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Research Article

Harbor Sedimentation Management Using Numerical Modeling and Exploratory Data Analysis

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Sedimentation in the harbors' basins is an environmental phenomenon that frequently disrupts safe shipping and necessitates costly dredging operations. The layout of harbors and the permeability of protective structures such as breakwaters influence sediment transport within harbor basins. Thus, through a multistep framework, this study investigates the sedimentation management issues for the Egyptian proposed Ezbet Elborg fishing harbor based on field measurements and a numerical morphodynamic coastal modeling system (CMS). First, field measurements were analyzed and evaluated for acquiring a full grasp of the research area's bathymetry and hydrodynamics. Second, a two-dimensional (2D) numerical simulation CMS model was set up and calibrated against field measurements wherein the developed CMS model highly correlated with actual measurements by 97%. CMS results demonstrate that the predominant NNW wave with the formed longshore current on both the harbor's sides affects sediment accumulation within the harbor's basin. Third, 100 simulations for the proposed harbor including different structural modulation scenarios affecting the sedimentation issue were investigated via the calibrated CMS model. Finally, an exploratory data analysis (EDA) is performed via correlation matrix and ANOVA test for the CMS's scenarios' results to gain an in-depth view of the relation between the harbors' layout and the structural characteristics with the sedimentation volumes. Results showed that breakwaters' orientation affects sediment accumulation more than its length. Also, breakwater permeability and basin width are significantly affecting sediment accumulation. Ultimately, the current study makes a substantial contribution to integrated coastal structure management (ICSM) by helping coastal stakeholders to mitigate the negative impacts of the harbors' sediment deposition aiming at sustaining both environmental and economic aspects.

1. Introduction

Sedimentation is an essential issue to consider when planning harbors because dredging and disposal can be expensive [1–5]. Most preliminary feasibility studies for harbors' planning focus on environmental implications during the construction stage while ignoring additional aspects that may occur during the operating stage, such as sedimentation issues [6, 7]. As a result, considering this issue from the conceptual design stage is crucial to minimizing sedimentation within the harbor basin. In general, harbor sedimentation rates are influenced by the interaction of several factors such as harbor layout (due to human intervention, such as the construction of breakwaters and docks), site condition (e.g., geological and geotechnical properties), and natural environmental changes (e.g., due to natural causes, such as storms) [8–10]. Furthermore, coastal protection structures such as rubble mound breakwaters are typically modeled as solid and impermeable bodies in coastal modeling applications. Certain rubble mound designs with more riprap in the core, for example, might result in large structural porosity, allowing flow and sediment channels that can weaken breakwaters, cause silt accumulation in the navigation channel, and raise dredging maintenance costs [11–15]. As a result, in coastal numerical modeling, it is critical to include breakwater parameters (such as riprap diameter and porosity) for estimating their influence on sediment movement inside harbor basins.

Recently, many research attempts have been made with physical and numerical models to investigate sediment transport in harbor basins for the purpose of mitigating sedimentation issues [2, 6, 16–25]. Physical modeling methodologies strive to incorporate diverse influences for assessing and determining harbors' sedimentation quantities. For instance, Yüksek [26] investigated experimentally the effect of breakwater geometries on sedimentation rates in fishery harbors' basins and the empirical relationship between sedimentation quantities and breakwater geometric parameters. However, physical models necessitate a huge area, a large sum of money, and a long period of time. In addition, scaling the prototype to a laboratory scale and vice versa requires similarity and dimensional analysis [24]. Numerical hydrodynamic models are another alternative for studying sedimentation issues. Numerous numerical models have lately gained popularity for studying harbors' sedimentation issues such as DHI's MIKE21 [25], Deltares' Delft3D models [6], and USACE's surface water modeling system (SMS). For instance, Sakhaee and Khalili [25] utilized Mike's 21 hydrodynamic modules to examine the effects of breakwater extension on sediment transport at an Iranian port in order to reduce sediment deposition rates inside the port's basin and propose efficient dredging techniques and procedures. Zikra et al. [6] used the Delft 3D model to mitigate the sedimentation issues in the Nagan Raya which resulted during the port's operations. Based on the two proposed scenarios, they found that the existing constructed breakwater was ineffective in protecting the port basin from sedimentation, so they suggested employing the sand bypassing system to mitigate sedimentation issues. Demirbilek et al. [27] used coastal modeling system (CMS) to evaluate various breakwater options for structural changes suggested for enhancing navigational conditions within the Kikiaola Harbor basin. The benefits and effects of each alternative are assessed to improve the safety of navigation and the utilization of the current harbor; thus, in the current study, the CMS has been used with considering the effectiveness of existing breakwater. Also, Li et al. [13] studied sediment transport along the American Dana's harbor's porous breakwater aiming at mitigating dredging costs. First, they used the CMS model to numerically assess how the breakwater's permeability affected the amount of stored sediment in the harbor basin. The model results were then verified by comparing the CMS sedimentation volumes to the total sediment accumulation available from historical dredging records. In Egypt, Sharaan et al. [18] conducted a study to analyze the impact of adding a perpendicular extension to the main breakwater of El-Burullus fishing harbor. The study aimed at mitigating sedimentation challenges of the harbor. Furthermore, the study utilized CMS to evaluate the effectiveness of five scenarios: the initial three involved different alterations to the existing conditions with the addition of the breakwater extension, while the remaining two scenarios explored adjustments to the current breakwater alignment and harbor layout. The objective was to investigate accretion and erosion rates across various scenarios to devise a sustainable solution for addressing sedimentation issues in the long term.

Ultimately, Damietta Governorate, aligned with the Egyptian government's vision 2030 for coastal development, plans to build a new fishing harbor in Ezbet Elborg, a seaside city, to tackle fishermen challenges. Currently, fishermen anchor within the Damietta Nile branch due to lacking proper harbor facilities, raising concerns about river contamination caused by boat debris. This new harbor, designed to house all necessary fishing services, aims to attract some fishing professionals, thereby creating job opportunities for young people in the region. Therefore, this research aims to develop a CMS model to evaluate various scenarios for the harbor's conceptual design, specifically addressing potential sedimentation issues.

2. Research Gap and Objectives

Based on the preceding information and literature, two main insights can be provided: (1) The majority of research has focused on specific aspects of the sedimentation problem, such as harbors' layout and breakwater characteristics, a holistic framework that integrates these aspects into a practical manner is still required, and (2) previous studies' finding can be drawn as recommendations based on the results from numerical and physical models without any further analysis and processing for the obtained results to comprehend the relation between sedimentation rate and the affected physical parameters for mitigating sedimentation issues. Therefore, this study fills this knowledge gap by suggesting an integrated framework for the Egyptian fishing harbor of Ezbet Elborg as a case study using a numerical CMS model and exploratory data analysis (EDA) to help the harbors' stakeholders in mitigating the harbors' sedimentation issues. The objectives of the current work are as follows:

(1) Applying a thoroughly tested and calibrated process-based numerical simulation coastal model system (CMS) that fully imitates the current status of the study area by using bathymetric and hydrodynamic field measurements.

(2) Estimating the proper harbor's layout design by applying a calibrated 2D numerical simulation CMS as the main tool to foretell the sedimentation rate within the harbor basin.

(3) Performing an EDA for investigating deeply the impact of physical parameters on the harbors' sedimentation accumulation.

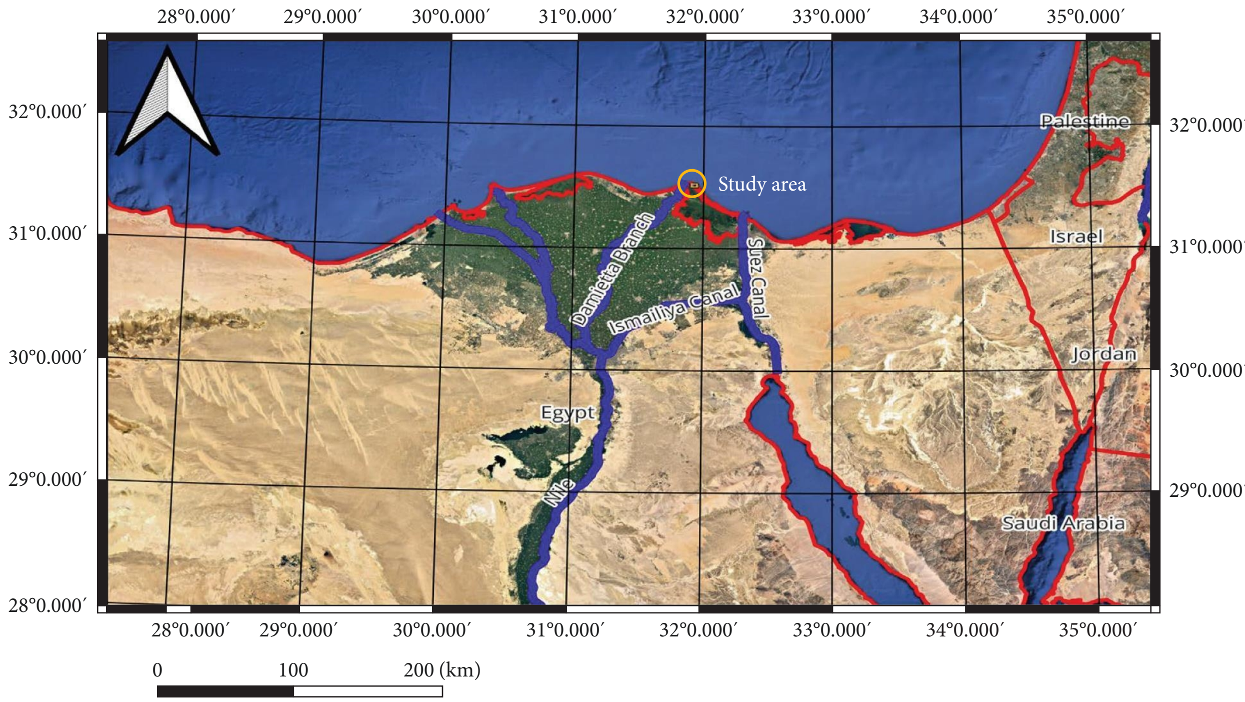


Figure 1: The location of study area.

