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Hydrodynamic Simulation of the Pagasitikos Gulf, Greece

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Abstract

Semi-enclosed sea basins have difficulty in recharging their waters due to limited communication with larger water bodies, with understandable consequences for their environmental status. This paper aims at the computational simulation of the hydrodynamic characteristics of the waters of the Pagasitikos Gulf (Greece), which has limited communication and water exchange with the Aegean Sea and is subject to intense environmental pressures The Estuary, Lake & Coastal Ocean 3d hydrodynamic Model (ELCOM 2.2) combined with its later version Aquatic Ecosystem Model-3d (AEM3D) were used for the simulation. The simulation included the topography of the area, the bay's bottom geometry, atmospheric loadings, tides, the influence of the Coriolis force and boundary conditions. The hydrodynamic behaviour of the bay, water circulation, velocities at the surface and in depth, water recharge and residence time throughout the bay, density variation and other factors were examined to determine the impact of all these on the aquatic ecosystem.

Keywords

Hydrodynamic Simulation, Semi-Enclosed Sea Basins, Pagasitikos Gulf, Greece

1. Introduction

The Pagasitikos Gulf is located in the prefecture of Magnesia in Northern Greece, communicating with the North Eubian Gulf and the Western Aegean Sea. It is a semi-enclosed almost round sea area (Figure 1) defined by the Chalkodonio mountain to the north, Mount Othris to the southwest, the mountain ranges of Pelion to the east and communicating with the Aegean Sea through the channel between Trikeri, Magnesia (east). In antiquity the country of the Magnesians occupied the whole of the curious horizontal division of the Magnesian peninsula, the south-eastern part of which, turned to the west, forms the leeward Pagasitic Gulf, named after the Pelasgian city of Pagasai, etymologically related to the verb "to ship". The area under study is subject to intense environmental pressures and is also characterised by its semi-enclosed morphology, which allows only limited communication with the open sea. One of the most important problems of semi-enclosed sea basins is the difficult mechanism for the renewal of the waters and their long residence time in the bay. The intense urbanisation and industrialisation of the area result in increased pollution of the bay. Given its economic, cultural and scientific importance for the development and evolution of the societies around, it has been the subject of a considerable number of studies mostly measurements from 1975 up to 2000. In recent years mainly assessment work has been carried out to record and analyse its physical, chemical and biological characteristics [1]-[10]. Similar simulations of other marine areas near Pagasitikos Gulf based on the models of Hodges and Dalimore have been carried out by researchers such as Kopasakis K., Konidaris A., Angelidis P., Kotsovinos N. [11]-[18] with remarkable results.

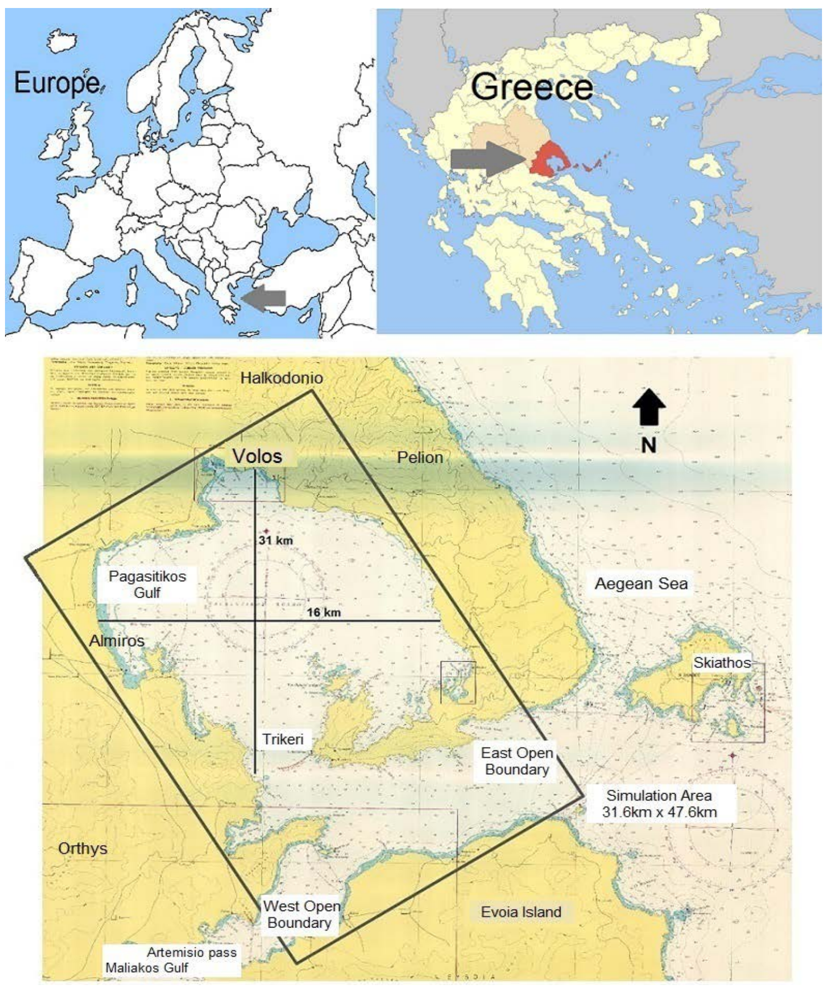


Figure 1. Pagasitikos Gulf map including the simulation area.

In the present study, the hydrodynamic characteristics of the Pagasitikos Gulf waters were simulated by computer. In the present study, the hydrodynamic characteristics of the Pagasitikos Gulf waters were simulated by computer. The Estuary, Lake & Coastal Ocean 3d hydrodynamic Model (ELCOM 2.2) was used for the simulation, combined with the improved Aquatic Ecosystem Model-3d (AEM3D) of Hydronumerics. The topography of the area, bay bottom geometry, tides and atmospheric loads were introduced with real meteorological conditions such as wind speed and direction, precipitation height, air temperature, solar radiation, atmospheric pressure, relative humidity. The hydrodynamic behaviour of the bay, water circulation, velocities at the surface and in depth, water recharge and residence throughout the bay area, changes in density, salinity and other variables were examined. The ultimate objective of the study is to predict the potential future environmental stress of the semi-enclosed marine basin under consideration, in order to explore ways of prevention to improve it. The methodology of this study and its conclusions will be useful in the study of other similar semi-enclosed sea basins.

2. Methods

2.1. Study Area

Geomorphologically Pagasitikos Gulf is a relatively shallow bay (average and maximum depth of 70 m and 101 m), in a basin-shaped area with a pronounced relief. In the western and northern part of the bay the bottom is smoothly sloping, while the eastern coast has a steeply sloping bottom. The coastline has several indentations, the largest of which form the bays of Volos and Almiros. The wider basin of the bay is an intercontinental basin with a total surface area of 165 Km^2 and an average volume of 36 Km^3. Its largest dimensions from north to south are 31 Km and from east to west 16 Km (**Figure 1**), while at the southern point of contact with the North Euboean and West Aegean Seas, at Cape Trikeri north of Evoia, it has an opening of 5.6 Km and an average depth of 75 m.

2.2. The ELCOM&AEM3D Hydrodynamic Models

The hydrodynamic-thermodynamic models ELCOM 2.2 and AEM 3D used simulate the behaviour of stratified flows over time, under the influence of environmental loads, in lakes and enclosed seas. The numerical method used by ELCOM solves the non-steady Navier-Stokes equations for incompressible flow. For the horizontal turbulence the Reynolds averaged Navier-Stokes equations are solved, the turbulence closure is realized by a turbulent coherence coefficient, while for the vertical turbulence a vertical mixing layer model is used [11] [12]. The transfer of passive and active gradient quantities (e.g. indices, salinity and temperature) is performed using the conservative ULTIMATE QUICKEST semi-selective discretization method [13]. The evolution of the free surface is based on the vertical integration of the continuity equation for incompressible fluid. Each water column in the model includes the effect of wind on the upper layer momentum, heating-cooling of the surface layer through heat exchange with the atmosphere, short-wave solar radiation, evaporation, sensible heat (direct heat transfer from the water surface to the atmosphere), long-wave radiation and precipitation.

