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Environmental State of a Harbor in Terms of Waters Renewal. A Case Study for a Fishery Harbor in Thessaloniki Gulf

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Abstract

The waters renewal of the fishery harbor of Nea Krini is presented here. The harbor is located at the east Thessaloniki Gulf (NE Thermaikos Gulf, Greece). The main research point is focused on the environmental state of the harbor which is under construction. Under that point of view, the description of a two-dimensional, depth average, hydrodynamic model follows, in order to simulate the wind generated circulation of waters, initially on the greater area of Thermaikos Gulf and then on the coastal basin of the fishing harbor. The renewal of waters in the harbor's basin is subsequently studied. Tidal effects on the waters' renewal are also studied. The calculation of the concentration of Biochemically Oxygen Demand (BOD) in the fishing harbor for the average time of waters' renewal is then examined for three different cases, concerning the existence and operation of openings on the body of the groins. Finally, the analysis of the results shows a good environmental state of the harbor. It is obvious that the use of numerical models for different scenarios of engineering and design approaches can lead to the prognosis of hydrodynamic and environmental sate of a harbor's basin so that the best possible technical design can be adopted.

Keywords

Harbor of Nea Krini, Hydrodynamic Circulation, Renewal of Waters, Tidal Generated Sea Currents, Wind Generated Sea Currents

1. Introduction

In recent years, numerical models are used more and more in order to contribute significantly to the best possible understanding of coastal processes and the prediction of the environmental impacts of harbor projects (ports, marinas, fishing shelters, etc.). The development and application of such models help the scientists and engineers to find alternative solutions in order to avoid or reduce unpleasant and negative environmental effects. For example, sediment transport which causes a dynamic change of the coastline, coastal erosion or deposition (Monioudi et al., 2017; Karambas, 2014) stagnant waters in a harbor (Winterwerp, 2005) or the environmental state and the seawater quality of a harbor (Savvidis et al., 2017; Savvidis & Keramaris, 2021) are some of the most characteristic cases which are well studied through the use of mathematical models and more specifically hydrodynamic models, sediment transport models, water quality or ecological models.

The renewal of the waters of a harbor of a coastal basin is determined by the replacement of waters of the basin with new fresh water from the open sea via one or more openings-entrances, through which the harbor basin communicates with the open sea. Elsewhere in the literature, it is stated that flushing time (i.e. renewal of the waters) is defined as the time required for the replacement of the whole water of the marina basin by clean water (Kalitzi & Memos, 2008). It is well understood that the time required to achieve such a process is directly related to the external dynamics that move the waters of the basin and the topographic characteristics of the specific aquatic environment.

As far as the hydrodynamic circulation and the time of waters renewal in ports and coastal areas are concerned, a lot of works were done at a research level. This time, was calculated for a wide range of ports and harbors worldwide but also in several Greek harbors, marinas and fishing shelters and ranges from time periods less than a day to ten days or even more. Some relevant examples include the characteristic case of Cabreras' harbor in Spain, where waters' renewal time is achieved in 6 days (Orfila et al., 2005) while for the case of the inner basin of Boston's Harbor (United States of America) the time needed for waters' flushing is achieved between 2 to 10 days (Chan Hilton et al., 1998). Finally, the time needed for the waters of the Port of Thessaloniki (Northern Greece) to be renewed is of the order of one day since the flushing time due to wind was estimated between 1 and 2 days and the flushing time due to tide was 11 days (Thessaloniki Port Authority, 1995). The renewal time for a fishing shelter on Libya, was found to be 5.48 days (Christopoulou, 2010), for a marina on the east coasts of Thermaikos Bay (NW Aegean Sea, Greece), in Northern Greece, 2.90 days (Koutitas et al., 1996) while for a marina in Mytilene (NE Aegean Sea, Greece) 4.90 days (Alifragis, 2009). Furthermore the renewal time for the waters of Harbor of Nea Moudania (NW Aegean Sea), was studied with mathematical models and field measurements and found to be 0.70 days (Savvidis et al., 2009). Finally, the time for the renewal of the waters of the harbor of Agios Nikolaos, Volimes (Zakynthos, Ionian Sea, Greece) was 0.80 days (Kougianos et al., 2018).

The above mentioned renewal times were calculated either by field measurements or by applying numerical models. The interested reader can seek for more details in the recent work which was realized in the context of a Master Thesis in International Hellenic University (Mamtsadeli, 2020).

It is pointed out that these studies leading to the relevant results do not take into account the same external forces that generate the hydrodynamic circulation and water renewal, but mainly the predominant forces concerning the specific study area. Additionally, these times are obviously not comparable since (apart from the different external forces) they also refer to different topographic and bathymetric characteristics of the harbor basin i.e. surface areas and water volumes of the basin.

It is very important to note that the processes and mechanisms of renewal and sediment transport leading to depositional phenomena constitute contradicted factors concerning the water quality of a harbor. More specifically, small renewal times, that result from large openings between harbours and open sea, ensure good environmental conditions (thus, high waters quality), since the waters of the basin are substituted by new fresh waters from the open sea. However, large openings are related to increasing amounts of suspended matter transported by the currents that cause turbidity (and low waters quality) and may lead to undesirable sedimentation. In addition the processes of renewal waters and wave disturbance also constitute contradicted factors. Respectively to the previous case, small openings lead to larger renewal times however ensure better wave protection. A very interesting study by Fountoulis and Memos (Fountoulis & Memos, 2004) focused on the optimization of openings for water renewal in a harbor basin concerning that latter contradictive factor. Furthermore recent studies of waters' renewal and sedimentation of an ideal square harbor encapsulated in a coastal front with seawalls due to wind generated hydrodynamic circulation in the greater coastal area (Savvidis & Keramaris, 2021) focused on the inverse relation between the waters renewal and depositional phenomena.

A significant environmental index is the harbor's self-purification capacity. This parameter can be evaluated by the calculation of the Biochemically Oxygen Demand (BOD) which is defined as the quantity needed for the oxidation of an organic component of waste materials from microbes in aerobic conditions (Kougolos, 2005) and constitutes a significant parameter for the estimation of the organic pollution of surficial waters as well as waste waters. Savvidis and Keramaris (2021) and Savvidis et al. (2009) have applied that methodology in previous research studies.

The environmental approach of a port project and more specifically the hydrodynamic circulation and the renewal time of the waters in the Fishery Harbor of Nea Krini in Kalamaria (Thessaloniki Bay, North Greece), constitute the main aim of this research. A preliminary, initial research was already done by Mamtsadeli (2020) and it is improved and completed here by the present study. More specifically, this paper focuses on the more detailed hydrodynamic study and the estimation of the environmental state of the harbor based on alternative engineering practices that can enhance the hydrodynamic circulation in the harbor's basin affecting thus the renewal rates of the waters. Furthermore, the useful parameter of BOD as an environmental index is used in the present study so that the environmental state of the harbor can be evaluated.

2. Materials and Methods

2.1. Study Area

The fishing shelter of Nea Krini in Kalamaria is described here. The study area is placed along the east coasts of Thessaloniki Gulf, along the NE Thermaikos Gulf which is located at the NW Aegean Sea. A geographical map of the greater area of Thermaikos Gulf is shown in **Figure 1** (Pell et al., 2003).