3. Study Area

The study was carried out along the Ezbet Elborg city's coastline, which is situated close to the Damietta promontory's northernmost point on the eastern coast of the Nile delta. The research area is located between latitudes 31°26′00″N and 31°32′00″N and longitudes 31°54′00″E and 32°20′00″E (Figure 1). Ezbet Elborg serves as a pivotal hub for 60% of Egypt's fishing activities, hosting the largest fleet of fishing boats. It is a vital center for the local fishing sector, serving as the primary source of income for the community. Many fishing vessels embark on extensive journeys across the eastern Mediterranean and Red Sea. Additionally, the town is a notable center for ship and yacht construction in Egypt. In a bid to elevate the quality of life in this locale, the Egyptian government is actively pursuing the establishment of a fishing port. This port aims to consolidate all fishing-related activities by providing a secure space for boat docking, fish trade, ship construction and maintenance, and the establishment of fish canning factories.

4. Materials and Methods

4.1. Field Data Collection. In this research, field data (bathymetry, tide data, current characteristics, sediment characteristics, and waves) are gathered by the Egyptian Coastal Research Institute (CoRI) for setting up the numerical model. The study delved into the bed characteristics of the research area through the examination of 56 bathymetry profiles. These profiles were strategically spaced at intervals of 50–100 m, extending up to 1,000–1,500 m offshore and aligning with 7–8 m water depth contours, as depicted in Figures 2 and 3. The selection of profile spacing aimed at ensuring an acceptable level of accuracy, following guidelines established by previous studies [28]. The numerical model was constructed using bathymetric data from October 2014, leveraging the field data available during that period. Calibration of the model was subsequently performed using data gathered in October 2015. Bathymetry data are obtained using DGPS Hemisphere R131 and multi-frequency survey echosounder SYQWEST with an accuracy of 0.1 m for providing high-quality depth information. Both the DGPS and the echosounder were joined to a marine laptop model Tetra Note-EX for data recording. The DGPS and echosounder data are collected jointly and filtered using a developed software by CoRI, specifically designed for this purpose, and then the data is analyzed using the CMS model. The developed CMS model generated numerous bathymetry points using bathymetric data and interpolation technique, which were visualized in both 2D and 3D through the contour module in the CMS model software, as illustrated in Figures 3(a) and 3(b), respectively.

Tide data in the research area were collected by measuring water surface elevation (WSE) at intervals of 0.5 hr from October 2014 to October 2015, covering the same period as the collected bathymetric data, as shown in Figure 4. Furthermore, the region tide characteristics are microtidal and semidiurnal with a range of −10.6 to + 79.6 cm.

Throughout the year 2010, wave measurements were collected using the gauge S4DW, which was deployed at the bottom (0.5 m above seabed) in the vicinity of Damietta harbor at a water depth of 12 m. The analysis of the observed wave data revealed that the majority of the waves (84%) blowed from the NNW, while small wave components approached from the W and NE directions, as shown in Figure 5. Furthermore, the significant wave height was in January 2010 with 4.2

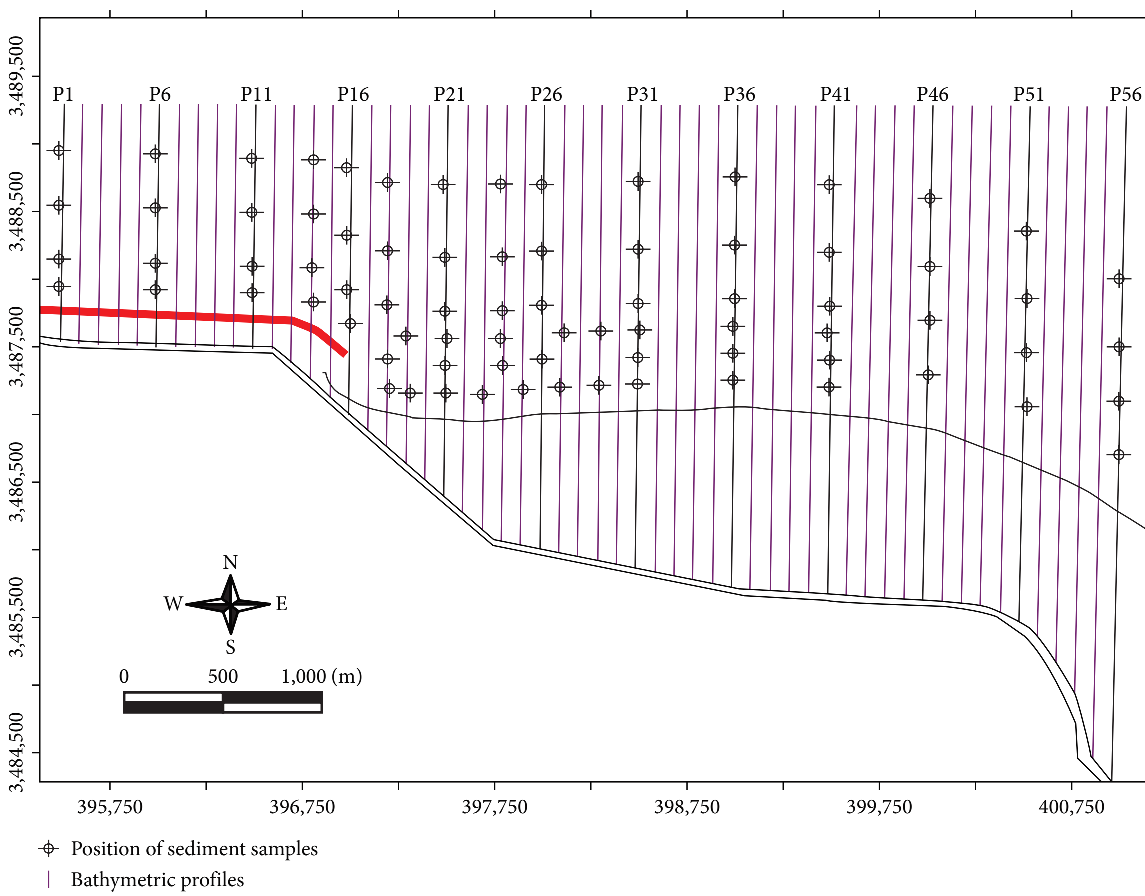
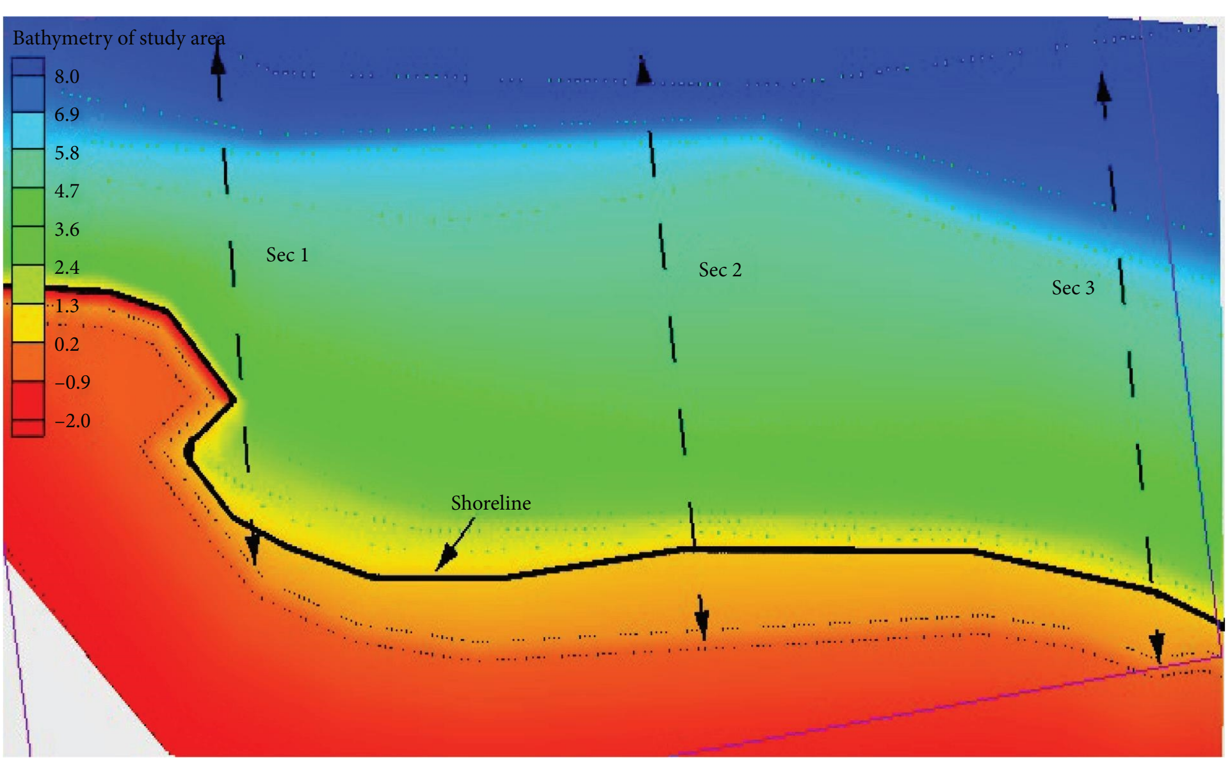
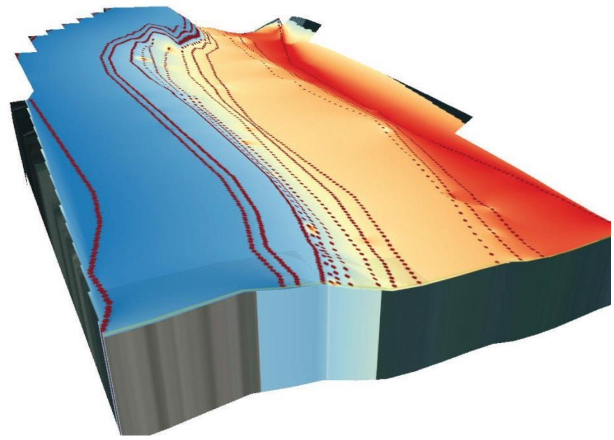