Both models produce and store final results of quantities such as velocity (component and components) at the surface and at depth, direction of water movement, water temperature, density, residence time and water recharge. The results can be recorded in the three directions and displayed in surface images, vertical sections and horizontal sections at any point in the computational domain. The two models were preferred over others (POM, HYCOM) as they have been successfully used in the past in simulations in Greece [14]-[22].

2.3. Model Setup

A simulation area of 47.6 km by 31.6 km (**Figure 2**) with a surface area of 1504 Km^2 was selected and created, enclosed by the shorelines of the Pagasitikos Gulf and North Evoia, with two open sea cross-sections to the left and right south of the Trikeri Channel. The first is located in the Artemisio Strait (east of the Maliakos Gulf) and the second is located east of the narrowest point between North Evoia and the southern coastline of the Pagasitikos (west of Skiathos). This field gives us ideal simulation conditions as it has no large open sea boundaries, is enclosed by solid boundaries with two relatively small and bounded open sections where boundary conditions are very well applied. The parts of the digitized maps are the whole Pagasitikos Gulf, and a part of Northern Evoia. Two maps (1:500,000 scale) were processed and digitized simultaneously for point depths, isobaths and shorelines. Considering the morphology of the bay, the surface size and the final shape of the computational field, successive tests were performed to determine the number of active water cells that the ELCOM 2.2 preprocessor could marginally read [13]. A fixed dimension of computational discretization cells of 400 m × 400 m was chosen, and the whole field was rotated by 32.1o clockwise so that the inflows and outflows at the open boundaries were horizontal. The construction of the simulation canal and the computational grid was done with Terrain and Surface Modeling type software, generated files that can be used in ELCOM 2.2. and resulted in the computational field depicted (**Figure 3**).

The Pagasiticos Gulf has depths up to and over 100 m marginal (maximum simulated depth −105 m), it was chosen not to round off the depths, so up to the deepest elevations were included and simulated and an accurate calculation was made for each of the 9401 computational cells of the seabed obtained by linear interpolation and using topographic software. The result was to obtain accurate altitudes (depths) in all the computational cells, so the bottom geometry of the bay was simulated in maximum detail (**Figure 3**). In order to have a smooth solution without numerical instability and achieve the highest possible accuracy in the vertical distribution of all considered parameters (velocities, temperatures, densities, etc.) 42 horizontal layers of constant height dz = 2.5 m were defined and a 3D grid of 394,842 cells with constant layer thickness. Thus uniformity of the levels was ensured as recommended by the authors for a simulation like this [11] [13].

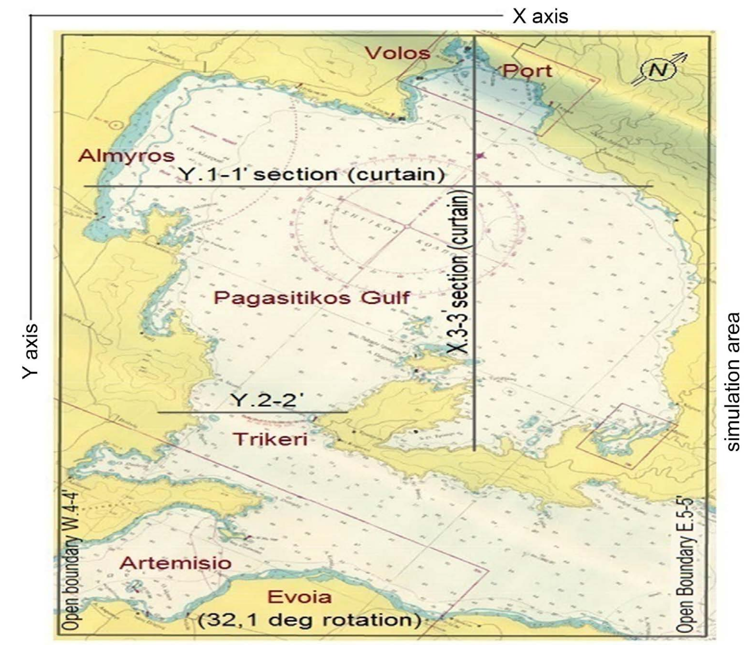


Figure 2. Simulation area (32.1˚ rotation), vertical sections and open boundaries.

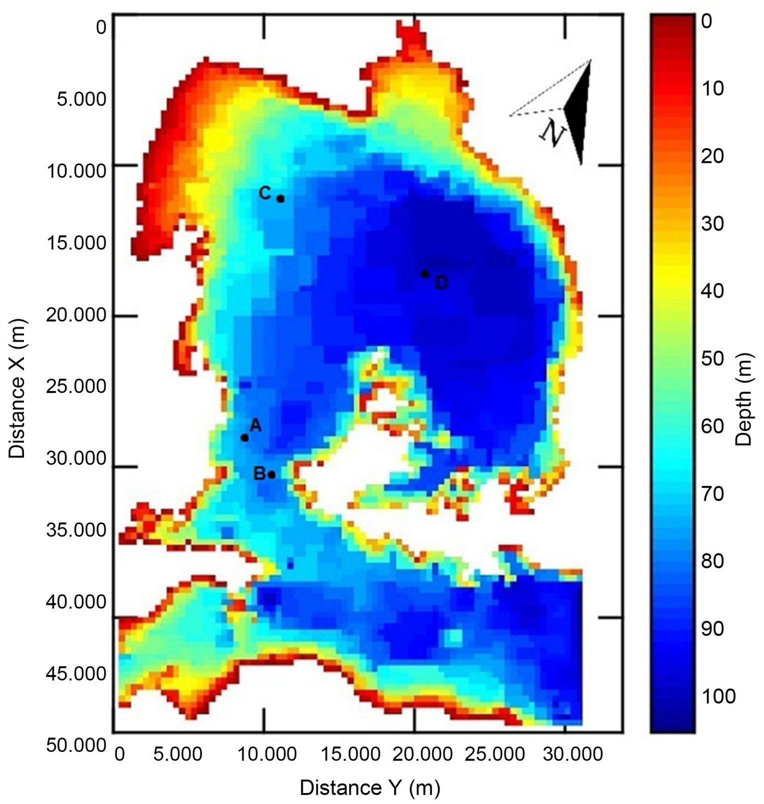


Figure 3. Bathymetric map of Pagasitikos Gulf simulation area (ELCOM 2.2) (including A, B, C, D measurement positions).

The recording and visualization of results was defined to be done in the horizontal layers corresponding to the following depths (layers): surface 0 m, 2.5 m, 5 m, 7.5 m, 10 m, 12.5 m, 15 m, 20 m, 25 m, 35 m, 45 m, 55 m, 75 m, 95 m and bottom. It has been observed that although the main mixing of the water masses occurs in the upper water layers, over time it reaches the deeper water layers and up to the bottom [16] [23]. Thus, the vertical discretisation was done in order to simulate more accurately the bay from the surface to 15 m where the phenomenon mainly develops, but also to have a representation of the phenomenon deeper down to the bottom without overburdening the execution of the computer code [20]. In addition, the following vertical results recording sections from the surface to the bottom (curtains) were constructed:

1) two perpendicular to the Y-axis at the height of Almiros (section Y.1-1') and at the entrance of the bay at the height of Trikeri (section Y.2-2'); and

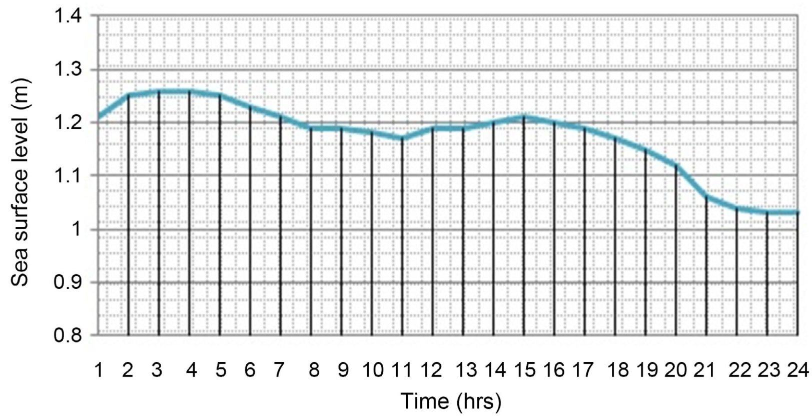
2) one perpendicular to the X-axis passing through the port of Volos (section X.3-3') (**Figure 2**). A turbulent bed boundary condition with a constant friction coefficient was applied to the bottom.

