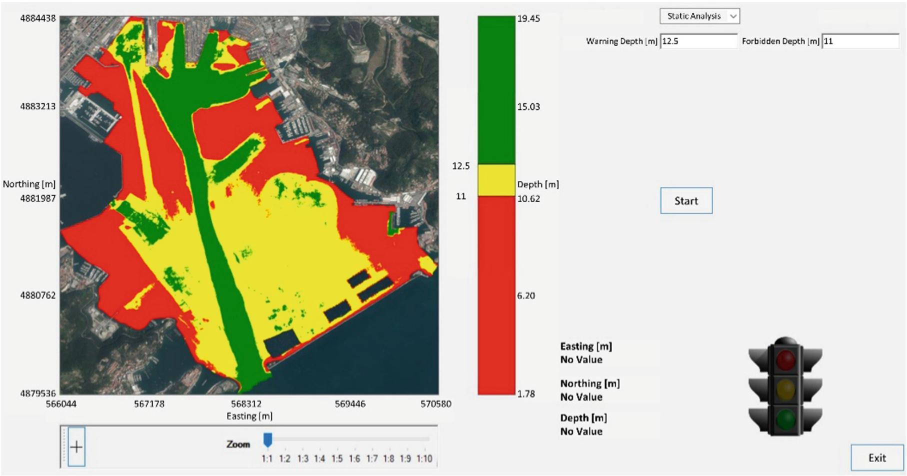

Fig. 2. Virtual traffic lights in the Gulf of La Spezia; thresholds equal to 11 and 12.5 [m].

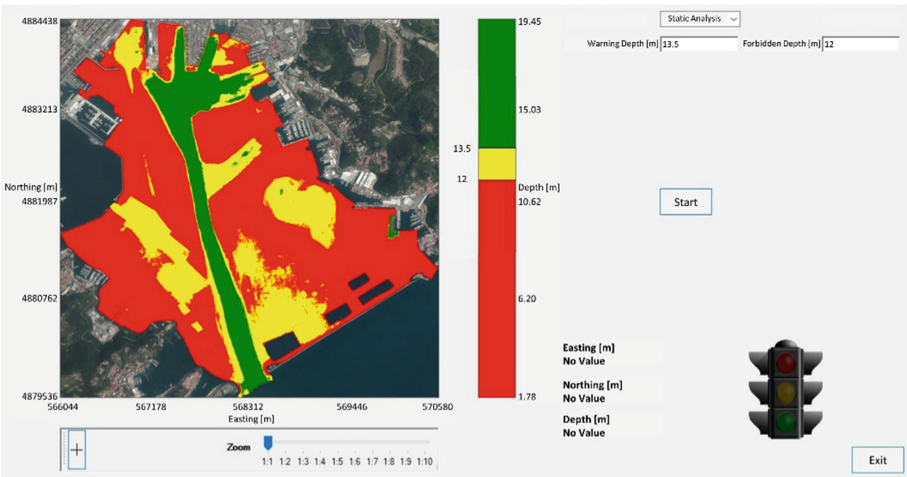

Fig. 3. Virtual traffic lights in the Gulf of La Spezia; thresholds equal to 12 and 13.5 [m].

3 Monitoring and Forecasting Tides in Harbours

Meteorological tides (briefly called "meteo-tides") are sea level oscillations related to atmospheric pressure changes over a coastal basin such as a port or a bay. These are due to Newtonian adaptations of the free water surface that re-balance the geodetic disequilibrium caused by atmosphere weight variations: a rise of atmospheric pressure causes a decrease in sea level (low meteorological tide) and vice versa (high meteorological tide). The phenomenon of meteo-tides is completely known in the open sea (the so-called "inverted barometer" effect: 1 [hPa] of atmospheric pressure variation induces about 1 [cm] of sea level change), but it needs further insights in coastal regions, where the coastline stops the horizontal movement of seawater mass and then enhances its vertical displacement. In addition to this, the relationship between atmospheric pressure and sea level (described by the so-called hydrobarometric transfer factor J_{ph}) is due to some characteristics of the considered basin (first of all its topography), so in the present work it has evaluated by means of a local monitoring and a statistical analysis of parameters involved. So, the knowledge of meteorological tides starts from the acquisition of atmospheric pressure and sea level in harbours; then, the following step is to evaluate the hydrobarometric transfer factor J_{ph} by studying all the events (sea level changes following atmospheric pressure variations) happened in a certain site along a given time interval (typically several years) [27–32].