Figure 2: Distribution of bathymetric profiles along the study area.



(a)

Figure 3: Continued.



(b)

Figure 3: (a) Contours map for bathymetric data and calibration profiles along the study area, (b) 3D map for bathymetric data along the study area.

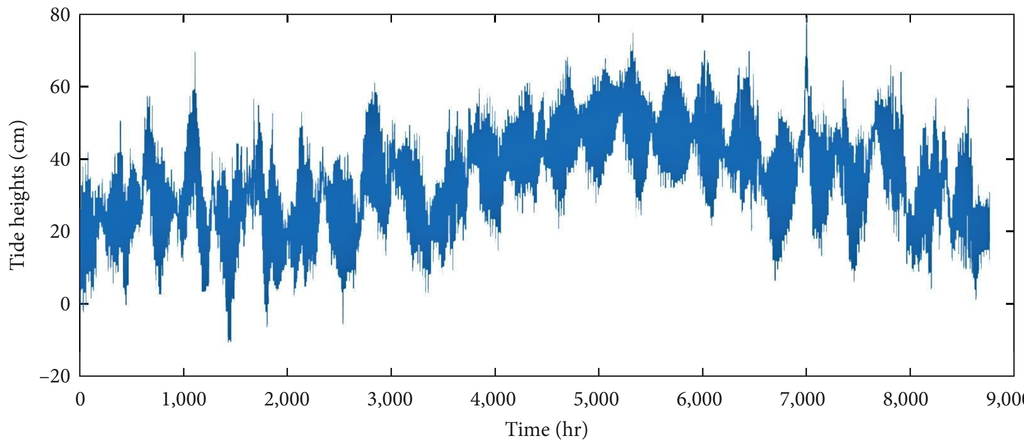


Figure 4: Tide as WSE records for 1 year starting from 1 October 2014.

m from N, which is consistent with the findings of earlier studies [29]. Moreover, the wave is transformed from the offshore wave station at a depth of 12 m to the model boundary at a depth of 8 m using the maximum entropy code, which was created by CMS developers, so that the directed spectrum may be utilized as input in CMS.

Utilizing a Van Veen grab sampler, 45 samples of surface and seabed materials will be gathered across the study area. The collected seabed sediment samples were analyzed at the geological laboratory of the CoRI. The nearshore zone sediment grain sizes (D_{50}) ranged from 0.15 to 0.25 mm, with an average size of 0.2 mm. In addition, the prevailing NNW wave creates an eastward-flowing alongshore current. Current measurements along the study region have shown that the majority of the alongshore currents (65%) flow from west to east and are generated by NNW waves with velocities between 10 and 120 cm/s. Ultimately, the construction of the CMS model incorporates the datasets from previous collections and analyses of bathymetric, hydrodynamic, and geological information.

4.2. Coastal Modeling System and Its Component. In coastal engineering and research, a morphodynamic CMS serves as a sophisticated tool to simulate and understand the complex interactions between waves, currents, sediment transport, and the evolving shape of coastal environments. This computational system integrates various mathematical models and algorithms to simulate the dynamic processes shaping coastlines, such as beach erosion, sediment deposition, and the formation of sandbars. By employing the CMS, researchers gain valuable insights into coastal evolution, helping to inform coastal management strategies, understand the impact of human interventions, and predict the response of coastal areas to natural forces and anthropogenic influences. Thus, in the current research, CMS modules are used in conjunction with a surface water modeling system (SMS) interface. CMS is a set of numerical models developed by the US Army Corps of Engineers to mimic tidal currents, waves, sediment transport, and morphological changes in coastal environments [30]. CMS was designed to provide a precise representation of coastal processes governing the use and upkeep of coastal inlet

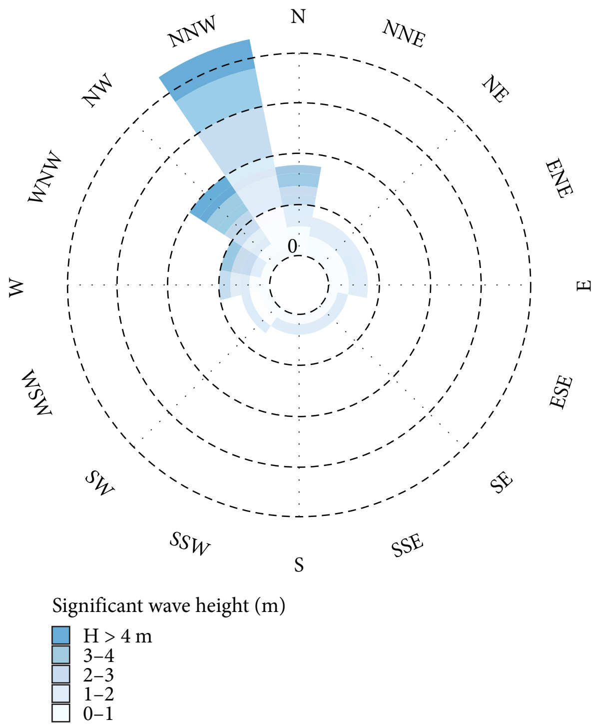


FIGURE 5: Annual wave rose on Damietta coast.

structures like jetties and breakwaters in navigation projects as well as to evaluate the safety of shipping in inlets and harbors. It is intended to be a research and engineering tool that works well on desktop PCs. The CMS makes use of the SMS interface for grid creation, model setup, charting, and postprocessing [31, 32].