The two open sea sections of the field are one to the east (E.5-5') where the study area is connected to the Aegean Sea and one to the west (W.4-4') in the Artemision Strait (**Figure 2**). At these locations two "open" boundary conditions of 10km and 5.2km length respectively were simulated in which free inflow and outflow of water from each cell is allowed according to the conditions prevailing at each computational step. Simulated sea level variation at the Eastern boundary (E.5-5') for a full year was simulated by importing a time series of actual measurements from the Navy Hydrographic Service from the nearest tide gauge to the area located near Skopelos Island, which are hourly sea level values. By inputting the sea level difference at the Eastern open boundary, the model automatically generates the corresponding velocities [12] and calculates sea level differences across the field as well as at the Western open boundary (**Figure 4(a)** & **Figure 4(b)**).

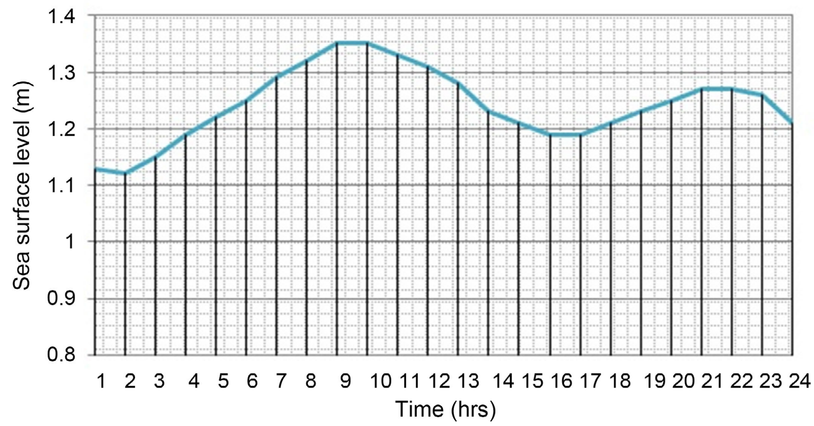
The atmospheric loading of the field was simulated by importing one year of meteorological data from the Institute for Environmental Research and Sustainable Development of the National Observatory of Athens [24] (wind speed and direction every 10 min) and data from the weather station of the University of Volos (solar radiation, temperature, humidity, atmospheric pressure, precipitation every 5 min) (**Figures 5(a)-(d)**).

The initial salinity and temperature conditions at the start of the simulation in all cells were 16.10˚C and salinity 37.40 psu, which are average values from measurements taken outside the bay [25].

In order to select the optimum simulation recirculation time step (dt), a sensitivity analysis was performed for time step values of 60 sec, 120 sec, 180 sec, 240 sec and the calculated velocities at four locations in the bay and at specific depths were compared with recorded velocity measurements with autographic current recorders [26]. The points A, B, C, D where the field measurements were held, were simulated in the computational domain with accuracy (**Figure 3**). The optimum time step dt = 180 sec was finally chosen as dt = 180 sec as the resulting velocities are closest to the measured values.

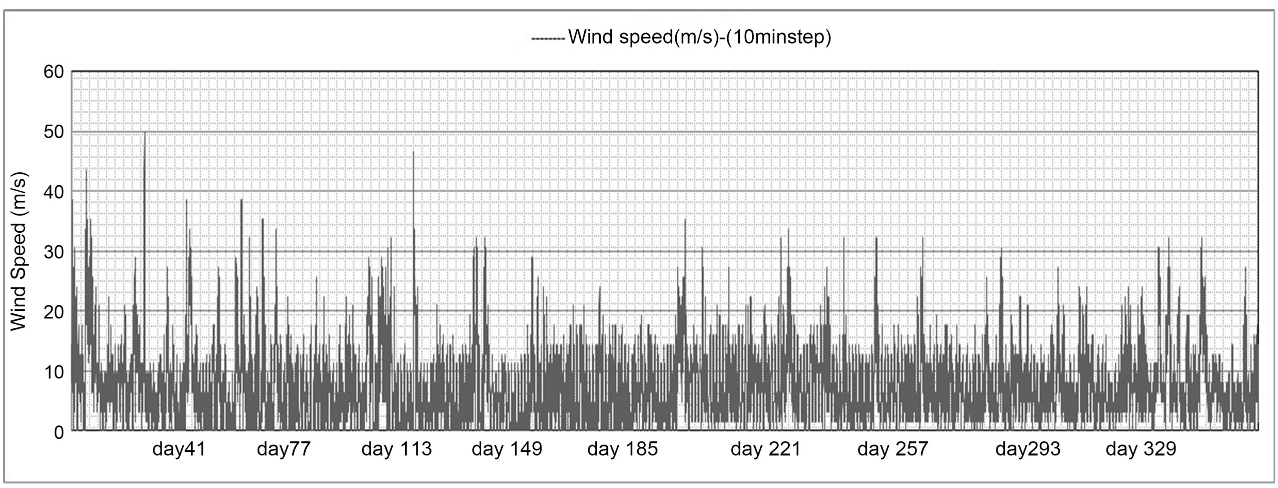


(a)



(b)

Figure 4. (a) 24 hours sea level change at East open boundary E.5-5'. (b) 24 hours sea level change at West open boundary W.4-4'.



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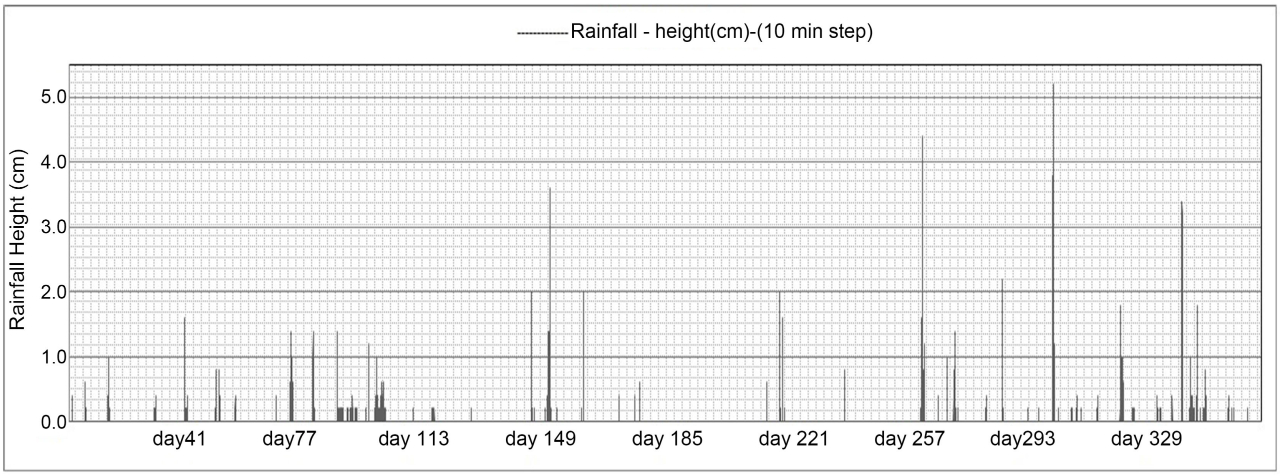