To monitor port environmental parameters in the port of La Spezia, data coming from the measurement station belonging to ISPRA's[1] National Tidegauge Network are used. It includes instrumentation to acquire meteo-mareographic data (the most interesting for our study are the hydrometer to measure water level and the barometer to acquire atmospheric pressure). Data used in this article and various information about ISPRA's monitoring station in La Spezia harbour are available on the website https://www.mareografico.it/. In Fig. 4 are explained parameters observed in the port of La Spezia from 28 February to 4 March 2020; the date and the time are reported to UTC (Universal time Coordinates), hydrometer measurements to IGM's 0 level.

The changes over time of the sea level recorded are comprehensive of contributes resulting from different causes, first of all astronomical (mainly diurnal and semidiurnal) and meteorological tides; other short-term effects induced by wind or storm surges were not considered in the present work (events happened in the presence of wind were not taken into account). To avoid components other than those of meteorological origin (characterized by low frequencies), data are filtered properly: a Low Pass filtering removes spectral components related to astronomical tides, that are represented by dashed lines in Fig. 4: only slow fluctuations, due to to atmospheric pressure variations, survive the filtering (solid lines in Fig. 4); respect to the time interval from 28 February to 4 March, an atmospheric pressure fall Δp (cause) of 28.6 [hPa] produces a low frequency sea level increase Δh (height of high meteorological tide, effect) of about 53 [cm].

[1] Italian Institute for Environmental Protection and Research.

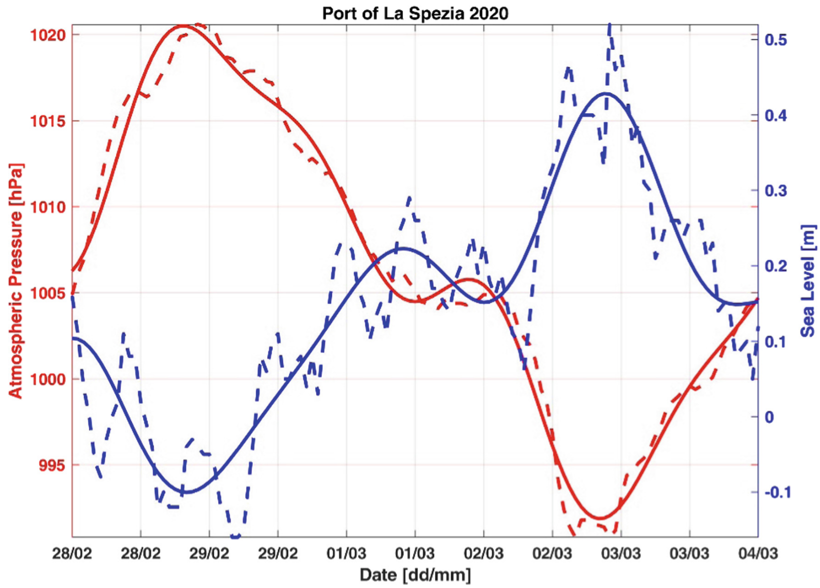

Fig. 4. Meteo-mareographic parameters acquired by ISPRA's monitoring station in the port of La Spezia from 28 February to 4 March 2020 (dashed lines) and their low frequency components (solid lines).

Then, for this event the hydrobarometric transfer factor J_{ph} [cm*hPa^{-1}] can be evaluated as indicated in Eq. 1:

$$J_{ph} = \Delta h / \Delta p \tag{1}$$

in this example a value of nearly 1.9 [cm*hPa^{-1}] is obtained, expressed in absolute value.