The water depths of the harbor's basin are generally shallow, reaching approximately 4.5 to 5 m, near the breakwater. The study and the relevant calculations were carried out using the important tool of mathematical models. As it is shown in **Figure 2**, according to the study of the project (Christopoulos et al.,

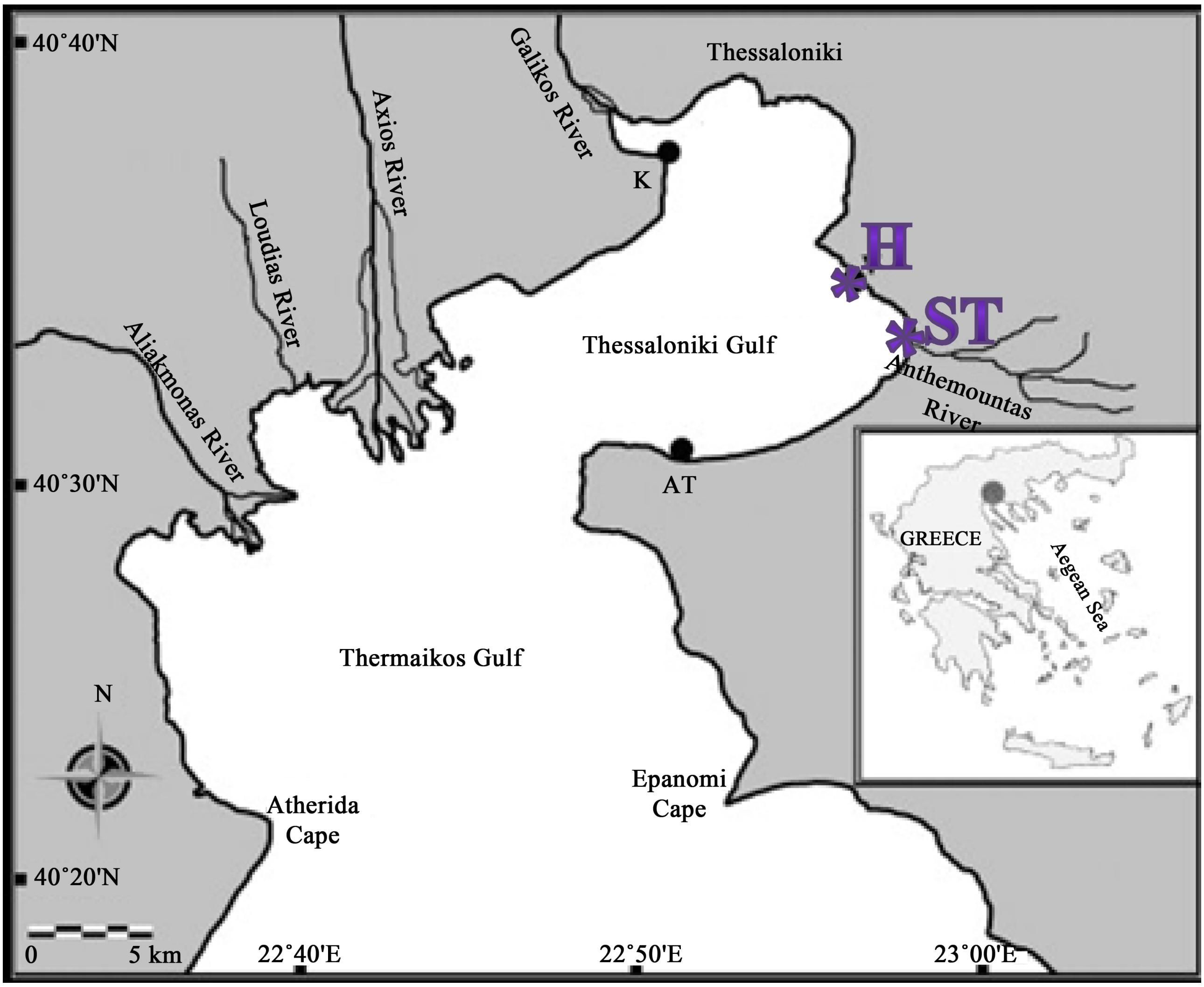

Figure 1. Thermaikos Gulf (Pell et al. 2013, slightly modified image, by adding H and ST). [H] indicates the location of the Harbor and [ST] indicates the location of the meteorological station.

Figure 2. The basic design of the harbor with the basic structural elements noted with numbers as follows: 1 shows the breakwater detached and parallel to the coastline, number 2 shows the two leeward external moles-groins with total length 155 m, number 3 shows the inner mole-pier of T shape in the middle of the basin, number 4 shows the seawalls and all the operational surfaces behind the walls and number 5 shows the land zone.

2018), the harbor consists of the following basic structural elements:

- A breakwater detached and parallel to the coastline (1 in **Figure 2**). The breakwater has a total length of 305.4 m and is placed at a distance of 195.0 m from the seawall of the harbor's waterfront and the entrance's width of the harbor is 40.0 m.
- Two leeward external moles-groins with total length 155 m (2 in **Figure 2**).
- An inner mole-pier of T shape in the middle of the basin with the length of the perpendicular to the land, part of the pier (of bridge type) 70 m and the length of the parallel part 95 m (3 in **Figure 2**).
- Seawalls and all the operational surfaces behind the walls (4 in **Figure 2**).
- Land zone (5 in **Figure 2**) which includes projects to serve the needs of the fishing shelter, such as: water supply network, sanitary facilities, fire protection network, electric lighting and special waste tanks.

2.2. The Mathematical Background

The present study was based on the development and application of a two-dimensional, mean in depth, hydrodynamic model, in order to simulate the circulation of water in the coastal environment and the renewal of waters in the basin of a marina or a fishing harbor. For this reason, the hydrodynamic model was initially applied to the greater basin in which the harbor is encapsulated.

The model simulations were applied for wind generated water circulation and for mean in the year (annual) weighted value of wind speed for all the directions of blowing winds. The equations governing the hydrodynamic circulation of the waters which can be found in Koutitas (1988) and also in Koutitas and Scarlatos (2015) are the well-known equations of momentum and mass conservation, given below:

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}=-g\frac{\partial \zeta}{\partial x}+fV+\frac{\tau_{sx}}{\rho h}-\frac{\tau_{bx}}{\rho h}+\nu_h\frac{\partial^2 U}{\partial x^2}+\nu_h\frac{\partial^2 U}{\partial y^2} \quad (1)$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}=-g\frac{\partial \zeta}{\partial y}-fU+\frac{\tau_{sy}}{\rho h}-\frac{\tau_{by}}{\rho h}+\nu_h\frac{\partial^2 V}{\partial x^2}+\nu_h\frac{\partial^2 V}{\partial y^2} \quad (2)$$

$$\frac{\partial \zeta}{\partial t}+\frac{\partial (Uh)}{\partial x}+\frac{\partial (Vh)}{\partial y}=0 \quad (3)$$

where h is the water depths i.e. the height of the water column, U & V are the mean in depth horizontal velocities of the sea currents, ζ the elevation of the sea surface, ν_h the horizontal turbulent coefficient of momentum diffusion, ρ the density of the sea water and g the gravity acceleration, f the Coriolis parameter (10^{-4} for the study area), τ_{sx} and τ_{sy} the wind shear stresses on the sea surface which are given by the following relationships:

$$\tau_{sx}=\rho\cdot C_s\cdot W_x\cdot\sqrt{W_x^2+W_y^2} \quad (4)$$

$$\tau_{sy}=\rho\cdot C_s\cdot W_y\cdot\sqrt{W_x^2+W_y^2} \quad (5)$$

where ρ is the seawater's density (1025 kg/m^3), W_x and W_y the wind velocity components 10 m above the sea surface and C_s is the surface friction coefficient with values of the order of 10^{-6} (usually between 1×10^{-6} and 3×10^{-6}) (Koutitas & Scarlatos, 2015; Koutitas, 1988), τ_{bx} and τ_{by} are the bottom shear stresses which are given by the following relationships:

$$\tau_{bx}=\rho\cdot C_b\cdot U\cdot\sqrt{U^2+V^2} \quad (6)$$

$$\tau_{by}=\rho\cdot C_b\cdot V\cdot\sqrt{U^2+V^2} \quad (7)$$

where ρ is the seawater's density (1025 kg/m^3), U and V the components of current velocity and C_b the bottom friction coefficient of the order of 10^{-2} (Koutitas & Scarlatos, 2015).

Alternatively the wind shear stresses on the sea surface can be given by the following relationships:

$$\tau_{sx}=\rho_a\cdot C_d\cdot W_x\cdot\sqrt{W_x^2+W_y^2} \quad (8)$$

$$\tau_{sy}=\rho_a\cdot C_d\cdot W_y\cdot\sqrt{W_x^2+W_y^2} \quad (9)$$

where ρ_a is the air's density (1.3 kg/m^3), W_x and W_y the wind velocity components as described above and K_s is the surface friction coefficient with values of the order of 10^{-3} (about 1.4×10^{-3}) (Beer, 1983).

The horizontal turbulent diffusion was based on the well-known Smagorinsky relationship which is described analytically in literature (Smagorinsky, 1963; Koutitas & Scarlatos, 2015).

The above differential equations are approximated by algebraic equations resulting from the application of the finite difference method, which are then encoded in the computer program using the FORTRAN programming language. In more detail, the derivatives of these well-known equations of mass and momentum conservation are approximated using explicit schemes for the finite differences' method. Time derivatives were approximated with forward differences, while the other derivatives are approximated with central differences. Concerning the mesh, a square staggered discretization grid (Arakawa C grid) was used, where *U*, *V* components are referred to the nodes' sides, while ζ is referred to the interior of each mesh as shown in Koutitas and Scarlatos (2015) (**Figure 3**).

Subsequently, after the computation of the velocity data on the mesh sides, the following half sums are computed, which refer to the mesh center.

$$Uc_{i,j} = \frac{U_{i,j} + U_{i+1,j}}{2} \quad \text{and} \quad Vc_{i,j} = \frac{V_{i,j} + V_{i,j+1}}{2} \tag{10}$$

Given that an explicit solution scheme is used, in order to provide the appropriate stability for the numerical solution the following Courant-Friedrichs-Lewy (CFL) criterion (Koutitas & Scarlatos, 2015) was applied:

$$\frac{\sqrt{2}c\Delta t}{\Delta x} < 1 \tag{11}$$

where c is the maximum phase velocity ($c = \sqrt{gh_m}$ and h_m is the maximum depth of the study area) and g is the acceleration of the gravity.

Concerning the initial conditions for the hydrodynamic model, it should be noted that model runs always started from scratch, i.e., zero water velocities and elevations.

As far as the conditions on the land-coastal boundaries are determined by the assumption of zero flow and consequently by the zero velocity normal to the land boundary of the coasts. The tangential component of the velocity is left free

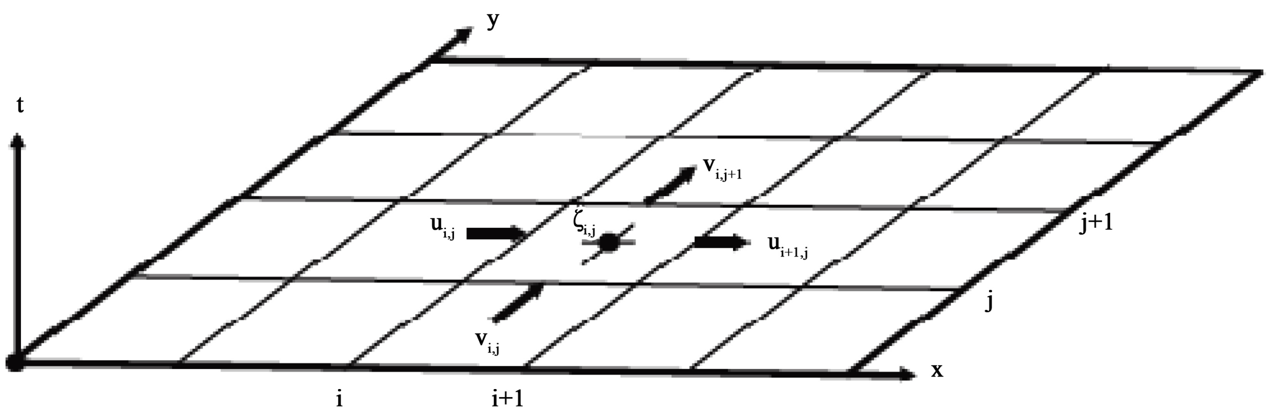

Figure 3. Computational grid for the calculation of flow characteristics (Koutitas & Scarlatos, 2015).

to develop, simulating thus any long shore currents (Koutitas, 1988).

Concerning the open sea boundary conditions the Orlanski boundary condition was applied. The interested reader can find details in (Orlanski, 1976).

The present study consisted of the two following basic successive steps:

1) the application of a two-dimensional, depth averaged, hydrodynamic model for the simulation of the water circulation in the area of Thermaikos Gulf with water depths varying from 2 m to 40 m, and discretization step $\Delta x = \Delta y = 1000$ m (forming a grid of 36 × 32 cells) and time step $\Delta t = 20$ s

2) the application of a two-dimensional hydrodynamic, depth averaged, model for the simulation of the circulation in the Harbor Basin, with water depths varying from 2 m to 5 m. In this case, the mathematical model is applied to the harbor basin after the horizontal discretization of the domain with spatial step $\Delta x = \Delta y = 5$ m (forming a grid of 72 × 72 cells) and time step $\Delta t = 0.25$ s.

This nesting approach is given in **Figure 4**.