CMS is composed of two modeling modules: CMS-Wave and CMS-Flow. Both CMS-Flow and CMS-Wave can be linked and controlled by an SMS steering module. While CMS-Wave uses the finite difference method to solve the wave action conservation equation, CMS-Flow employs a finite-volume volume approach to solve the 2D depth-integrated continuity and momentum equations [31] as follows:

$$\frac{\partial(h+\eta)}{\partial t}+\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}=0, \tag{1}$$

$$\frac{\partial q_x}{\partial t}+\frac{\partial u q_x}{\partial x}+\frac{\partial v q_x}{\partial y}+\frac{1}{2}g\frac{\partial(h+\eta)^2}{\partial x}=\frac{\partial}{\partial x}D_x\frac{\partial q_x}{\partial x}+\frac{\partial}{\partial y}D_y\frac{\partial q_x}{\partial y}+fq_y-\tau_{bx}+\tau_{wx}+\tau_{sx}, \tag{2}$$

$$\frac{\partial q_y}{\partial t}+\frac{\partial u q_y}{\partial x}+\frac{\partial v q_y}{\partial y}+\frac{1}{2}g\frac{\partial(h+\eta)^2}{\partial y}=\frac{\partial}{\partial x}D_x\frac{\partial q_y}{\partial x}+\frac{\partial}{\partial y}D_y\frac{\partial q_y}{\partial y}-fq_y-\tau_{by}+\tau_{wy}+\tau_{sy}, \tag{3}$$

where h = still-water depth relative to a specific vertical datum; η = deviation of the water surface elevation from the still-water level; t = time; q_x = flow per unit width parallel to the x-axis; q_y = flow per unit width parallel to the y-axis; u = depth-averaged current velocity parallel to the x-axis; v = depth-averaged current velocity parallel to the y-axis; g = acceleration due to gravity; D_x = diffusion coefficient for the x direction; D_y = diffusion coefficient for the y direction; f = Coriolis parameter; τ_{bx} = bottom stress parallel to the x-axis; τ_{by} = bottom stress parallel to the y-axis; τ_{wx} = surface stress parallel to the x-axis; τ_{wy} = surface stress parallel to the y-axis; τ_{Sx} = wave stress parallel to the x-axis; and τ_{Sy} = wave stress parallel to the y-axis.

Following this, CMS-Flow transfers water level and current velocity data to CMS-Wave. CMS-Wave is a spectral wave transformation model that addresses the steady-state wave-action balance equation on a nonuniform Cartesian grid as follows:

$$\frac{\partial C_x N}{\partial x}+\frac{\partial C_y N}{\partial y}+\frac{\partial C_{\theta N}}{\partial \theta}=\frac{k}{2\sigma}\left[\left(CC_g\cos^2\theta N_y\right)-\frac{CC_g}{2}\cos^2\theta N_{yy}\right]+S_{\text{in}}+S_{\text{dp}}+S_{\text{nl}}, \tag{4}$$

where $N = E/\sigma$ is the frequency and direction dependent wave-action density, defined as the wave energy density $E = E\ (x, y, \sigma, \theta)$ divided by the intrinsic frequency σ; N_y, and N_{yy} denote the first and second derivatives with respect to y, x, and y are the horizontal coordinates; θ is the wave direction measured counterclockwise from the x-axis; C and C_g are wave celerity and group velocity; C_x, C_y, and C_θ are the characteristic velocity with respect to x, y, and θ, respectively; and k is an empirical parameter representing the intensity of the wave diffraction effect.

A CMS-Wave spectrum can be generated using statistical wave parameters such as wave height, period, and incident angle. It is possible to combine or use CMS-Flow and CMS-Wave individually. In the coupling mode, the variables significant wave height, peak wave time, wave direction, and wave-breaking dissipation are transferred from CMS-Wave to CMS-Flow. CMS-Wave also made use of the bathymetry, water levels, and currents from the CMS-updated flow. The coupled steering module can simulate a wide range of essential short- and long-term processes, such as combined circulation (current and sea surface elevation), waves, shoreline changes, and morphological changes [30]. As a result, in this study, the coupled steering module has been employed to examine how different harbors' layout scenarios may affect sedimentation in the proposed Ezbet Elborg fishing harbor.

In this study, a CMS-Flow model grid is firstly created utilizing bathymetric data with a variable-sized rectangular cells covering the study area (Ezbet Elborg fishing harbor and the adjacent coastal structures). The grid was extended offshore to the closure depth (8.0 m), at which point sediment movement could be ignored. The grid resolution varied from 10 m in the most crucial location (within the entrance of the Ezbet Elborg harbor and the nearby seawall) to 60 m at the research area's boundary. Refined cells near critical locations were used to generate a realistic simulation of sediment

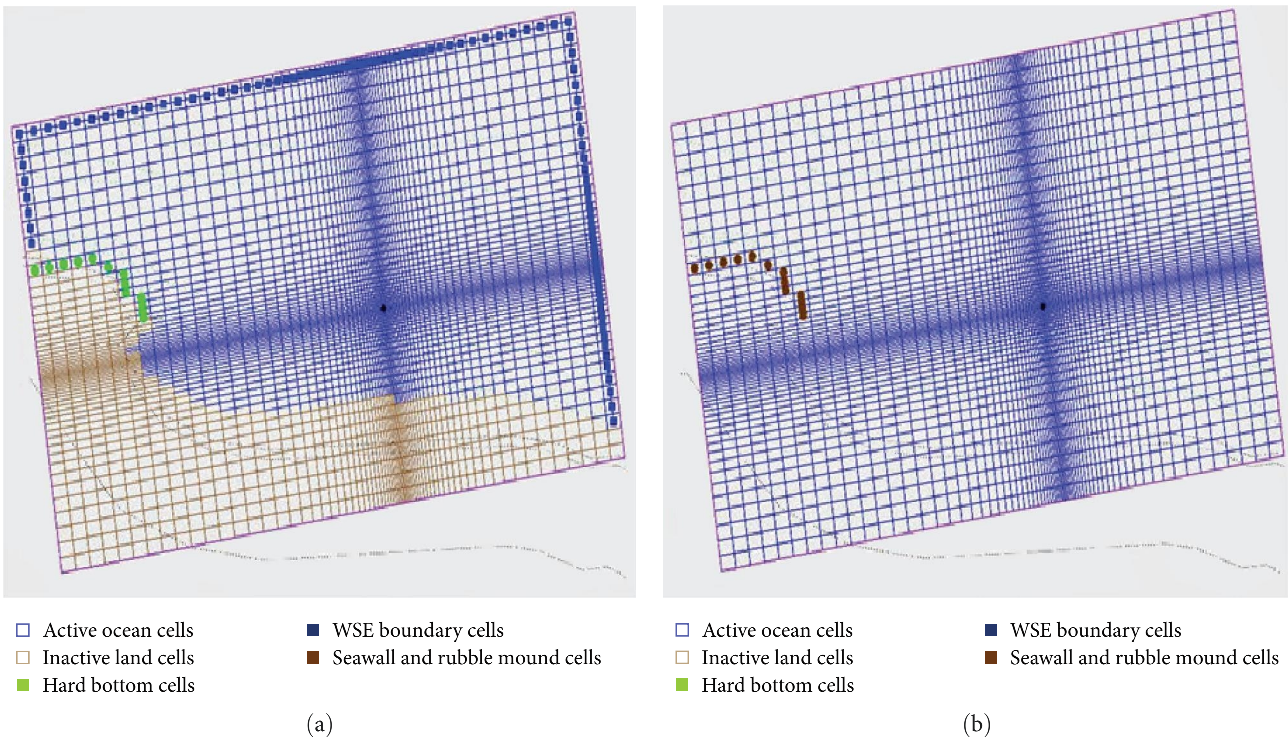


FIGURE 6: Model grids with boundary condition for the study area: (a) CMS-flow grid, (b) CMS-wave grid.

transport and morphological change processes in the places where they happened the most frequently. CMS-Flow was driven by the recorded tide at the upper open boundary and given the sediment, particle sizes D50, and Manning roughness to mimic the flow process. The CMS-Wave was then generated utilizing the same dimensions as CMS-Flow and provided by the wave data. Moreover, shoreline surveying is used to separate land and ocean cells, and finally, the geometry and characteristics of the coastal structures are defined in the CMS. The full details for both the CMS-Flow and CMS-Wave grids are shown in Figure 6.

For calibrating the utilized CMS model, a sensitivity analysis is performed to investigate the impact of tunning CMS parameters on its performance. During the sensitivity analysis, several sediment transport formulas, hydrodynamic time step, Manning coefficient, scaling factor for bed load, and suspended load were investigated. In addition, the chosen parameters were altered within the CIRP's recommended ranges. The calibration of numerical models is often conducted by quantifying the agreement between the model's predictions and field data that represent the real world. Bathymetry data collected in October 2014 are used to set up the CMS model, while data from October 2015 are utilized to calibrate the morphodynamic model. The CMS model is run using a coupling steering module to anticipate the bottom evolution over a 1-year period starting in October 2014 and finishing in October 2015. As illustrated in Figure 7, three profiles scattered throughout the research region are subjected to sensitivity analysis and compared to measured field data. In addition, according to Reed et al. [31], different statistical indicators such as the root mean squared error (RMSE) and correlation coefficient (CC) for the bed depth changes are calculated for the calibrated profiles as follows:

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(M_i - F_i)^2}, \tag{5}$$

$$R = \frac{\sum_{i=1}^{n}(M_i - M^{-})(F_i - F^{-})}{\sqrt{\sum_{i=1}^{n}(M_i - M^{-})^2 \sum_{i=1}^{n}(F_i - F^{-})^2}}, \tag{6}$$

where M_i refers to the modeled value, F_i refers to field measurements value, M^{-} is the mean value of model results, and F^{-} is the mean value of field measurements. The calculated values of RMSE and CC for the bed depth variations for the calibrated profiles are depicted in Table 1. Also, from sensitivity analysis, it is found that the CMS model is highly qualified to predict coastal morphodynamic processes when using the Van Rijn formula for sediment transport and the values of the hydrodynamic time step, scaling factors, suspended load, total adaptation length for bed are 450 s, 1, 1, and 1, respectively. The results affirm the model's precision and indicate its potential for replicating investigations into coastal processes within the study region. Additionally, the model may be utilized to forecast morphodynamic variations and alterations in the coastal area.