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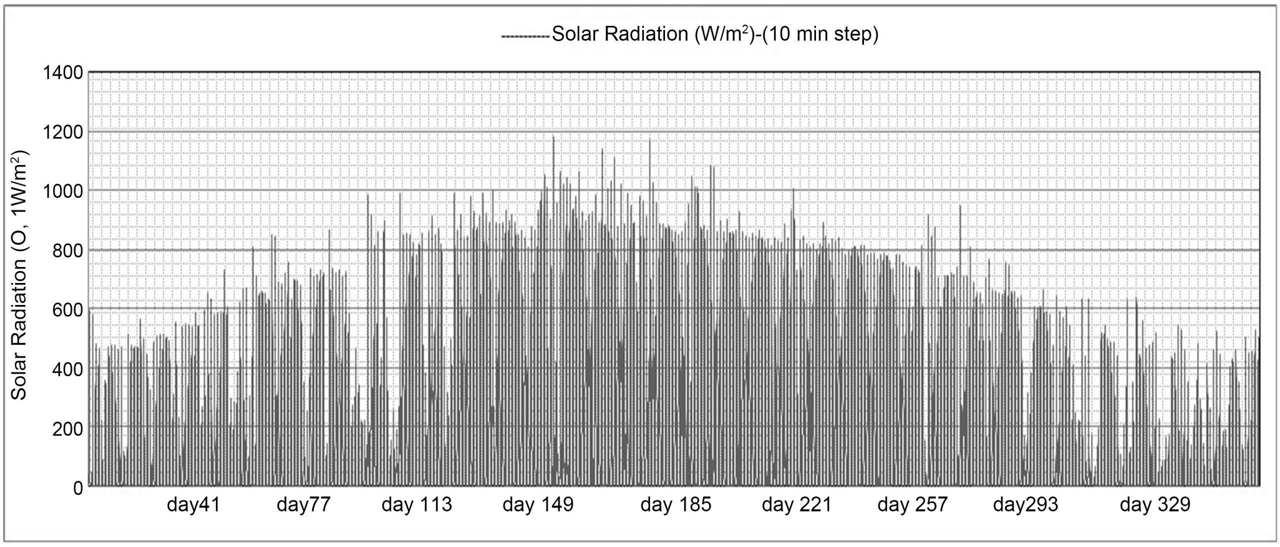

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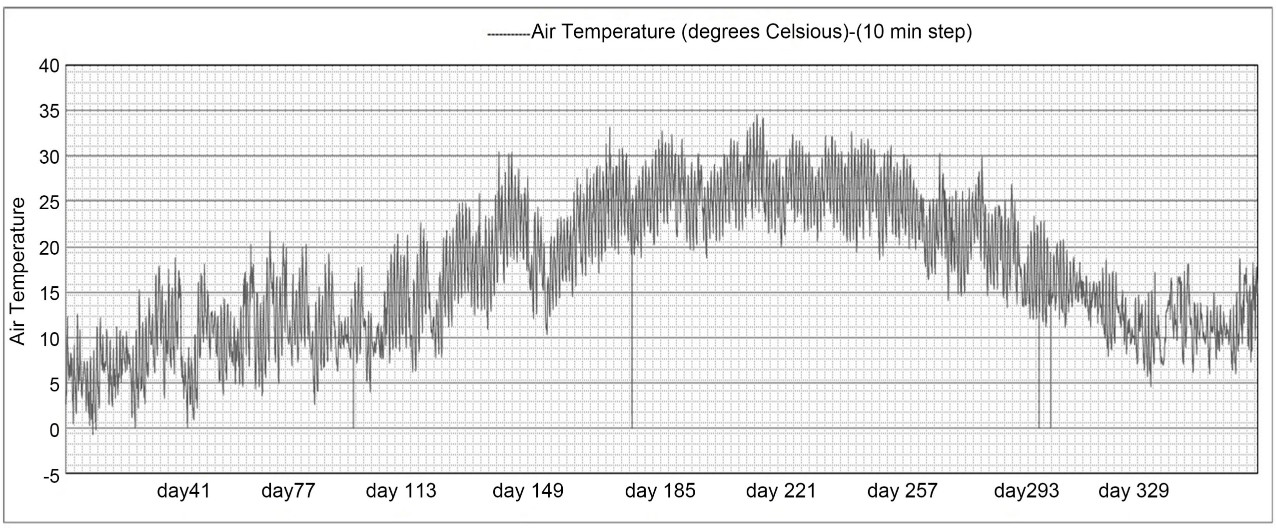


(d)

Figure 5. Meteorological data (every 10 min-52.560 steps): (a) Wind speed, (b) Rainfall, (c) Solar radiation, (d) Air temperature.

3. Results

The simulation was carried out for one year and the resulting values of velocity, temperature, density, salinity and water residence time are shown below on the surface and on the vertical sections of the bay at positions (Y.1-1'), (Y.2-2') and (X.3-3') (**Figure 2**).

3.1. Speed Results

Current measurements in the Pagasitic Gulf have shown that velocities are generally weak (<40 cm/sec) [25] [26]. In the eastern part of the bay currents have surface values: mean 10 cm/sec and maximum 38 cm/sec and near the bottom: 6 and 32 cm/sec respectively, while in the western bay the surface currents are: mean 6 cm/sec and maximum 29 cm/sec and near the bottom: 5 and 24 cm/sec respectively. The water flow velocity values obtained from the simulation in the three months (**Figure 6**) bay surface and (**Figure 7**) vertical section X.3-3' show considerable convergence with the sampled data. Surface velocities in the eastern part of the bay appear slightly higher with values between 0.10 m/sec and 0.50 m/sec, while in the western part they are between 0.05 m/sec and 0.30 m/sec. The velocity values in the vertical distribution (section X.3-3') start from 0.70 m/sec (maximum surface value) and are clearly reduced towards the bottom with values between 0 and 0.10 m/sec. The flow resembles the flow of a sea current—a river entering the bay (Trikeri channel) and taking the form of a whirlpool under the influence of meteorological conditions and the morphology of

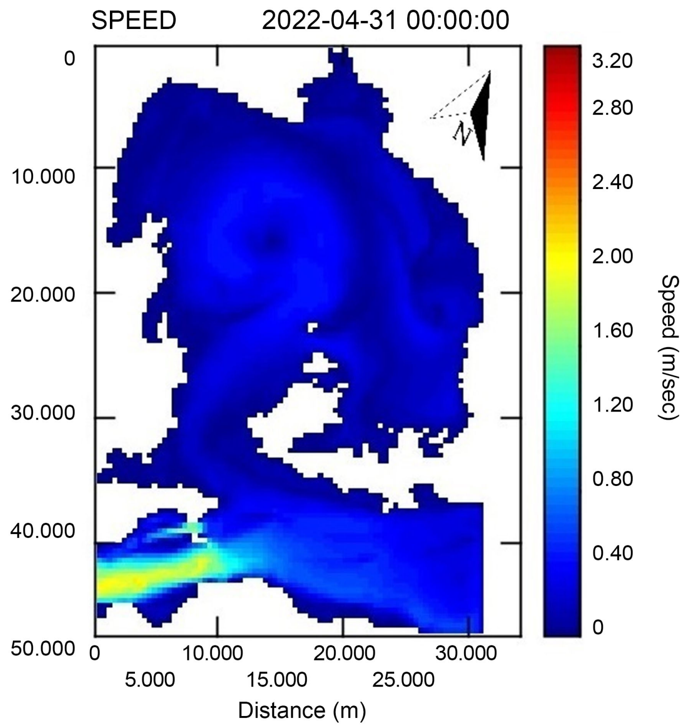


Figure 6. Spatial distribution of water flow velocity at 3 months on the surface of the bay.