In more detail, a coarser two-dimensional hydrodynamic model was primarily applied over the greater area of the Thessaloniki Gulf. Then, the computed sea current velocities, corresponding to the grid cell which encapsulates the harbor,

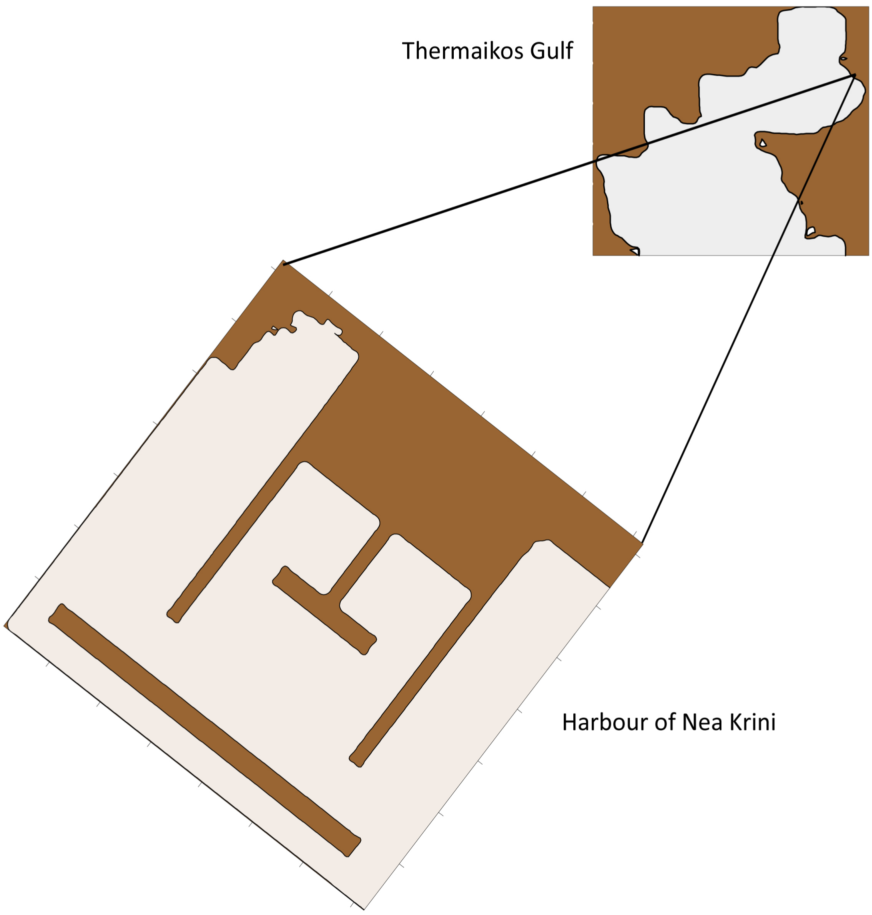

Figure 4. The computational domains of the coarse model of the Thermaikos Gulf (depicted in the small map of the upper part of the figure) and the study area of the harbor (depicted in the zoomed map of the lower part of the figure).

were applied along the northwest or southeast open sea boundary of the computational domain of the harbor basin. For the case of N, NW, NE and W winds that generate the sea water circulation over the Gulf, the current velocities, resulted by the coarser model on the cell that encapsulates the harbor domain, were applied along the northwest open sea boundary of the harbor's basin (properly interpolated) since these currents seem to contribute to the waters renewal of the harbor. Accordingly, for the case of S, SE, SW and E winds that generate the water circulation over the Gulf, the computed current velocities by the coarser model were applied along the southeast boundary of the harbor's basin. It is noted that for the study of the hydrodynamics on the harbor's basin, the model domain of the harbor is rotated at an angle of 35˚. Thus, the wind over the area and the sea current velocities on the open sea boundaries are properly projected on the x and y axis.

The above described nesting technique was successfully adopted and applied in past research studies (Savvidis & Koutitas, 2000; Savvidis et al., 2007; Papadimitriou et al., 2021).

The hydrodynamic study of the harbor waters can be supplemented by the renewal of the waters in the basin while at a next stage the concentration of BOD in the fishing harbor can be calculated for the average time of waters' renewal (corresponding to a long time period). According to this process the self-cleaning capacity of the fish harbor can be calculated and, then, alternative technical practices concerning the harbor's design can be tested.

Three different alternative scenarios, concerning the structural design of the harbor, were studied in detail (**Figure 5**).

Case A, constitutes the initial "reference" case, and refers to a compact construction, with no openings in the "body" of the moles or the central pier. Thus the only communication paths of the waters of the basin with the open sea are the two inlets of 40 m long each, between the outer edges of the moles-groins and the breakwater.

Case B results from a modification of the initial case with some openings on the external moles as well as on the internal central mole as well as on the internal central mole as well on the internal central mole. More specifically, case B is the one that better simulates the proposal of the existing, initial, study. In this case we have the construction with an opening of 5 m at the base –root of each one of the two external moles, and 5 openings of 10 meters in the inner central mole-pier. The central pier is now made of a bridge type with the construction of a deck that rests on pedestals. In this way there is communication of the waters of the basin with the open sea from the new openings in the root of the external moles. In addition, however, there is communication between the waters of the two internal basins.

Finally case C refers to a modification of the initial case with even more openings on the external moles than those of case B. In more detail, in the third case, a hypothetical construction is studied, according to which, the openings at the base-root of the outer moles-groins are enlarged from 5 m to 10 m, while