The findings of this stage are the first step toward the study of most suitable scenarios for the geometry layout of

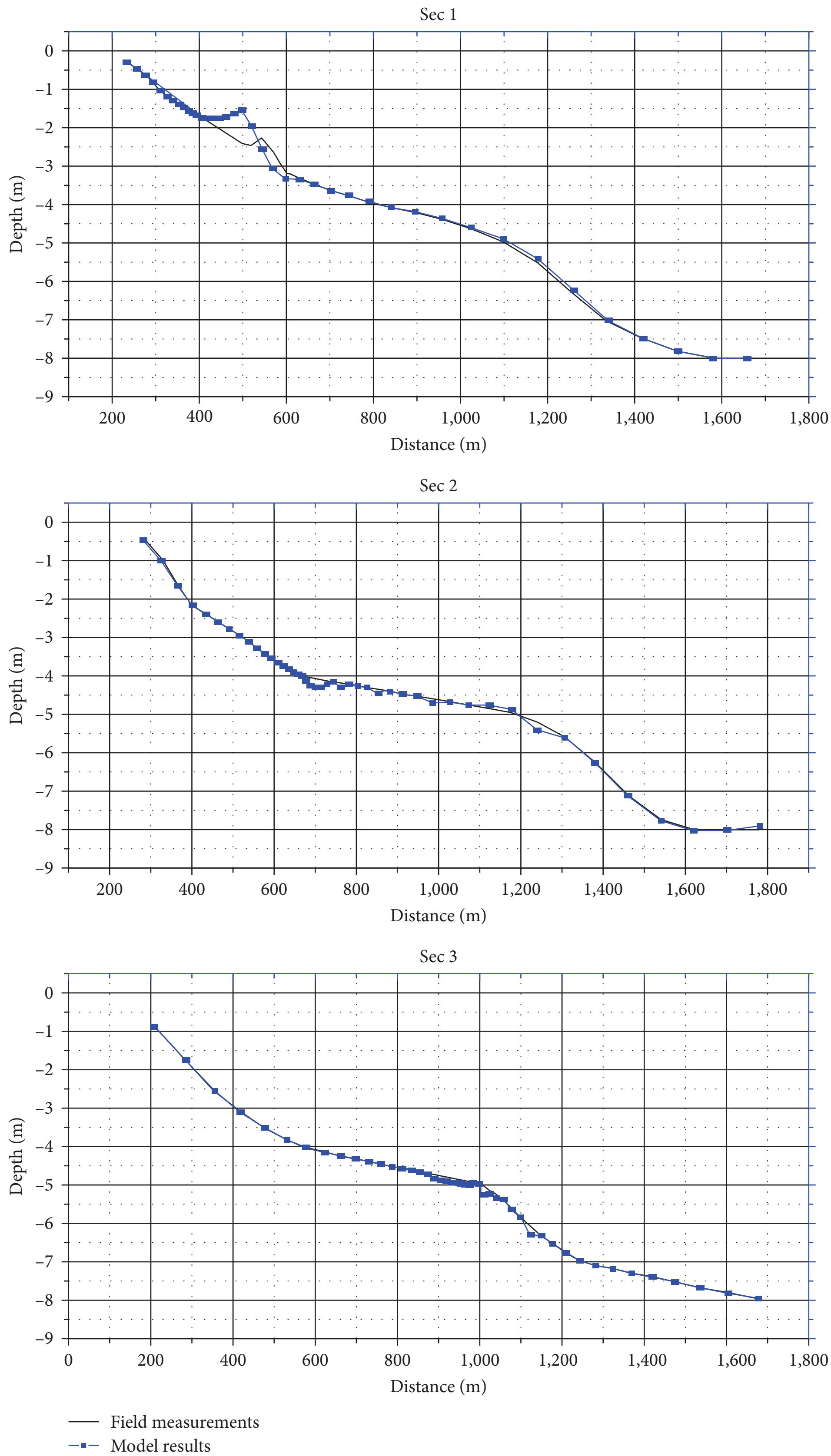


Figure 7: Comparison between measured and modeled cross-shore profiles in 2015.

Table 1: Values of RMSE and CC for the bed depth changes of calibrated profiles.

Section ID	RMSE (m)	CC
Sec 1	0.164	0.976
Sec 2	0.151	0.99
Sec 3	0.145	0.994

the suggested fishing harbor at this location. This optimized model setup assures the ideal conditions to predict the morphodynamic changes in this study area, and this will undoubtedly contribute to find long-term sustainable dredging maintenance of the proposed harbor entrance.

4.3. Methodology Framework. The hydrodynamic numerical modeling procedure for studying and analyzing sedimentation within harbors' basins is carried out in seven main steps: (I) data collection, (II) model setup, (III) assign hydrodynamics parameters for the study area, (IV) data training, (V) calibration of CMS model, (VI) study morphology change for different scenarios for the proposed harbor, and (VI) analysis of results. A brief description of each step is presented below (Figure 8):

(i) Data collection: In this step, bathymetry and geometrical data including topographical survey and existing coastal structures "seawall, breakwater, etc." are specified for the investigated area.
(ii) Model setup: A refined rectangular grid is created based on the bathymetric data to encompass the study area.
(iii) Assign hydrodynamics parameters: To simulate the flow through the study area, the CMS model is provided by hydrodynamics boundary conditions "water surface elevation (WSE), wave measurements, bed sediment characteristics D_{50}, etc."
(iv) CMS model training: To simulate the hydrodynamic processes within the study area, a steering module-based numerical CMS (coupling CMS-Flow and CMS-Wave models) is conducted over a 1-year simulation period.
(v) Calibration of the CMS model: By evaluating the degree of agreement between the model's predictions and field data. The simulation results represented in the bed morphology are calibrated with the observed field data.
(vi) Study morphology change for different scenarios of the proposed harbor: The calibrated model is ready to efficiently simulate the coastal hydrodynamic process of the study area and assess the different proposed scenarios.
(vii) Analysis of results through EDA: After running different scenarios, the resulted data for morphological change is analyzed to assess the effect of each physical parameter on the harbors' sedimentation accumulation.

4.4. Test Scenarios for Structural Modulation of the Ezbet Elborg Fishing Harbor. In this study, the proposed Ezbet Elborg harbor is simulated numerically using the calibrated CMS model to check the effects of harbor geometry on the harbor sedimentation. Moreover, rubble mound breakwaters are frequently portrayed as solid structures in CMS, impervious to both flow and sediment transport. Some designs with larger riprap in the core, on the other hand, may have enough structure porosity to let flow and fine sediment through while also storing a significant amount of sediment. Therefore, it is important that the CMS simulates their effects [30]. To this end, the tested parameters were the lengths of the breakwaters (L_1, L_2, and L_3), their inclination angles with shoreline ((α_1), (α_2), and (α_3)), rock diameter (D), porosity (n), and harbor basin width (B) as shown in Figure 9.

After conducting the calibration of the CMS, the model is modified by incorporating breakwater into the CMS to form the suggested layout of the harbor as shown in Figure 10.

The present calibrated, hydrosedimentological CMS model is then applied to forecast and simulate the consequences of numerous harbor layout scenarios in terms of varying breakwater parameters using the current geometry and condition of the study area. With the exception of the harbor's basin's bathymetry, which is set to the planned level of 6 m below mean sea level, the boundary conditions and model setup have not changed. For further investigation, various model's outputs for the considered scenario choices are discussed.

5. Results and Discussion

5.1. Structural Modulation Scenarios of Ezbet Elborg Fishing Harbor. Figure 11 shows morphological changes of harbor based on simulated hydrodynamic processes. In this study, 100 scenarios were run to investigate the relationship between the quantity of sedimentation inside the harbor basin and breakwater parameters. Regarding the US Army Corps of Engineers specifications for coastal shore protection and CMS model simulation tool limitations, the tested breakwater parameters are changed continually to numerically simulate different scenarios. At the end of simulation, the CMS model computes the accumulated sedimentation volume (Vs) within the harbor basin for each scenario. This calculation involves drawing a polygon around the sedimentation area and multiplying its area by the average change in depths, as detailed in Table 2 and Figure 11(a).