Similarly, for all the events occurred in the time interval of study, the gradient Δh of sea level and the variation Δp of atmospheric pressure are considered, and J_{ph} is recalculated. Thus a lot of couples (Δp, Δh) and corresponding estimations of J_{ph} are computed, one for every occurrence of the phenomenon in the period under consideration: as a first approximation, the average of J_{ph} values can be employed as a linear estimate of J_{ph} (the resulting error is acceptable for our purposes); a better representation could consider a non-linear (e.g. cubic) dependence of Δh from Δp, as shown in Fig. 5. The knowledge of the hydro-barometric transfer factor allows calculating, for a given basin, an expected variation of sea level Δh based on the measurement or forecasting of atmospheric pressure: simply multiply the future change Δp by the estimated J_{ph} factor and then change the sign, given that atmospheric pressure and sea level variations have opposite signs: if the first rises, the second falls and viceversa.

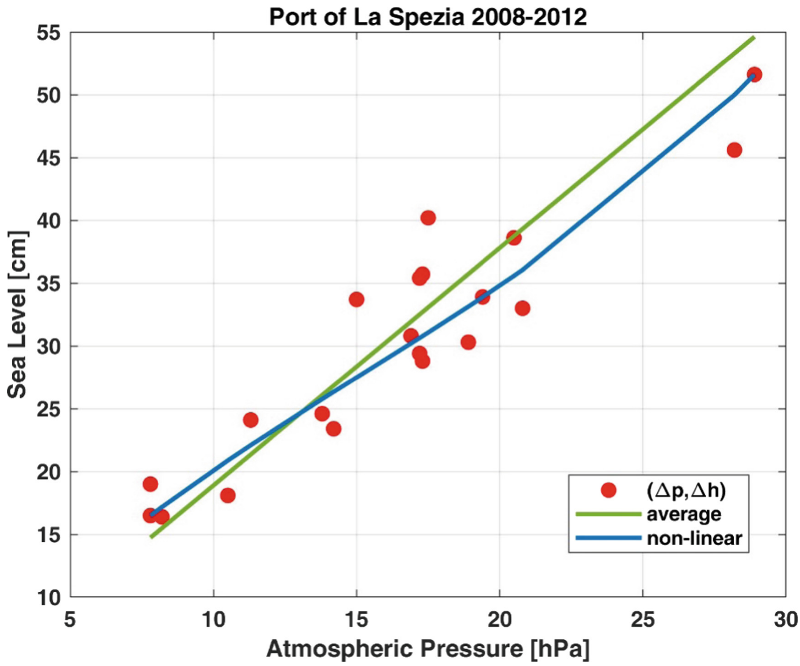

Fig. 5. Couples (Δp, Δh) for the events occurred in the port of La Spezia from 2008 to 2012 (red dots), linear (green line) and cubic (blue line) approximations. (Color figure online)

The estimation of J_{ph} is very useful in order to manage port activities: the effects of atmospheric pressure changes on sea level (and on water depth) can be applied to bathymetric maps in harbours to know in advance their evolution: a variation of atmospheric pressure can be turned, through J_{ph}, into an expected meteorological tide and then, by adding to it the expected astronomical tide, in a forecasted sea level and finally in a new bathymetry. In La Spezia harbour and, more in general, along Italian coastline, typical values found by means of a multi-year statistical analysis carried out for J_{ph} are often very larger (about twice) in comparison to the characteristic value 1 [cm*hPa^{-1}] of the offshore.

Furthermore, it is worth to highlight that it is needed to recalculate periodically the J_{ph} factor, especially following variations of the topography of the basin (due to dredging activities, coastal erosion, accumulation of sediments, seabed subsidence).

Anyway, a multi-decade statistics is necessary to assess the possible influence of long-term phenomena such as climate change on the hydrobarometric transfer factor.

4 Results

Sea level measurements are added to the initial seafloor depth to recalculate instant by instant the real bathymetry and update the so-called dynamic bathymetric map (it varies as time varies). Sea level values can be data recorded in an archive (if critical events that occurred in the past are being processed, e.g. to replay accidents) or measurements coming from meteo-mareographic stations in harbours (if we are interested in the real-time variation of the bathymetry); finally, they can be forecasted values (if we are estimating the expected trend of the bathymetry concerning a future event).