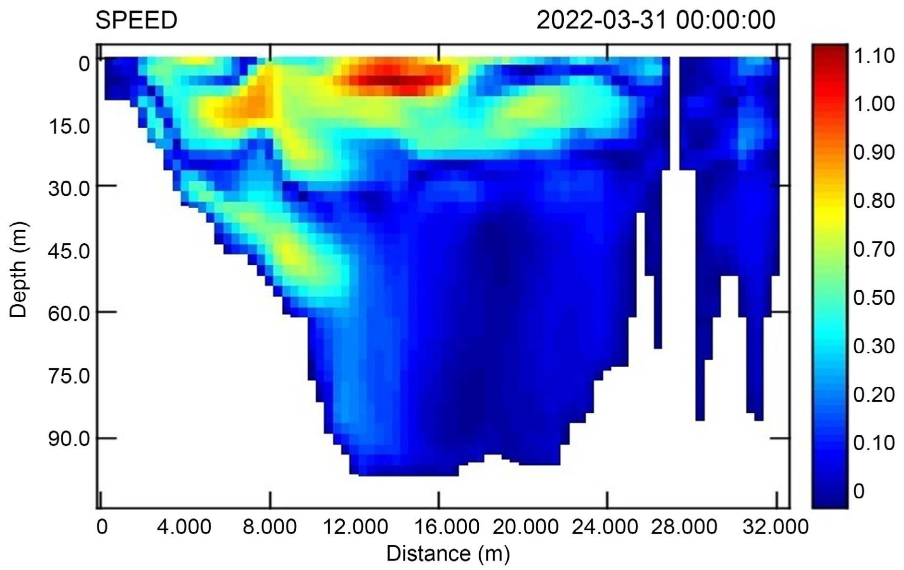


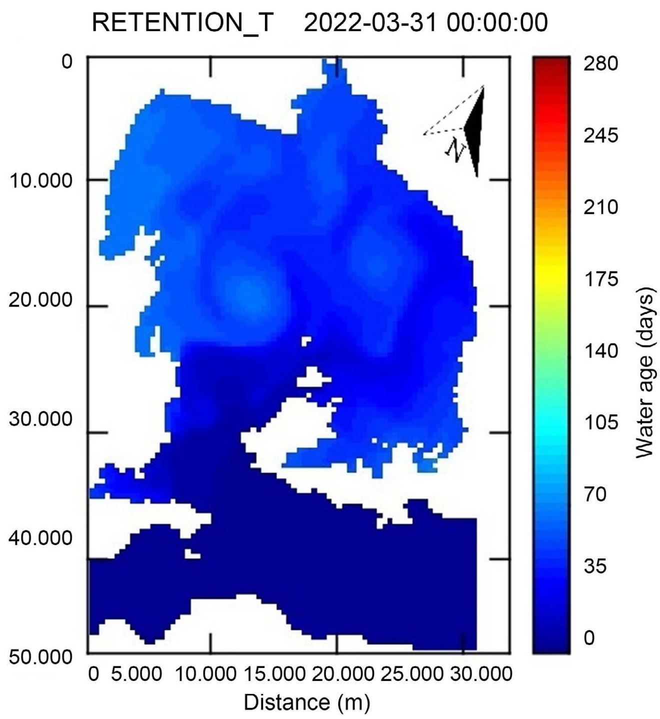
Figure 7. Vertical distribution of water flow velocity—section X.3-3'.

the area. This is in agreement with published measurement results [26] where it has been found that the bay has an almost stable dipole, an anticyclone in the eastern bay and a cyclone in the central western bay combined with smaller eddies.

3.2. Water Age, Retention and Renewal Results

3.2.1. Results on the Surface

Water residence time in the surface cells is illustrated at snapshots of 3, 6, 9 and 12 months (**Figure 8**). At the end of March (90 days) the water age is greatest in the Northwestern area of the Bay and least in the Southeastern area. The corresponding mean ages are 70 days in the Northwest and 30 days in the Southeast, so water recharge is greatest in the East of the Bay (**Figure 8(a)**). This differentiation is maintained and becomes more pronounced with time. At the end of June (180 days) average water ages are 140 days in the Northwest and 95 days in the Southeast (**Figure 8(b)**). At the end of September (270 days) average water ages are 200 days in the Northwest and 150 days in the Southeast (**Figure 8(c)**). At the end of December (365 days) average water ages are 270 days in the Northwest and 180 days in the Southeast (**Figure 8(d)**). It is observed that at the end of the year the Northwestern part of the bay and a small part in the inner Southeastern area remains without significant recharge while there is moderate recharge in the Volos harbour area and better recharge on the Eastern beaches. Full water renewal is consistently observed in the area around the Trikeri channel (entrance to the bay). **Figure 8(c)**, **Figure 8(d)** where the simulation is quite advanced in time (270 and 365 days) show that the average age of the water at the surface of the bay in 9 months ranges between 140 and 170 days and in one year between 220 and 250 days. Subtracting the calculated age of the water from the simulation time gives an average water renewal time of respectively 100 - 130 days at 9 months and 110 - 140 days at one year. Field measurements have shown that the average renewal time of the Pagasitikos waters is about 105 days with a significant standard deviation of 51 days [6] [25] [26], which is consistent with the simulation results.



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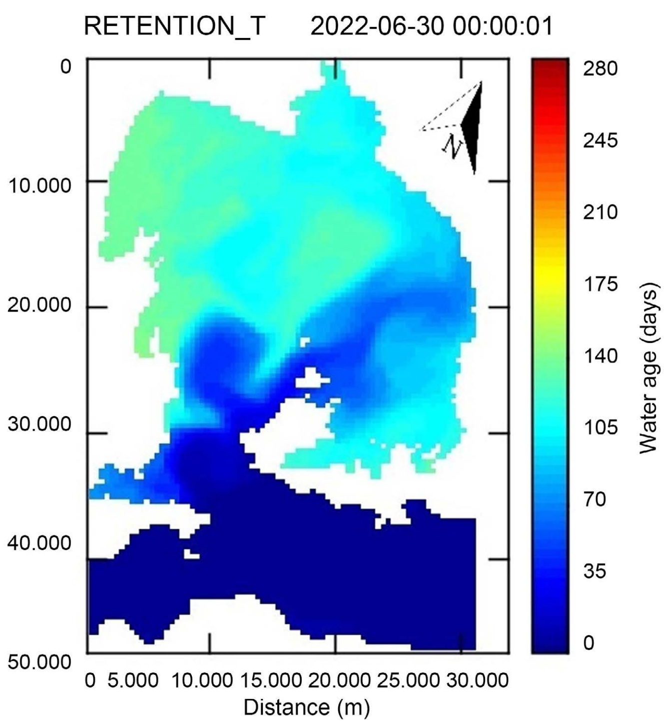

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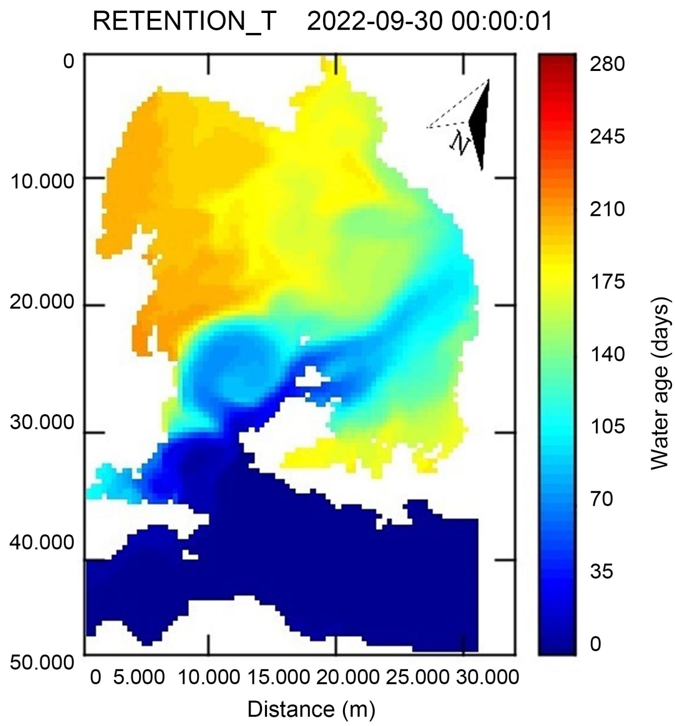

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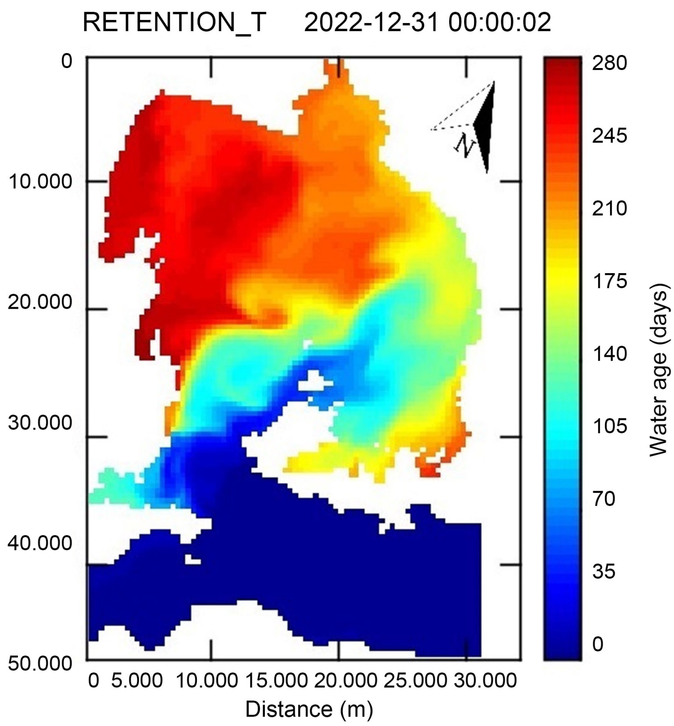


(d)

Figure 8. Water retention on the surface of the bay (a) 3 months, (b) 6 months, (c) 9 months, (d) 12 months.