For the majority of different scenarios, the position of erosion/accretion pattern looks similar but quantitively different and can be compared with each other by analyzing the effect of tested breakwater parameters on sedimentation quantities, as presented in Figure 11. This depicts the sedimentation pattern after the whole simulation. This spatial map shows that the harbor basin is filled with sediment to a depth of around 0.3 m. As illustrated in Figure 11(a), the differences mostly manifest in the spatial extent of the accreted area within the harbor's basin, particularly the area adjacent to the secondary breakwater. This confirms the importance of the harbor layout and the permeability of

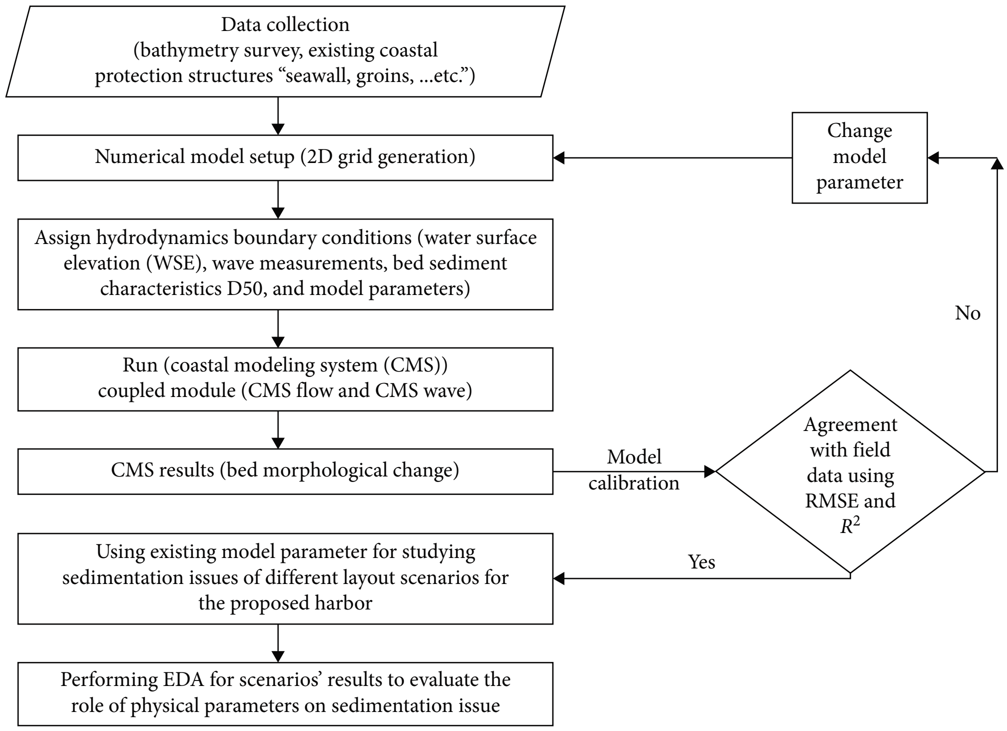


Figure 8: Methodological flow chart of the proposed CMS morphodynamic model.

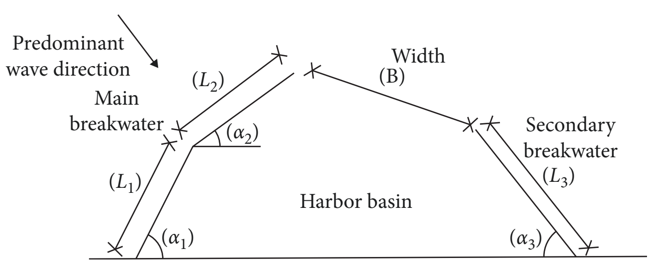


Figure 9: Harbor geometry parameters.

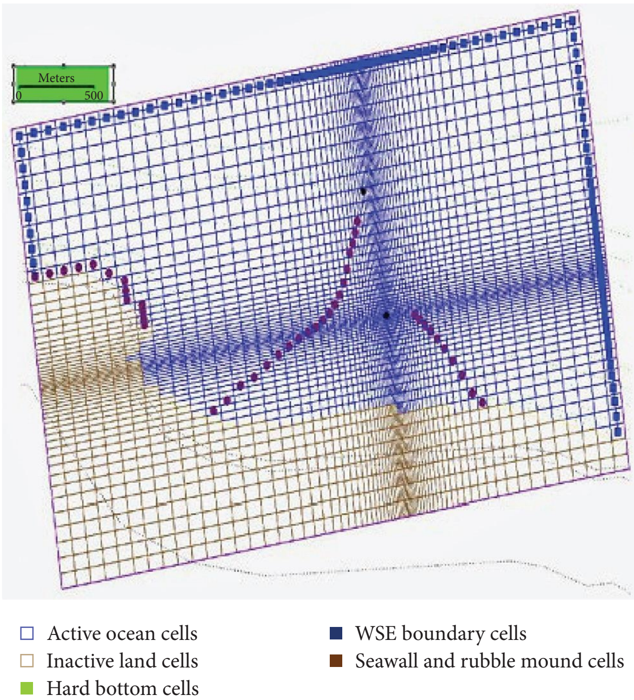
breakwater to the overall morphodynamic evolutional of the study area.

An examination of the wave height and current velocity patterns, in addition to the erosion/accretion patterns, can contribute to a better understanding of the other characteristics of the morphological phenomena that took place. A typical wave height pattern during the simulation is shown in Figure 11(b). The wave direction is almost NNW with an average height of 2.5 m on both sides of the harbor's entrance, as shown in this sample. In addition, Figure 11(c) depicts the current pattern at the moment of a given peak during simulation. As can be seen, the longshore current forms on both sides of the harbor basin, with bypassing occurring near the harbor basin's entrance. Accordingly, these mechanisms are expected to be the most significant in terms of sediment transport within and around the harbor's entry.

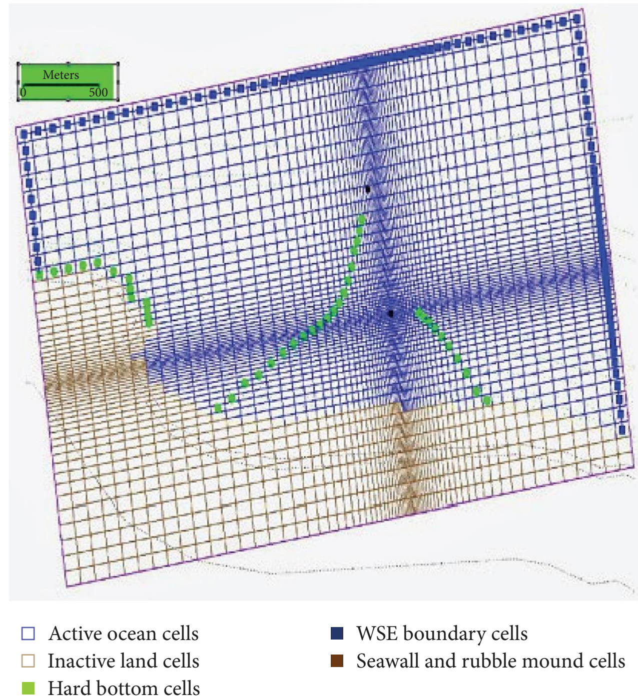
5.2. Exploratory Data Analysis of CMS Results. To better understand the effect of each breakwaters' parameters on the sedimentation volume (Vs), an exploratory data analysis (EDA) was conducted and the results are given in Figure 12 to graphically illustrate the aspects of the acquired data and the relationship between different variables. The diagram depicts a 10×10 matrix with the sedimentation volume dependent variable (Vs) and the nine breakwaters' parameters independent variables depicted on the rows and columns. The figure is broken into three blocks to ease interpretation: the diagonal (Block 1), the lower left (Block 2), and the upper right (Block 3). The EDA provides three insights: (1) input variables smoothed frequency curves to examine their distribution within (Vs); (2) a sensitivity test that investigates how Vs is influenced by various input variables; and (3) a sensitivity test that investigates the interdependence of different variables.

Regarding the first insight, the boxes in Block 1 show the smoothed frequency curves of input variables with the target Vs. The normalized distribution of variables shows that $(\boldsymbol{L_1})$, (α_1), $(\boldsymbol{L_2})$, and (n) are normally distributed with Vs. Input variables as $(\alpha_3).(\boldsymbol{D})$ are positively skewed, whereas $(\boldsymbol{L_3})$, (α_2), and (B) are negatively skewed. The second and third insights are inferred through a correlation matrix that illustrates the dependencies among the variables. The scatter plots of every two variables are shown in the boxes in Block 2. The correlation values (ranging from +1 to −1), which characterize the strength and direction of the association between the variables, are shown in the boxes in Block 3. The magnitude of a correlation value indicates the strength of a relationship between two variables, whereas the sign of the correlation indicates the relationship's direction (whether there is a positive or negative correlation between the data values).