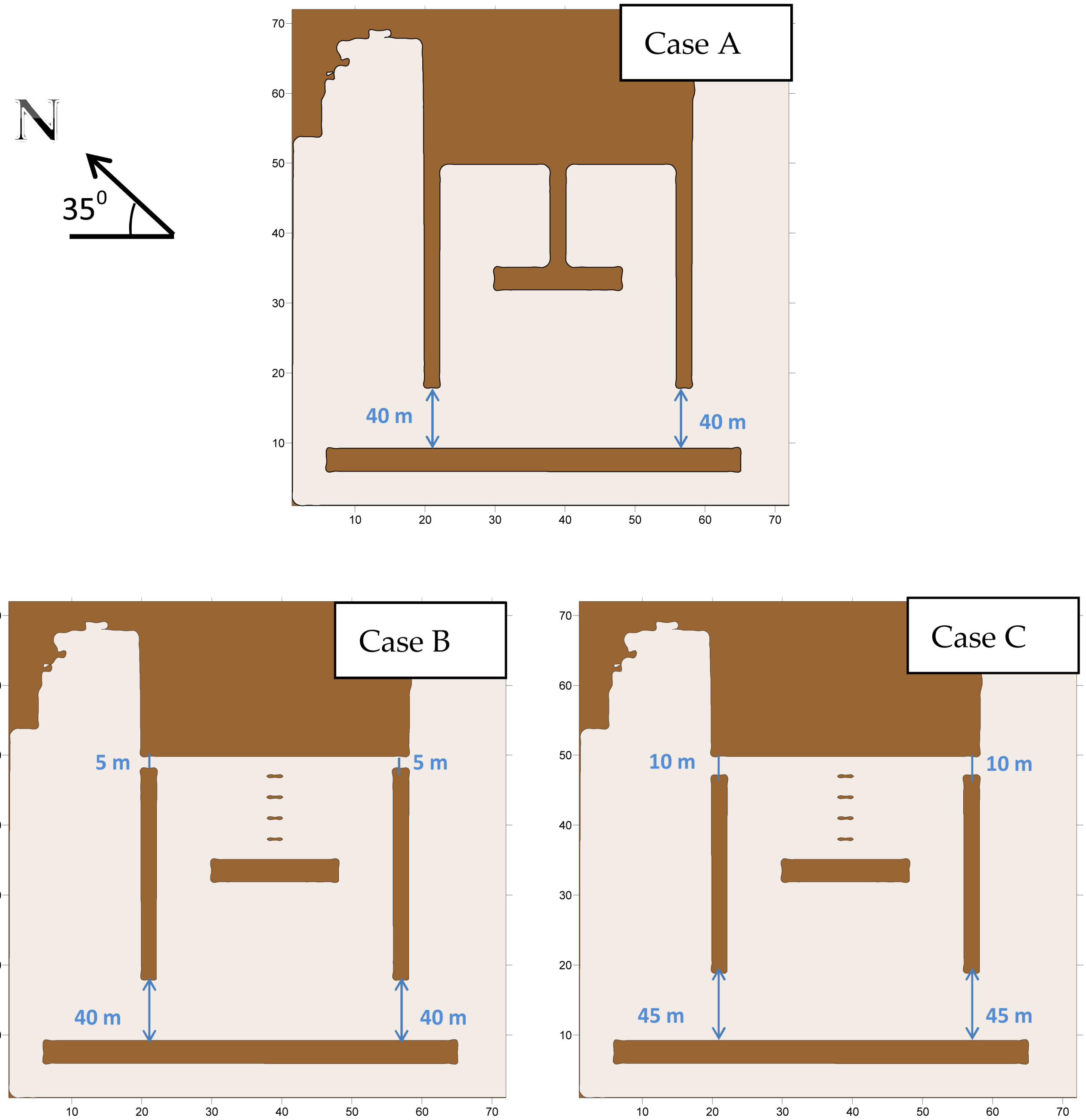

Figure 5. Alternative case studies concerning the design of the harbor. The x and y axes represent the discretization of the field in orthogonal segments (number of grid points). N indicates north direction.

another opening to the end-edge of the external moles is added (located towards the breakwater). The inner central pier remains with the 5 openings of 10 m as in case B. In this way we have increased the communication between the waters of the harbor's basin and the open sea by 20 m in total.

The value of the wind speed W which was used in the simulation was obtained from the statistical processing of a series of years and for a weighted average of the wind intensities of each different direction taking into account the occurrence frequencies f of each direction.

The weighted average intensity for north wind direction is

$$W_N = \left(W_c f_c + W_w f_w + W_m f_m + W_s f_s\right) / \left(f_c + f_w + f_m + f_s\right) \quad (12)$$

where the index c denotes calm conditions, w denotes weak wind intensity, m denotes moderate wind intensity and s denotes strong wind intensity.

Respectively, the weighted averages of intensity for the other directions of blowing winds are obtained resulting to the values of W_{NE}, W_{NW}, W_S, W_{SE}, W_{SW}, W_E and W_W.

1) Renewal time of the harbor's waters due to wind generated hydrodynamic circulation

The renewal of the waters of the harbor's basin due to the wind generated currents was then calculated by the simple equation as follows:

$$RT_{wind} = \Omega / Q \quad (13)$$

where Ω is the water volume of the study basin (m^3), Q the waters' renewal flow rate (m^3/s) due to wind generated currents which results from the half of the sum of the entering and the leaving flow rates Q_+ and Q_- respectively, and T is the waters' renewal time of the basin of the harbor (in seconds or days). The flows rates Q_+ and Q_- (resulting almost equal in steady state conditions) were computed from the currents' velocity data using the following relationships:

$$Q_+ = \sum_i \left[V_{i(+)} \times A_i\right] \quad (14)$$

$$Q_- = \sum_i \left[V_{i(-)} \times A_i\right] \quad (15)$$

where $V_{i(+)}$ and $V_{i(-)}$ are the mean in depth components of current velocity perpendicular to the line of the openings between the main harbor's basin and the greater area of the open sea, i.e. the velocity of the currents entering or leaving the inner harbor's basin respectively from the area A_i (= $\Delta x \cdot H_i$) corresponding to the cell i of the grid along the remaining opening for the free communication between the main channel and the lateral basin.

The weighted averages of water renewal in each of the three cases A, B and C are given as follows:

$$\begin{aligned} RT_{Awind} = \big(&T_N f_N + T_{NW} f_{NW} + T_{NE} f_{NE} + T_S f_S + T_{SW} f_{SW} + T_{SE} f_{SE} + T_E f_E \\ &+ T_W f_W\big) / \left(f_N + f_{NW} + f_{NE} + f_S + f_{SW} + f_{SE} + f_E + f_W\right) \end{aligned} \quad (16)$$

Accordingly the values RT_{Bwind} and RT_{Cwind} were computed for case B and case C.

2) Renewal time due to tidal effect

Although the renewal time due to tidal effects could be computed by a relevant numerical model for tidal circulation, the well-known method of tidal prism was adopted since it was considered as a simple and reliable calculating procedure which is also can be found in previous published works (Savvidis et al., 2009).

The renewal time of the harbor RT_{tide} due to the tide and the tidal renewal flow rate Q_{tide} were computed by the tidal prism (from the elevation data of the sea surface due to tide). RT_{tide} and Q_{tide} are related through the following equation:

$$RT_{tide} = \Omega / Q_{tide} \tag{17}$$

where Ω is the water volume of the study basin (m^3).

The water volume which is exchanged between the harbor's basin and the open sea in a tidal period constitutes the "tidal prism". The volume of the tidal prism is

$$V = S \times (2 \times \alpha) \tag{18}$$

where S is the area of the sea surface of the harbor and α is the amplitude of the tide (half of the tidal height) and consequently the renewal time of the harbor due to the tidal signal is given by the following relationship:

$$RT_{tide} = (\Omega / V) \times T_{tide} \tag{19}$$

where T_{tide} is the tidal period

The ultimate mean renewal time RT due to tide and wind is finally given by the following equation:

$$RT = \frac{1}{\frac{1}{RT_{tide}} + \frac{1}{RT_{wind}}} \tag{20}$$

The computation of the renewal time of harbor waters does not give concrete information about the environmental state of the waters, which however can be drawn from the estimation of self-purification capacity of the harbor waters through assessing the BOD concentrations of the waters. This latter parameter is described in the following paragraph.

3) Self-purification capacity of the harbor waters

The computation of the waters' renewal time allows for the subsequent calculation of the harbor's self-purification capacity. In more detail, the harbor's self-purification capacity, is computed from the mean renewal time T (here RT) of the harbor's waters, and the harbors waters' volume Ω, and the polluting load q that corresponds to sewage waters of a maximum number of the people on all the vessels moored in the harbor at the same time (i.e. q is the entering flow discharge) and the concentration C_o of BOD of untreated sewage (220 - 400 mg/lit, here 400 mg/l) and the biodegradation coefficient λ which for urban sewage is of the order of 0.1 per day (Tchobanoglous & Burton, 1991). A maximum value C_{max} of BOD in the basin, of the order of 5 mg/lit is considered as acceptable. The present study considers 1000 people on the boats. Taking into account a mean value of sewage, 200 lit per person per day, then a load of $q = 200\ m^3/day$ (1000 × 200 lit/day) is used for our computations. In order to avoid eutrophic problems in the harbors' basin the parameter BOD can then be calculated since it is one of the most important environmental indicators. Subsequently the mean concentration C, of BOD in the harbors' basin is given by the following relationship (Koutitas et al., 1996; Savvidis et al., 2017):

$$C = \frac{q \times C_o}{q + (\Omega/T) + \Omega \times \lambda} \tag{21}$$

3. Results

As it was referenced in the previous sections, the hydodynamics focused on the renewal time of the harbor's waters in relation with the calculations of BOD concentration in the waters, was the key process in odrer to evaluate the environmental condition of the harbor's waters. The basic factors that were under consideration for the relevant computiations concerned the wind and tidal influence.