Then, the subdivision of the harbour into different coloured zones is updated by retaining the threshold values fixed (for the same ship assumed in Fig. 6, threshold levels are kept equal to 12 and 13.5 [m]). Consequently, as the sea level changes, a zone that before was allowed (green), can turn into a warning (yellow) or prohibited zone (red) for the same ship, or vice versa. This constitutes what is known as dynamic analysis, since the real bathymetry changes as time varies.

In Fig. 6 the bathymetric map of the Port of La Spezia is refreshed according to the values measured on 12 March 2019 at 06:50, while Fig. 7 refers to 23 November at 18:30; the graphical user interface indicates date, time and sea level for every single acquisition loaded: as can be seen, the sea level is equal to −0.41 [m] in the first case, while it is 0.72 [m] in the second case: then, there is a gradient of 1.13 [m] between the two different situations illustrated; this induces an expansion of the permitted area (we highlight the green waterway that crosses the gulf) and the warning one (e.g. the appearance of the yellow channel in the north-western corner of the map), and a shrinkage of the forbidden (red) zone; the remarkable difference in sea level is induced in part by astronomical tides and in part by a gradient of atmospheric pressure, which drops about from 1025 to 1001.5 [hPa] and then contributes to uppering the sea level.

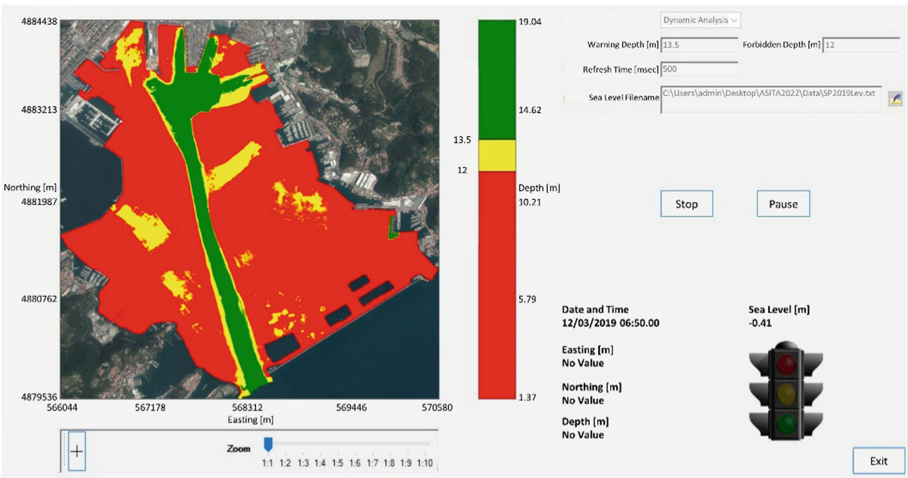

Fig. 6. Virtual traffic lights in the Gulf of La Spezia on 12 March 2019 at 06:50; thresholds equal to 12 and 13.5 [m]. (Color figure online)

Moreover, a particular of the harbor can be shown in more detail: for example, Figs. 8 and 9 show that the permitted area near the access to quays in the northern part of the gulf expands, and this is induced by the sea level increase of 1.13 [m]. In addition, moving mouse pointer over the gulf, the graphical interface displays the coordinates of its position and the corresponding depth instant by instant; finally, the traffic light indicates at any moment whether that position is prohibited, permitted or included in a warning zone, by turning on the appropriate light: keeping the pointer in a given place, we can observe how its state changes as time passes. In this example of comparison of two situations, the bottom depth in position Easting 567318, Northing 4883902 [m] indicated by the mouse pointer in the area between Garibaldi (in the upper left corner) and Fornelli (in the top middle) piers on the western part of the port changes from 11.38 to 12.51 [m], then the corresponding traffic light goes from red (forbidden position) to yellow (warning position) colour (lower threshold is fixed to 12 [m]).