Both the last row and column represent the relationship between input variables with the target Vs. The first and second boxes in the last row demonstrate the impact of the first part of main breakwater parameters on sedimentation; it

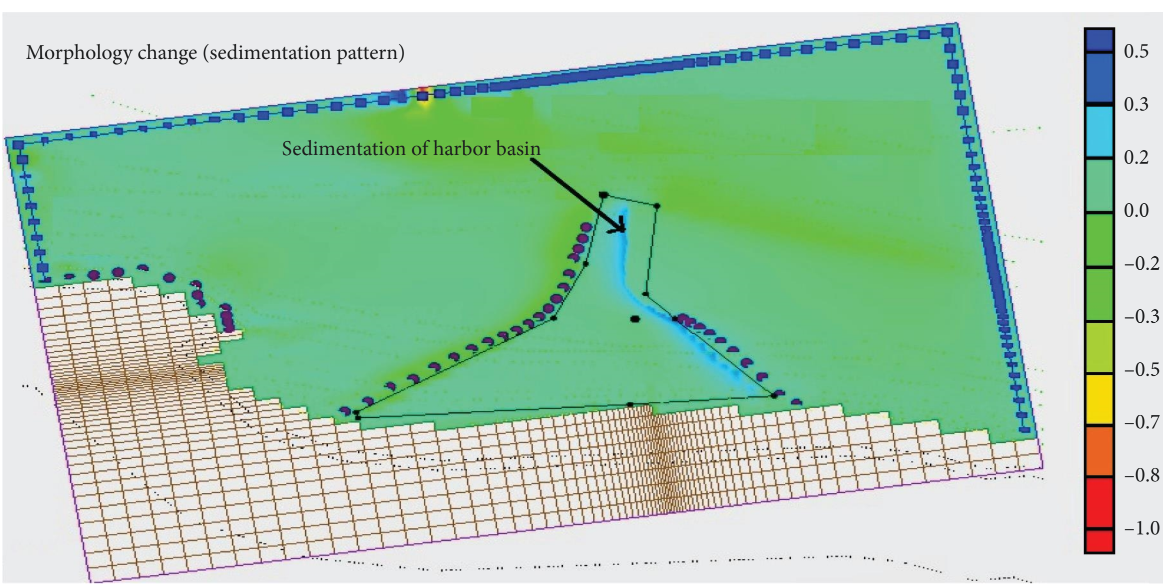


(a)



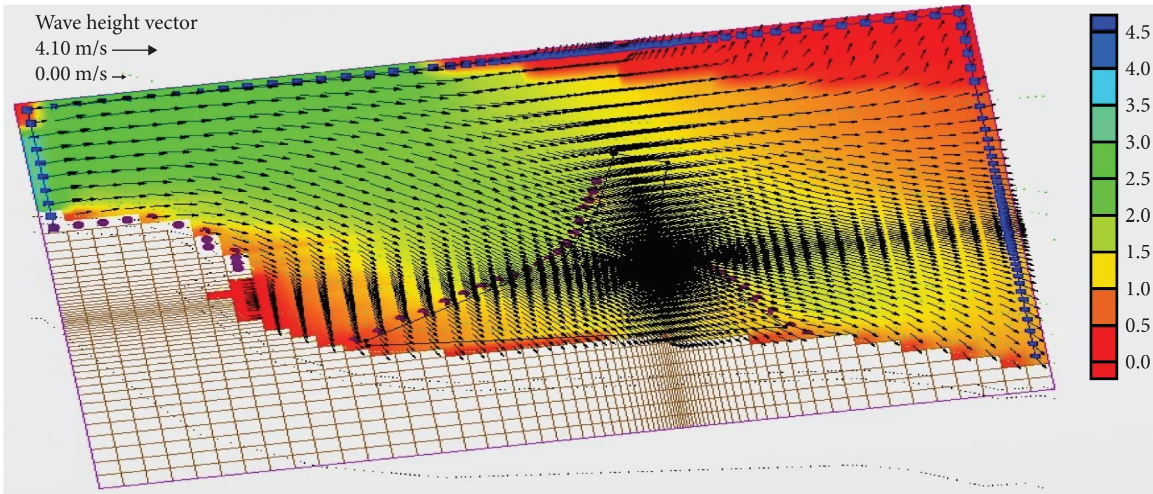
(b)

Figure 10: Model grids with boundary condition for the proposed Ezbet Elborg harbor: (a) CMS-flow grid, (b) CMS-wave grid.

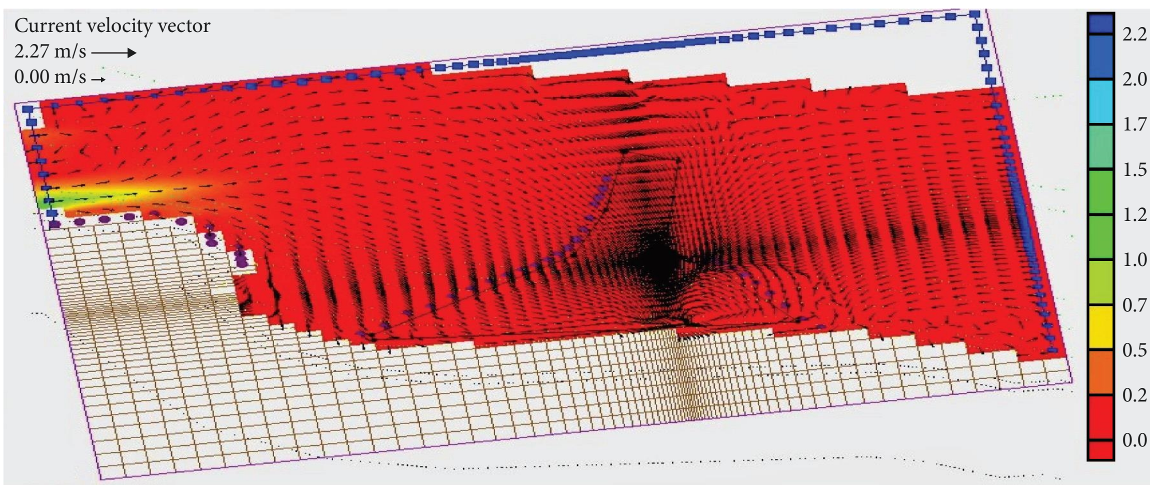


(a)

Figure 11: Continued.



(b)



(c)

Figure 11: Morphological changes with associated hydrodynamic processes: (a) the pattern of sedimentation following the simulation (side bar: erosion/accretion in meters), (b) a vector velocities map with associated average wave height during simulation, (c) current pattern map at a chosen peak time.

is apparent that the increase in angle (α_1) and decrease in length ($\boldsymbol{L_1}$) result in a decrease in Vs. The effect of the second part of the main breakwater's parameters is presented by the third and fourth boxes of the last row, the results show that an increase in ($\boldsymbol{L_2}$) does not show an obvious change in harbor basin sedimentation, but the orientation angle (α_2) mainly decreases sedimentation volume as the increase of (α_2) so that the main breakwater's second part is perpendicular to the dominant wave direction. For the secondary breakwater, it is noticed that its orientation (α_3) has more impact than length ($\boldsymbol{L_3}$) (Boxes (5) and (6) in the last column).

Box (7) of the last column depicts the influence of harbor entrance width on sedimentation within the basin. Based on the findings of the numerical simulations, it can be determined that wider entrances cause greater sedimentation inside the basin, as they diminish the total intensity of currents throughout the basin, resulting in more sedimentation. Additionally, the impact of changing the breakwater's porosity from 0.2 to 0.4 and the rock diameter from 1.5 to 2.0 m also revealed that as the structure's porosity or rock diameter grows, the potential for sediment seepage through the structure increases (Boxes (8) and (9) in the last column). The following are the important conclusions gained from the exploratory and sensitivity analyses: (1) Parameters (α_1). (α_2).(α_3) are negatively correlated with sedimentation volume (Vs); (2) the increase in the value of these variables decreases the (Vs); (3) (B), (n), and (D) are positively correlated with sedimentation volume (Vs); the increase in the value of these variables will also increase (Vs). Generally, the orientation of the breakwater (α) affects sediment volume more than length ($\boldsymbol{L}$). The present findings align with outcomes derived from earlier physical models, affirming that the slope of the primary breakwater, basin width, and breakwater porosity significantly contribute to sediment deposition within the harbors' basin [16, 26].

Table 2: Scenarios' results of the harbor sedimentation study.