The wind data were kindly provided by the Hellenic National Meteorological Service, from Macedonia Airport Station, (2009-2017). After the relevant statistical process (Karaberi, 2019) the relevant percentages are given **Table 1**. These wind data were taken from the closest (to the harbor) met station. As far as for the case of the extended area of the Gulf the assumption of the same wind forcing over the whole area of the gulf was adopted.

The calculations, concerning the mean wind speed of different directions, show that in all cases the weighted average wind intensity is approx. 3.5 m/s. This value (i.e. 3.5 m/s) obviously corresponds to a weak wind and its adoption for the calculations of the renewal times constitutes definitely the worst possible scenario that could be taken into account (since the wind generated currents are low leading thus to large renewal times of the harbor's basin).

Applying the hydrodynamic model described in Section 2, for the study of wind generated circulation forced by the most frequent NW winds with mean speed of 3.5 m/s the following water circulation patterns were resulted for the sea currents of the Thermaikos Gulf (**Figure 6**) as well as for the sea currents of the harbor basin (**Figures 7-9**) for each one of the three cases, A, B and C. It is

Table 1. Wind Direction and Wind Speed. (Data provided by the Hellenic National Meteorological Service, from Macedonia Airport Station, (2009-2017) and processed by Karaberi (2019)).

Frequency of Wind Directions %									
Wind intensity	N	NE	E	SE	S	SW	W	NW	Variable wind
Calm	3.43	0.23	4.86	3.98	3.01	0.84	4.21	5.67	6.16
Weak	6.06	0.40	8.58	7.04	5.32	1.49	7.44	10.01	10.87
Moderate	1.04	0.07	1.47	1.21	0.91	0.25	1.27	1.72	1.86
Strong	0.07	0.00	0.09	0.07	0.06	0.02	0.08	0.10	0.11
Gale	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SUM	10.60	0.70	15.00	12.30	9.30	2.60	13.00	17.50	19.00

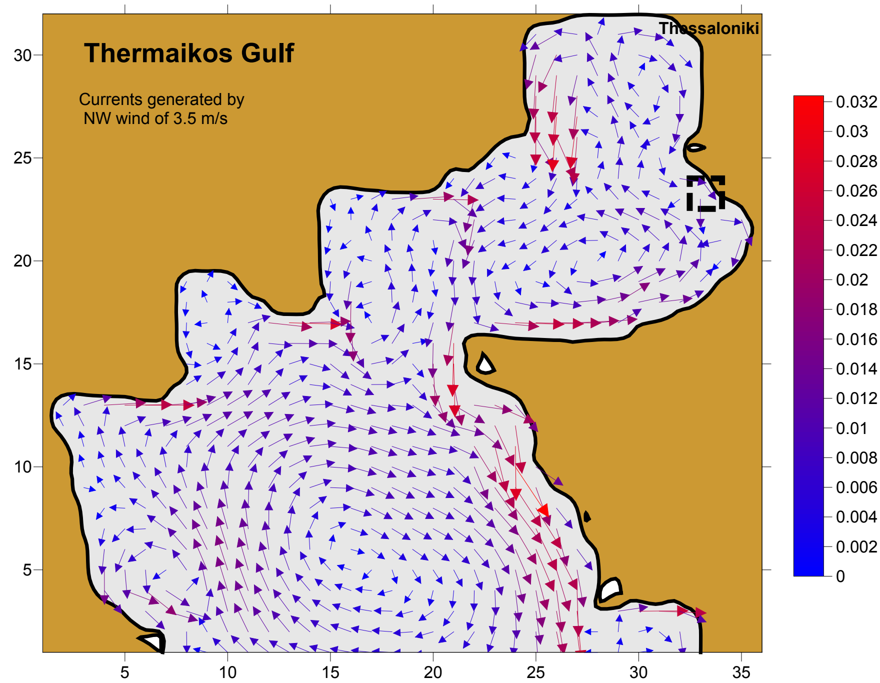

Figure 6. The wind generated currents due to NW wind of 3.5 m/s for the greater area of Thermaikos Gulf. In X and Y axes the discretization of the field in orthogonal segments is shown (number of grid points). The velocity speeds vary between ~0.001 m/s (blue vectors) and 0.03 m/s (red vectors).

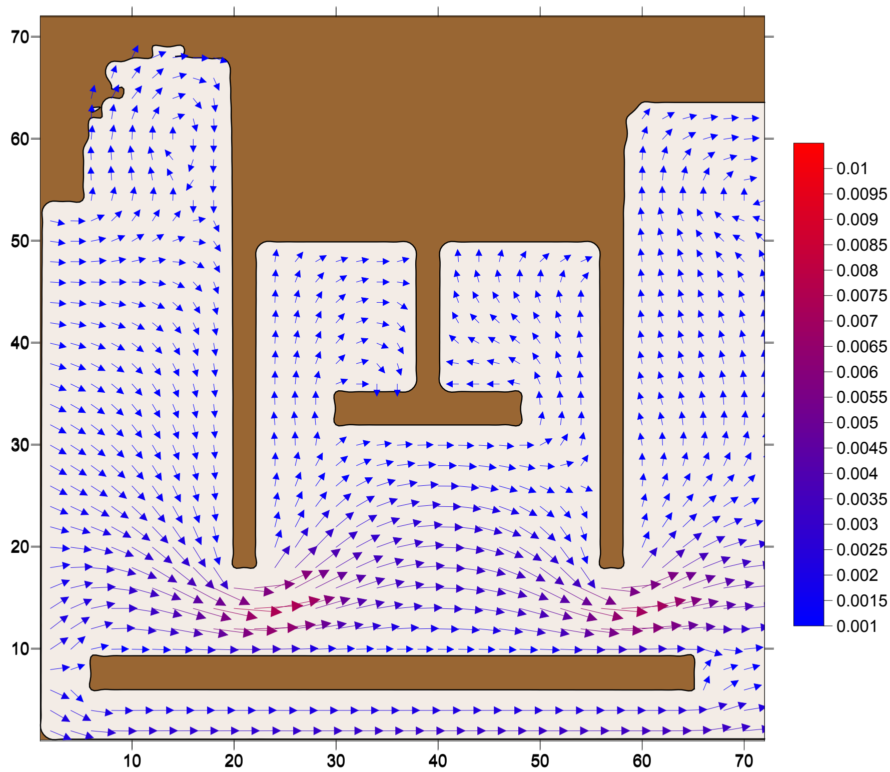

Figure 7. The wind generated sea currents due to NW wind of 3.5 m/s for case A In X and Y axes the discretization of the field in orthogonal segments is shown (number of grid points). The color scale corresponds to the current velocity speeds.