Then, the graphical user interface achieves the idea of the so-called virtual traffic lights (subdivision in forbidden, warning or allowed zones) customized ship by ship, based on its draft: changing the sea level, a zone that before was red (prohibited), can turn into a yellow (warning) or green (permitted) zone for the same vessel, or vice versa; this prototype application is aimed at providing support to port operators in planning and optimizing coastal maritime transport (e.g. deciding when a ship can enter or leave a port or tracing its best route), vessel moorings and docking performances (e.g. to which dock a ship can access), vessel loading (e.g. determining the cargo of a ship at the departure port based on the expected tide at the destination), and maritime works (e.g. sizing breakwaters); above all, it can represent a useful tool to port communities (port authorities, coast guards, pilots, terminal operators) to improve coastal navigation safety, to avoid maritime accidents, to manage events occurred as vessel stranding, or to minimize environmental damages and economic losses.

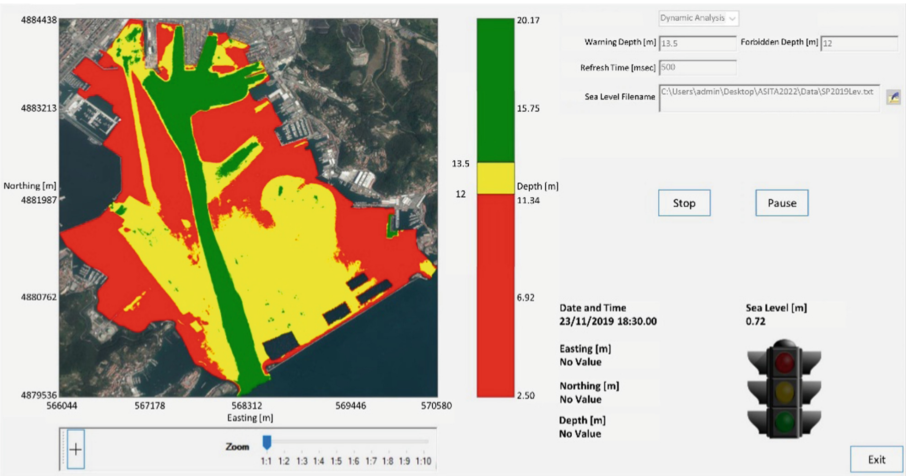

Fig. 7. Virtual traffic lights in the Gulf of La Spezia on 23 November 2019 at 18:30; thresholds equal to 12 and 13.5 [m].

In general, the utility of this software tool is that it can identify hazardous situations in specific positions, at particular moments, and for a certain vessel: in fact, the current state of virtual traffic lights relies on the location, on the current time, and on the thresholds selected that, in their turn, rely on the draft of the vessel taken into account.

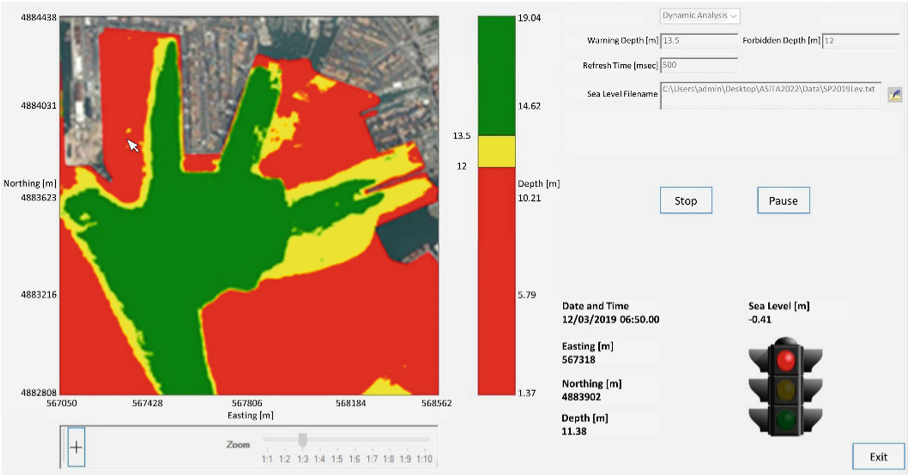

Fig. 8. Detail of virtual traffic lights in the Gulf of La Spezia on 12 March 2019 at 06:50; thresholds equal to 12 and 13.5 [m].