3.2.2. Results at Vertical Section U.1-1' at Almyros Region

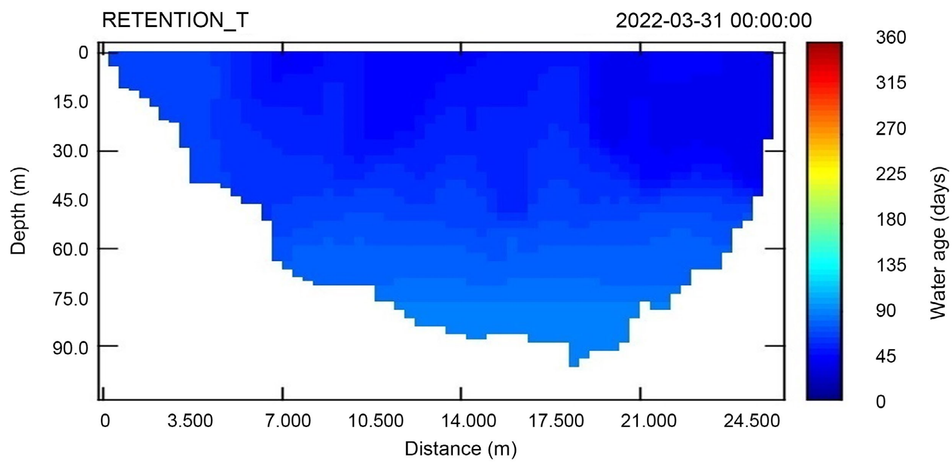
The vertical distribution of water age from the surface to the bottom in the

Y.1-1' section is illustrated at snapshots of 3, 6, 9 and 12 months (Figure 9).

At the end of March (90 days) the water age is highest at the bottom of the bay and much lower at the surface. The corresponding average water ages are 45 days at the surface and about 90 days at the bottom, so water recharge is greatest at the surface and almost zero at the bottom (Figure 9(a)). This effect also persists and becomes more pronounced with time. At the end of June (180 days) the corresponding average water ages are 130 days at the surface and 170 in the bottom area (Figure 9(b)). At the end of September (270 days) the corresponding average water ages are 200 days at the surface and 240 in the bottom area (Figure 9(c)). At the end of December (365 days) the corresponding average water ages are 260 days at the surface and 330 in the bottom region (Figure 9(d)). It further follows that the water age is shorter in the East and increases as we move from East to West. This agrees with the renewal at the surface (Figure 7) where it is better in the East.

3.2.3. Results at Vertical Section U.2-2' at Trikeri Region

The vertical distribution of water age from the surface to the bottom in section Y.2-2' is illustrated at snapshots of 3, 6, 9 and 12 months (Figure 10).



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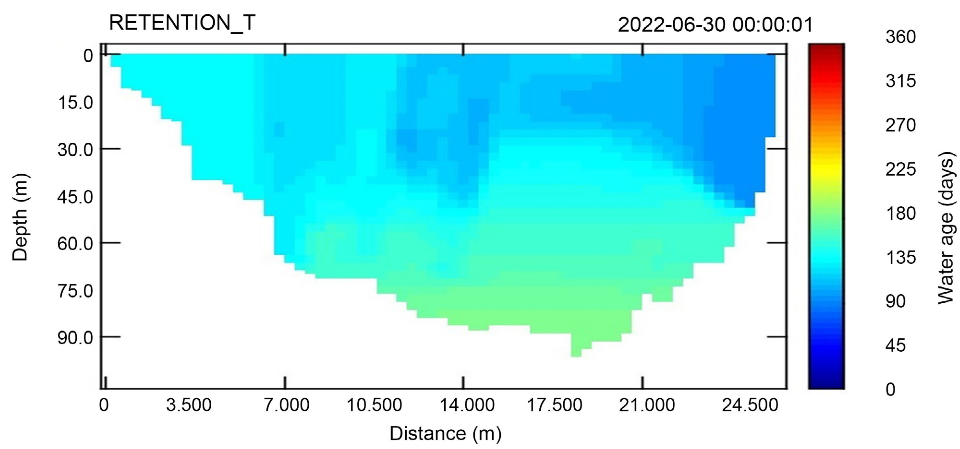

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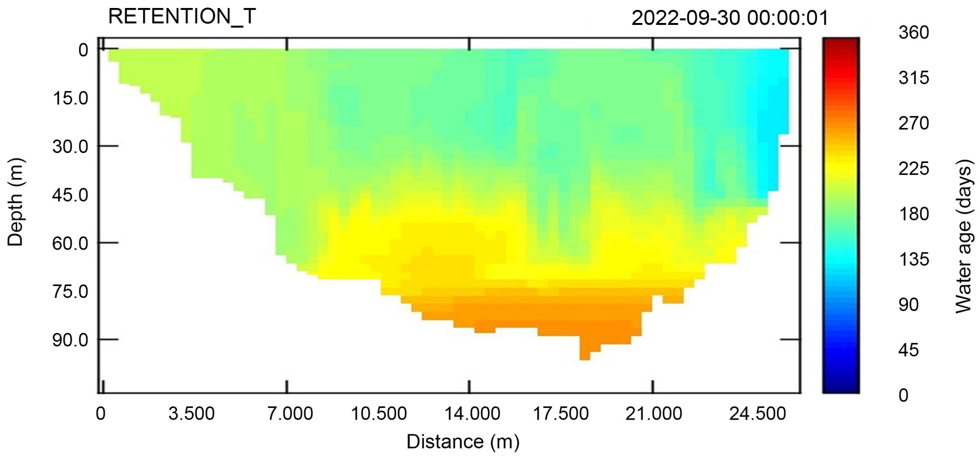