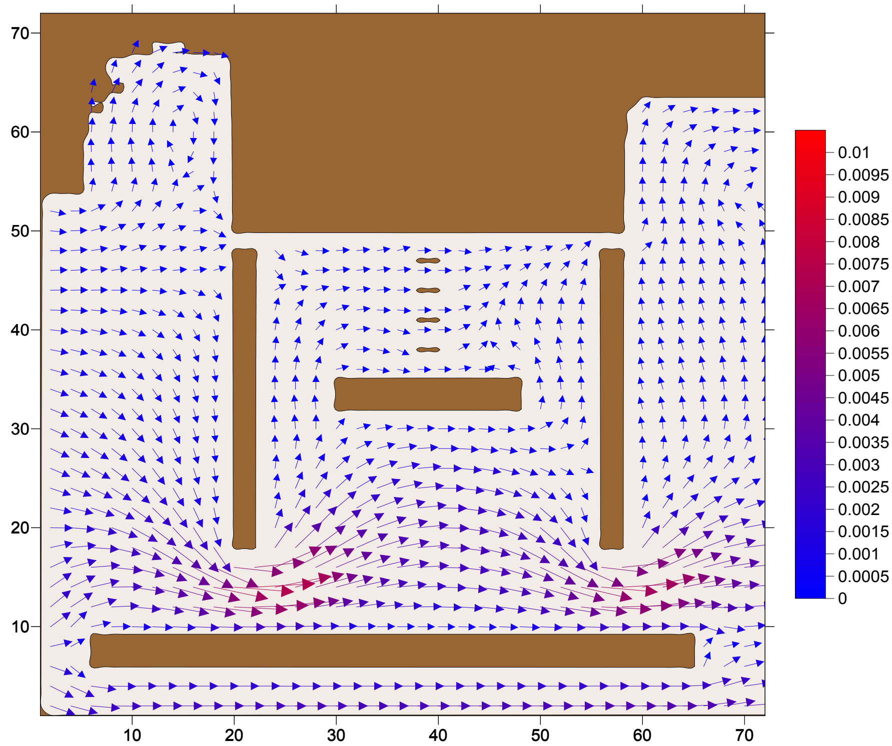

Figure 8. The wind generated sea currents due to NW wind of 3.5 m/s for case B. In X and Y axes the discretization of the field in orthogonal segments is shown (number of grid points). The color scale corresponds to the current velocity speeds.

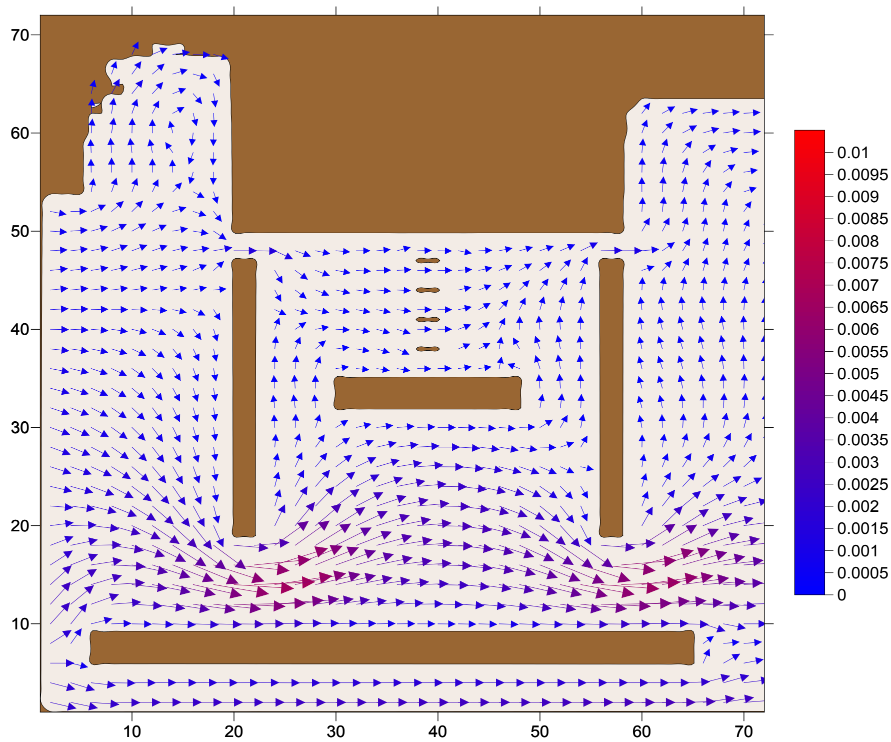

Figure 9. The wind generated sea currents due to NW wind of 3.5 m/s for case C. In X and Y axes the discretization of the field in orthogonal segments is shown (number of grid points). The color scale corresponds to the current velocity speeds.

noted here that all the different wind directions were considered in the present study; however only the pattern of sea currents generated by NW wind was given, as an indicative case as well as the most representative one. Besides it is well known that NW winds dominate over the area of Thermaikos Gulf (Hyder et al., 2002).

It should be noted that four rivers are inflowing on the west coasts of Thermaikos Gulf (Galikos, Axios, Loudias and Aliakmonas), as shown in **Figure 1**, however the influence of the river water discharges, is not important, and they are neglected in the present study. More specifically, there are several decades since now that these riverine inflows have been dramatically reduced (Savvidis & Koutitas, 2000; Hyder et al., 2002) In addition there is a small river (Anthemountas) inflowing on the coastal area south of the harbor's basin, (shown in **Figure 1**), but that flow is also of minor importance and most of the time with zero values. Furthermore, the water depths of the basin are generally quite shallow. Consequently the assumption of barotropic circulation on the basin of Thermaikos Gulf can be generally considered as realistic.

Figure 6 shows that, under the influence of NW winds, two eddies are formed near the south boundary of Thermaikos Gulf. More specifically a clockwise circulation is developed just over the southern boundary forming a large eddy in the central part of the gulf; also an anticlockwise circulation is developed with a small eddy, limited in the west part. The two eddies near the south boundary, distributed almost equally over the south part of the basin, are also formed by the influence of NNW wind and can be found in international bibliography (Poulos et al., 2000; Ganoulis, 1994; Volakos et al., 1998).

Hydrodynamic wind generated water circulation due to NW wind of 3.5 m/s (Case A).

The area of the water surface of the basin is 31,050 m^2 while the volume of the waters of the basin is 123038.5 m^3.

Figure 7 also shows clearly the inflow of waters along the northwest boundaries of the harbor and the waters outflow from the southeast open boundaries, as well as the trend of a formation of two anticyclonic eddies (clockwise movement) on either side of the central pier. Current intensities seem to be very low and especially below 0.008 m/s.

Hydrodynamic wind generated water circulation due to NW wind of 3.5 m/s (Case B).

The area of the water surface of the basin is 31,925 m^2 while the volume of the waters of the basin is 125783.5 m^3

As shown in **Figure 8**, a large clockwise movement tends to be formed around the horizontal part of the central pier as in this case the holes allow the circulation of water between the smaller sub-basins. The sea currents are quite low (below 0.007 m/s). Similarly, in this case, the renewal of the waters takes place mainly through the northwestern openings while the outflow takes place mainly through the southeastern opening. The renewal of the harbor waters is enhanced by the small openings at the base of the external piers, where in particular the entrance through the small opening at the base of the northwest (left) mole and the exit through the small opening at the base of the southeast (right) mole.

Hydrodynamic wind generated water circulation due to NW wind of 3.5 m/s (Case C).

The area of the water surface of the basin is 32,175 m^2 while the volume of the waters of the basin is 126,746 m^3.