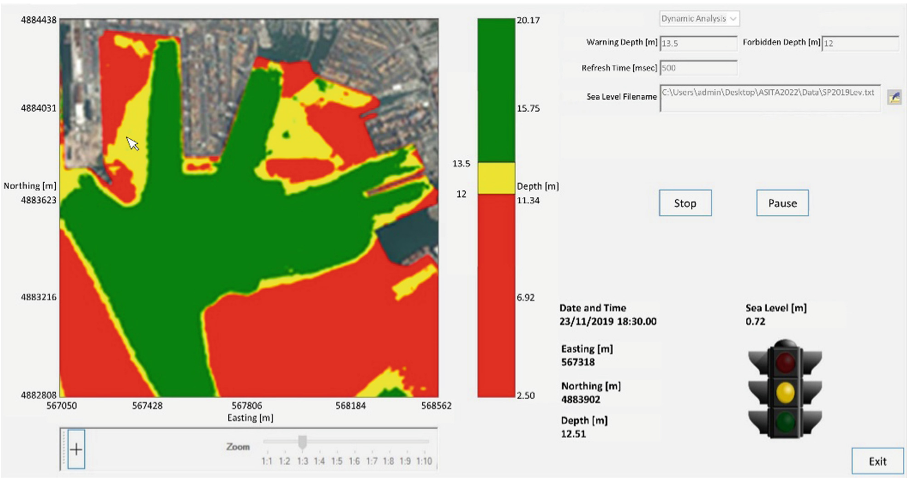

Fig. 9. Detail of virtual traffic lights in the Gulf of La Spezia on 23 November 2019 at 18:30; thresholds equal to 12 and 13.5 [m].

5 Conclusions

This work shows the usefulness of a prototype application developed to support port communities and decision makers (port authorities, coast guard, pilots) in order to mitigate risks induced by sea level oscillations and then to increase maritime safety in ports by identifying hazardous areas for a certain ship at a given instant. It is highlighted the importance of observing, processing and forecasting environmental parameters in harbours. The results of monitoring and analysing activities in La Spezia harbour (Eastern Ligurian Sea, Italy) are described.

Using this tool in the framework of harbour water management can be helpful to authorities in analysing a posteriori maritime accidents occurred in the past as well as to decision makers in optimizing port activities or planning them in advance, in particular:

- in improving effectiveness and safety of port navigation by determining, for a certain ship, the ideal route to be flown depending on its draft (to minimize the risk of stranding), or in which pier it would be better to berth, or the optimum instant when it should enter or leave a basin;
- in optimizing the cargo (how much a ship can be loaded in the departure port according to the expected tide at the destination port);
- in managing the refloating of stranded vessels (in case of accident occurred), in order to minimize the impact on marine environment and economic losses for the port community.

Moreover, forecasting tides in harbours may also be useful to optimize:

- the berthing of vessels (how much to pull the berths to avoid breaking ropes);
- the dimensioning of maritime works (e.g. outer dams, quays and piers) according to the highest tides expected;
- the marine water exchange in port areas and the quality control of coastal environment: evaluating the concentration of pollutants (solute) at a given time based on the actual volume of marine water (solvent) measured or forecasted.

In a hypothetical operational scenario, a display showing the dynamic bathymetry of the sea basin could be hosted in a command and control center managed by a local authority, that in this way would receive useful information to take the best decisions, with the aim of improving safety for the community working in harbours. The same tool could also run on board vessels, e.g. on mobile devices.

Virtual traffic lights are of course reliable as long as the parameters passed to the tool are, i.e. that the starting static bathymetry is still valid (otherwise a new map should be acquired by performing new multibeam surveys), that the forecasting of meteorological parameters and sea level are accurate, and that tide measurements carried out by a meteo-mareographic station operating in a given location are representative of the whole harbour; anyway, having more hydrometers spread over a harbour would permit a better spatial resolution in the dynamic updating of the bathymetric map by making available more sea level values, one for each subdomain into which the basin is divided.

Lastly, the application is able to include other phenomena, such as wind effect and storm surges (not relevant and therefore not considered in this work), which particularly in certain sites can be very important and thus should be passed as inputs to the sea level forecasting algorithm to enhance its effectiveness.

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