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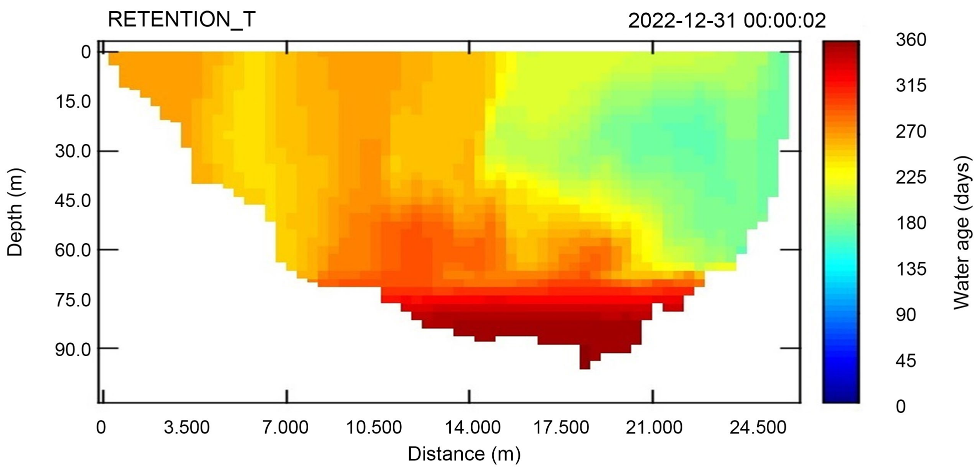
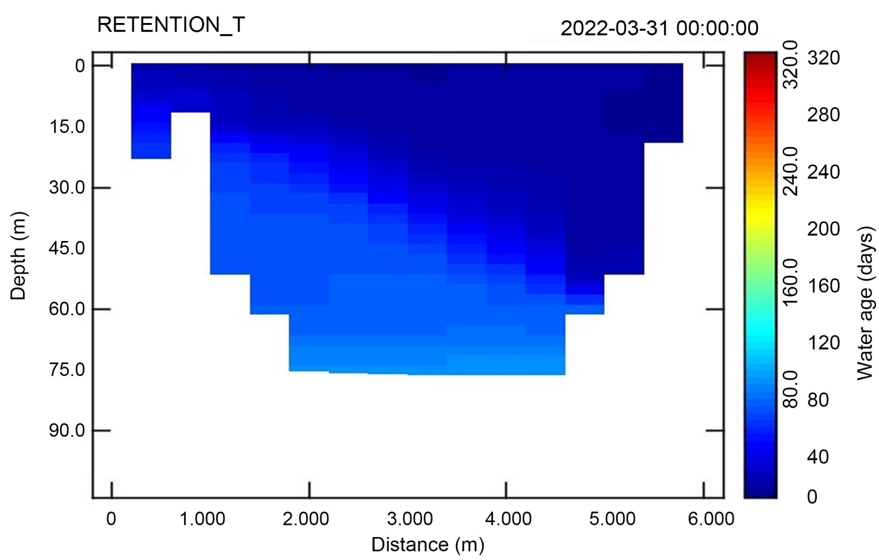


(d)

Figure 9. Water retention at vertical section Y.1-1': (a) 3 months, (b) 6 months, (c) 9 months, (d) 12 months.



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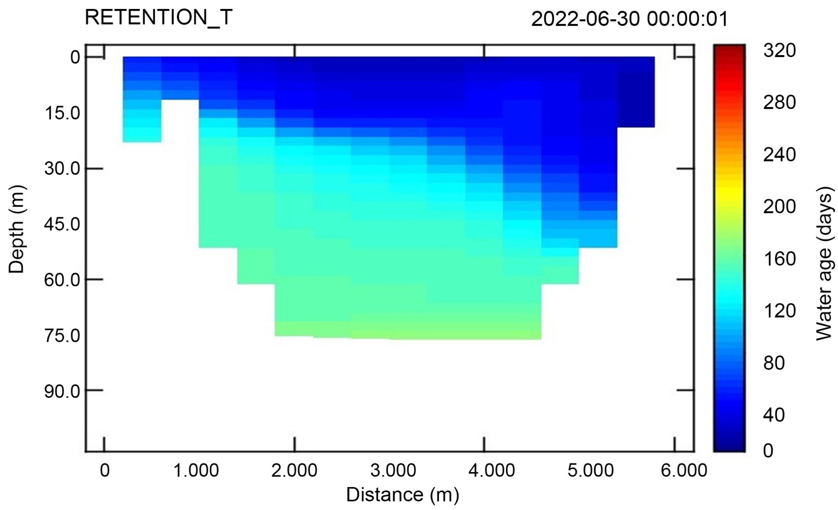

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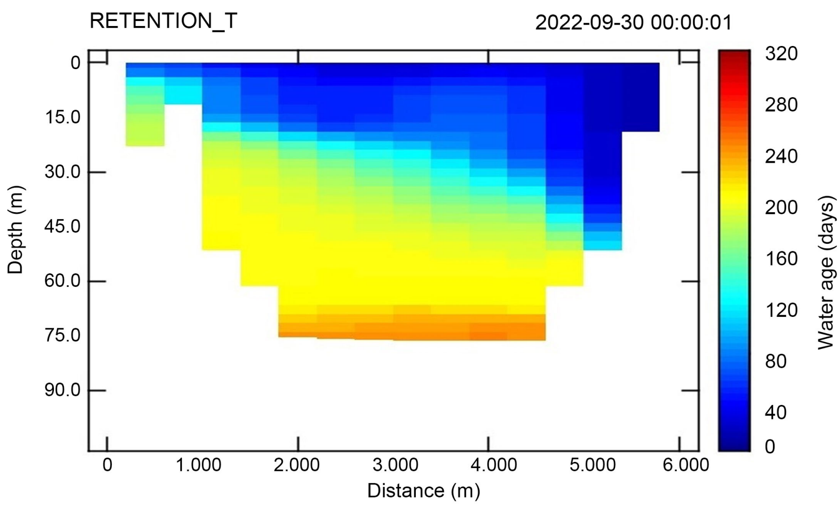

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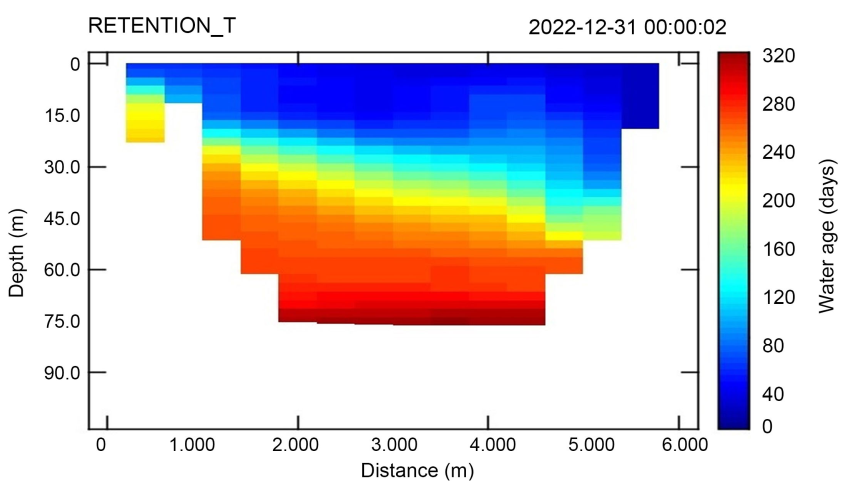


(d)

Figure 10. Water retention at vertical section Y.2-2': (a) 3 months, (b) 6 months, (c) 9 months, (d) 12 months.

At the end of March (90 days) the water age is again higher at the bottom of the bay and much lower at the surface. The corresponding average water ages are 5 days at the surface and about 70 days at the bottom, so water recharge is greater at the surface and much less at the bottom (**Figure 10(a)**). This effect also persists and becomes more pronounced with time. At the end of June (180 days) the corresponding average water ages are 30 days at the surface and 160 in the bottom area (**Figure 10(b)**). At the end of September (270 days) the corresponding average water ages are 30 days at the surface and 240 in the bottom area (**Figure 10(c)**). At the end of December (365 days) the corresponding average water ages are 30 days at the surface and 300 in the bottom area (**Figure 10(d)**). It is also observed that the water age is generally lower in the eastern part of the Trikeri Channel, so there is a stronger inflow of water in the east. It thus appears that the entry of water into the bay takes place in the Eastern part of the channel and the exit in the Western part. Also at depths above 40 m the water recharge is significantly reduced and recharge at depths above 60 m is very small.