As shown in Figure 9, the pattern of the hydrodynamic circulation in case C, is similar to that of case B. The currents are very low and specifically lower than 0.0065 m/s. The water renewal takes place through the openings formed between the end of the outer moles and the breakwater. In particular, the inflow of waters takes place from the open sea on the left (northwest opening) while there water outflow which takes place mainly through the opening on the right (southeast opening. The water renewal is enhanced even more by the small openings at the base of the external moles.

Finally, the waters' renewal times due to wind generated circulation, computed by the model runs for all the wind directions, are given in Table 2. It is noted here, that in all case the values of current velocities are very low, because the currents are generated by weak winds. Moreovere, these velocities correspond to mean in depth current intensities.

Table 2. Renewal time of waters, due to wind generated currents for all the wind directions blowing over the harbor.

	N	NW	NE	S	SE	SW	E	W
Case A								
Renewal Time RT_{wind} (days)	1.25	1.52	2.33	2.30	2.51	3.47	4.96	4.26
Case B								
Renewal Time RT_{wind} (days)	1.21	1.46	2.24	2.26	2.47	3.41	4.83	4.10
Case C								
Renewal Time RT_{wind} (days)	1.15	1.40	2.16	2.20	2.41	3.33	4.72	4.03

3.1. Renewal Time of Waters of the Harbor's Basin Due to Wind

The weighted averages of waters renewal in each of the three cases A, B and C, according to Equation (12) are given in Table 3.

Table 3. Renewal time of the harbor's waters due to wind generated currents.

Renewal time of waters of the harbor's basin due to wind (days)		
RT_{Awind} **(case A)**	RT_{Bwind} **(case B)**	RT_{Cwind} **(case C)**
2.87	2.79	2.71

It is obvious that Case A leads to the higher value of the water renewal followed by Case B and Case C respectively. Of course, the lowest renewal times show better environmental state since the water of the basin is renewed more quickly.

3.2. Renewal Time of Waters of the Harbor's Basin Due to Tide

The region is characterised by weak tides (Hyder et al., 2002; Tsimplis, 1994; Kombiadou & Krestenitis, 2012; Savvidis et al., 2005) with very weak currents (of the order of 1.5 cm·s^{-1}) and mean tidal height 0.25 m (Savvidis et al., 2005). Taking into account the mean tidal hight of 0.25 m (i.e. tidal aplitude of α = 0.125 m) simple calulations can follow as given just below.

The volume V, of water exchanged between the harbor basin and the open sea in a tidal period i.e. the "tidal prism", is given by the Equation (18), where S is the Area of the harbor's basin which for the three cases has the following values: S_A = 31,050 m^2 for Case A, S_B = 31,925 m^2 for Case B, and S_C = 32,175 m^2 for Case C.

Taking into account the corresponding volumes of the waters of the harbor's basin, ΩA = 123038.5 m3 for Case A, ΩB = 125783.5 m3 for Case B, and ΩC = 126,746 m3 for Case C as well as the tidal period, T = 12 hrs (43,200 seconds) the renewal time of the harbors waters due to tide results from Equation 19.

Concequently, the waters renewal in each of the three cases A, B and C are given in **Table 4**.

Table 4. Renewal time of the harbor's waters due to tide.

Renewal time of waters of the harbor's basin due to tide (days)		
RT_{Atide} **(case A)**	RT_{Btide} **(case B)**	RT_{Ctide} **(case C)**
7.93	7.88	7.87

The above results show that renewal times due to astronomical tide in the region are 2.5 to 3 times higher than the renewal times due to winds blowing over the area. However, since these two different phenomena develop in parallel the combined effect of these two external factors to the renewal of the harbor waters needs to be determined. It is interesting to note that the mean tidal signal is a relatively fixed variable for an area (even if the study examines the high and low tides) and consequently the waters renewal due to tidal effect is calculated as a function of the topographical-geometrical characteristics of the harbor. On the other hand, the winds blowing over an area can vary significantly in both intensity and direction and consequently the waters renewal due to winds can vary quite a lot, since they respectively determine the sea currents that enter and leave the harbor basin. It is reminded here, that the winds and tides constitute the prevailing factors that generate hydrodynamic circulation and renewal of the waters of the harbor basin in the study area.

3.3. Renewal Time of Waters of the Harbor's Basin Due to Winds and Tide

The renewal times due to the combined effect of winds and tide is given to **Table 5**.

Table 5. Renewal time of the harbor's waters due to winds and tide.

Renewal time of waters of the harbor's basin due to winds and tide (days)		
RT_A (case A)	RT_B (case B)	RT_C (case C)
2.10	2.06	2.01

Therefore, based on Equations (20) and (21), the combined effect of wind and tide lead to the following results for the waters renewal time and the mean concentration of BOD in the harbors' basin:

Case A RT_{wind} = 2.87 days and RT_{tide} = 7.93 days which leads to a mean resultant renewal time of the harbor waters RT_A = 2.10 days or 50.4 hours. and a mean concentration of biochemacally oxygen demand BOD_A = 1.13 mg/lt.

Case B RT_{wind} = 2.79 days and RT_{tide} = 7.88 days and respectively.

RT_B = 2.06 days or 49.44 hours and a mean concentration of biochemacally oxygen demand BOD_B = 1.08 mg/lt.

Case C RT_{wind} = 2.71 days and RT_{tide} = 7.87 days and respectively.

RT_C = 2.01 days or 48.24 hours and a mean concentration of biochemacally oxygen demand BOD_C = 1.05 mg/lt.

4. Summary and Conclusions

The present study shed light on the following points:

- In all the three cases A and B the renewal times due to the combined effect of winds and tide are approx. 2 days. The renewal time due to the winds, prevailing over the study area, ranges from the order of 1 or 2 days for winds of north or south directions to 4 or 5 days for winds of west or east directions. The renewal time due to tide is nearly 8 days.
- In each one of the three cases the time renewal of the waters due to the wind under the specific wind conditions (with prevailing weak winds) are about 3 times lower than the renewal time due to tide.
- It is obvious that if moderate or strong winds are taken into account, the water renewal times are expected to be greatly reduced which of course lead to even better environmental conditions.
- According to the wind climate of the study area the lower renewal times (and higher renewal rates respectively) are those due to N winds while the relevant lower renewal times correspond to E winds.
- As for the openings in the inner central pier, although they do not affect the ultimate renewal of the waters of the harbor basin as a whole, they obviously affect the waters renewal of the sub-basins. It is obvious from the water circulation that their construction is considered very important since it allows

the water to move between the two sub-basins on either side of the central pier.

- In each of the three cases that were studied, the BOD concentrations for 1000 people in the harbor are much lower than the maximum acceptable values in terms of the self-cleaning capacity of the harbor, i.e. 5 mg/l. From this point of view, the construction of the external moles without openings would not create significant differences or severe problems except in prolonged periods of calm conditions. Based on the statistical investigation, it seems that the case of calm conditions reaches 25%, which is not a negligible percentage. So the design of the moles with the openings that allows the water to move freely is rather positive.

Based on the above presented points, it seems that case B and case C are the best alternative solutions (with case C being more recommended) because of the exchange of water masses between sub-basins of the harbor since they allow the water circulation to develop in the harbor through the openings of the central pier.

The present study shows that the significant tool of the numerical models can help the engineers and researchers to study effectively and possibly modify and adapt a project so that a more friendly design to the environment can be ensured.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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