Inputs										Output
Scenario no.	Length (L_1)	Angle (α_1)	Length (L_2)	Angle (α_2)	Length (L_3)	Angle (α_3)	Base width (B)	Porosity (n)	Rock diameter (D)	Accreted volume
Unit	m	Degree	M	Degree	m	Degree	M	—	M	m^3
Sec 1	1,000	45	600	80	800	30	200	0.4	2	47,600
Sec 2	1,000	45	600	80	800	45	200	0.4	2	49,500
Sec 3	1,000	45	600	80	800	60	200	0.4	2	34,200
Sec 4	900	45	700	80	700	60	150	0.3	1.5	33,120
Sec 5	900	30	700	80	700	30	150	0.3	1.5	24,500
Sec 6	900	60	700	80	700	30	150	0.3	1.5	28,602
Sec 7	800	60	600	80	800	30	200	0.2	1.5	19,850
…..	…..	…..	…..	…..	…..	…..	…..	…..	…..	…..
…..	…..	…..	…..	…..	…..	…..	…..	…..	…..	…..
Sec 99	800	45	600	80	800	30	200	0.2	1.5	21,300
Sec 100	800	45	400	80	800	45	200	0.2	1.5	33,200

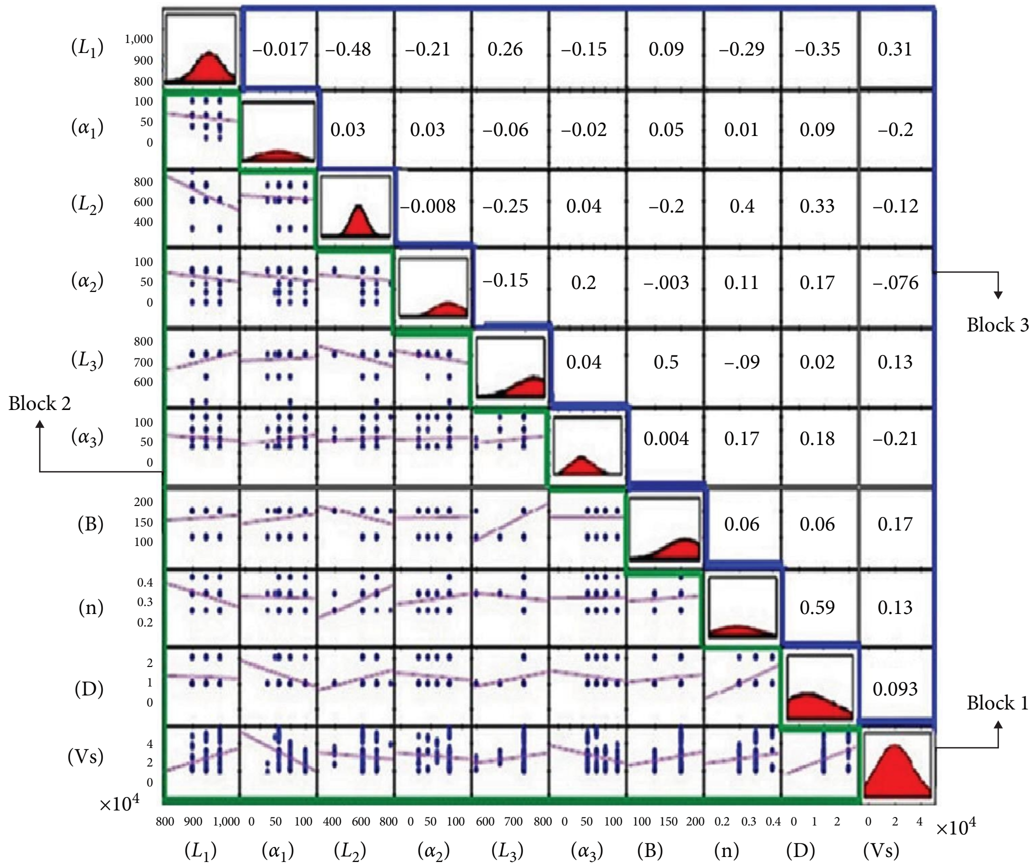


Figure 12: Correlation analysis between input and output variables.

In a separate endeavor, the analysis of variance (ANOVA), a t-test extension, is employed to evaluate how different the means of multiple groups are. To run the test, two hypotheses are assumed. The null hypothesis states that "there is no difference between means," implying that the variables have no effect on the dependent variable; however, the alternative hypothesis states that "there is a significant difference between means," implying that at least one variable affects the dependent variable.

By applying ANOVA to the results of the CMS model, an investigation is performed on (Vs) as the dependent variable and nine independent input variables. In the ANOVA test, the interaction effect was examined in addition to the effects of each of the nine independent variables on the dependent variable. Furthermore, the least-squares method was used to demonstrate the accuracy of the experimental data. If the P value is greater than 0.05, the null hypothesis should be accepted because the threshold of significance, or P value, is less than 5%. In the event that the P value is less than 0.05, the alternative hypothesis ought to be accepted. Table 3 shows a sample of ANOVA statistical analysis findings generated with MATLAB.

Table 3: Samples of analysis of variances (ANOVA) for CMS results.

Case no.	Source	Mean square	F	P
1	$(\boldsymbol{L_1})$, (α_1)	66,088,397	19.84	0.0008
2	$(\boldsymbol{L_1})$, (α_3)	1,147,222	0.34	0.5682
3	$(\boldsymbol{L_1})$, $(\boldsymbol{n})$	10,795,305	3.24	0.0749
4	(α_1), $(\boldsymbol{L_2})$	103203.1	0.03	0.8632
5	(α_1), (α_2)	37,558,279	11.27	0.0057
6	(α_1), (α_3)	66,088,397	19.84	0.0008
7	(α_1), $(\boldsymbol{n})$	1,928,410	0.58	0.4614
8	$(\boldsymbol{L_2})$, $(\boldsymbol{n})$	1.44E + 08	43.22	0.0001
9	(α_3), $(\boldsymbol{n})$	1,673,577	0.5	0.7349
10	(α_3), $(\boldsymbol{D})$	1,710,983	0.51	0.6109
11	$(\boldsymbol{B})$, $(\boldsymbol{n})$	112,225	0.03	0.8574

It can be observed that the P values for cases 1, 6, and 8 are less than 5%. As a result, in these cases, the null hypothesis should not be accepted. Furthermore, these results lead to the conclusion that all independent variables, with the exception of $(\boldsymbol{L_3})$, have an effect on the (Vs). Furthermore, when multiple dependent variables are involved, the model does clearly explain a significant influence in (Vs), especially for cases 1, 6, and 8.

Upon a comprehensive examination of the outcomes stemming from the structural modulation scenarios and taking into account the aforementioned interpretations, it becomes evident that predicting the sedimentation process is an intricate task, marked by numerous variables exhibiting high nonlinearity and stochasticity. Given this complexity, it is proposed that the designated harbor authority adopts advanced measures, such as a flow-diverted wall (FDW), sediment trap (ST), random radial channels (RC), and lateral wide channel (LWC), to effectively tackle sedimentation challenges. Additionally, regular implementation of bathymetric measurements is necessary to evaluate the effectiveness of the proposed solutions. Here, it should be mentioned that the proposed technique can be accurately applied in the same areas located on the Mediterranean Sea using the same depths; however, the design concept can be applied to other similar regions using different depths.

6. Conclusions

Sedimentation within the Egyptian harbors is a critical coastal issue that creates an obstacle for coastal navigation. Accordingly, in this study, a 2D hydrodynamic numerical CMS model has been developed and calibrated against field measurements and showed high agreement. Then, the calibrated model is used to investigate the effects of multiple layout scenarios of Ezbet Elborg harbor in terms of variable breakwater parameters on sedimentation within harbor basin. Furthermore, the permeability of rubble-mound breakwaters is described in the CMS for incorporating void space by defining the breakwater porosity and the diameter of riprap rocks during numerical modeling process. One hundred scenarios for harbor planforms have been examined by the CMS model, the sedimentation at the harbor entrance accumulated as a result of littoral drift by the longshore current that conveys deposits from both sides of harbor basin to gather at the harbor entrance. Also, it is noticed that the sedimentation pattern is concentrated next to the secondary breakwater which confirms the importance of the harbor layout and the permeability of breakwater to the overall morphodynamic evolutional of this study area.

On the other hand, an exploratory data analysis is performed on the collected dataset to understand the distribution of input variables with respect to the target variable. Additionally, a correlation matrix is generated to analyze the strength of the relationship between each variable. It is found that the orientation of breakwater (α) affects more than the length ($\boldsymbol{L}$). Intuitively, the impact of increasing the porosity (n) and rock diameter (D) of the breakwater result in increasing the potential sediment seepage through the breakwater. Additionally, the ANOVA test is performed for investigating the interaction influence of input variable combination on (Vs). The ANOVA model demonstrates that a significant effect on (Vs) when the combination of (($\boldsymbol{L}_1$), (α_1), and (α_1), (α_3), and ($\boldsymbol{L}_2$) and ($\boldsymbol{n}$)) are involved.

The results of the simulation for the tested scenarios can assist the decision-makers to avoid or mitigate the negative environmental impacts from harbors in terms of the sediment deposition via ICSM, hence reducing the costly maintenance dredging strategies. The approach utilized in this study, which was based on field data and numerical modeling, can only be used for the study of similar harbors in Egypt with similar environmental and geometrical parameters. Additionally, the authors aim to explore the potential of utilizing different numerical software, including Delft 3D, in a comparative analysis with CMS. This investigation will assess performance metrics, including computational time and modeling precision, to provide insights into the strengths and limitations of each modeling tool. As a concluding remark, the obtained numerical CMS model result database represents the third series of the proposed framework for sustaining ICSM and is regarded as the main step toward developing an optimization model using genetic algorithms to assist decision-makers and local communities in making the best decisions regarding the best planning of harbors to mitigate the detrimental environmental effects of harbors' sediment issues.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding this work.

Acknowledgments

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