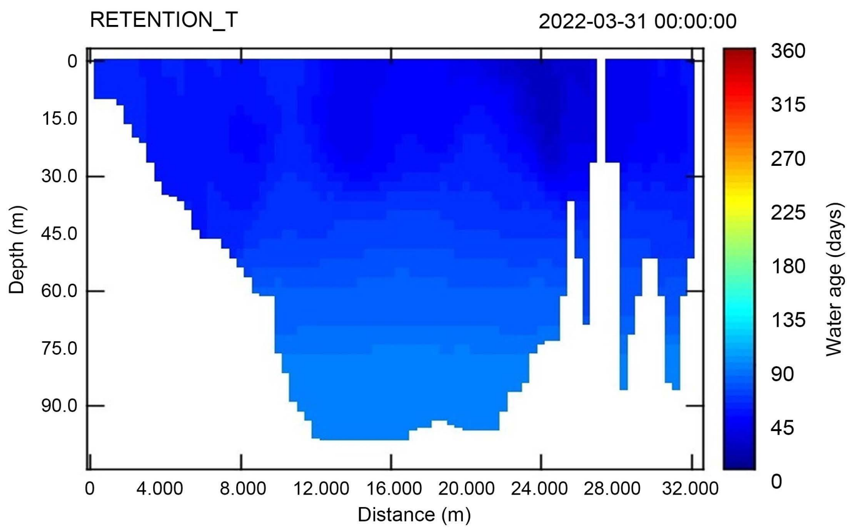
3.2.4. Results at Vertical Section X.3-3'

The vertical distribution of water age from the surface to the bottom in section X.3-3' is illustrated at snapshots of 3, 6, 9 and 12 months (**Figure 11**). At the end of March (90 days) the water age is again higher at the bottom of the bay and much lower at the surface. The corresponding average water ages are 50 days at the surface and about 70 days at the bottom, so water recharge is similarly greater at the surface and much less at the bottom (**Figure 11(a)**). At the end of June (180 days) the corresponding average water ages are 100 days at the surface and 170 days in the bottom area (**Figure 11(b)**). At the end of September (270 days) the corresponding average water ages are 120 days at the surface and 250 days in the bottom area (**Figure 11(c)**). At the end of December (365 days) the corresponding average water ages are 200 days at the surface and 330 days in the bottom area (**Figure 11(d)**). It is also observed that there is more significant water renewal in the central part of the bay (near the entrance) and relatively less in the northern part (towards the harbour) than in the southern part (South Pelion beaches). Water age is generally lowest at depths from the surface to about 30 m and increases with increasing depth. The renewal at depths of 70 metres and above is significantly less.

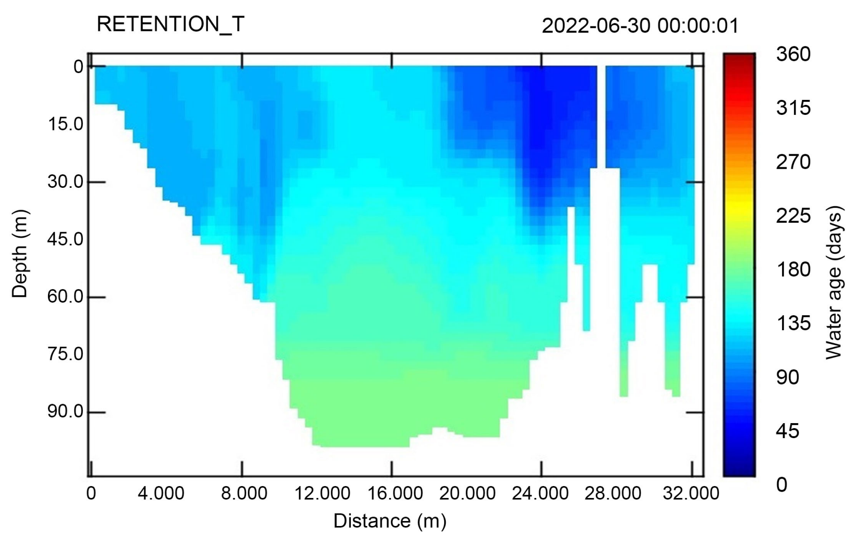
3.3. Temperature Results

Figure 12 shows the vertical variation of water temperature in early autumn (250 days) in the three vertical sections Y.1-1', Y.2-2' and X.3-3' in relation to the water depth. There is a stratification of the temperature in three layers: 1) 0 - 30 m, 2) 30 - 50 m, 3) 50 - 100 m. The temperature change is most pronounced in the intermediate layer where it drops 4˚C - 5˚C and the formation of a thermocline is evident in this layer. In the upper and lower layers the temperature differences are in the order of 1˚C - 2˚C.

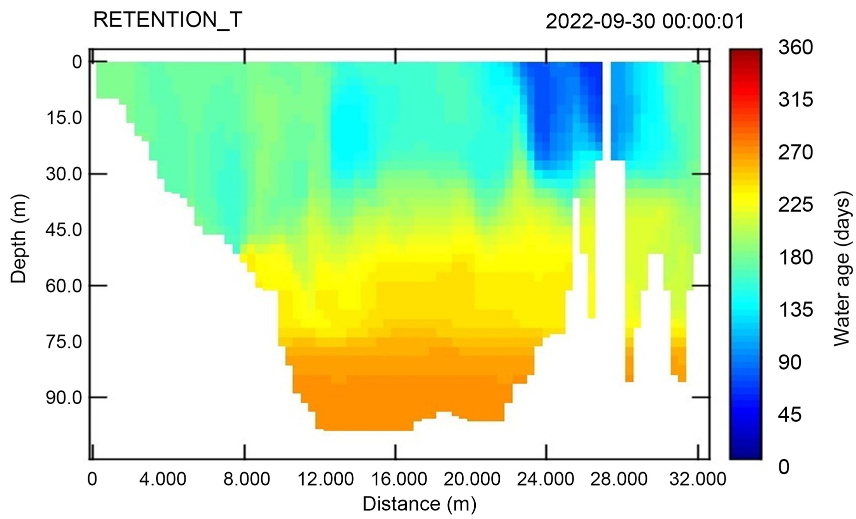
The validity of the simulation temperature results was checked against the measurements-published results of realised sampling and a significant coincidence of values was found. **Figure 13** shows the comparison of the vertical variation of water column temperature at the same time of the year between realised T (˚C) temperature measurements in the Pagasitikos [25] [26] and the results of the simulation of the present study in the same column, shown in **Figure 12(c)**, which is located in the central area. The comparison of the two curves shows that the simulation gives water temperature values that vary like the actual ones. In general, the water temperature decreases from the surface to the bottom, appears almost unchanged for depths from 0 m to 30 m, decreases significantly at depths from 40 m to 70 m, and also remains unchanged at depths above 70 m. The depths at which the temperature changes in the simulation agree with the corresponding depths of the measurements [25], while a slight deviation in the temperature values is observed at shallow depths due to an increase in the external air temperature affecting the upper layers of water.



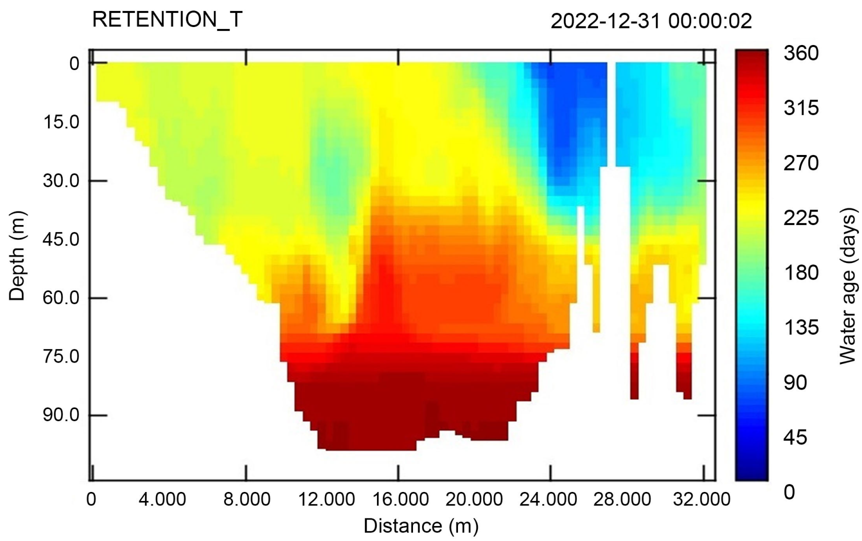
(a)



(b)



(c)



(d)

Figure 11. Water retention atvertical section X.3-3': (a) 3 months, (b) 6 months, (c) 9 months, (d) 12 months.

3.4. Salinity Results

Figures 14(a)-(c) show vertical variation of water salinity (180 days) in the three vertical sections Y.1-1', Y.2-2' and X.3-3' with respect to depth. There is a stratification of salinity similar to that of temperature in three layers: 1) 0 - 30 m, 2) 30 - 60 m, 3) 60 - 100 m. Salinity shows a more pronounced change in the intermediate layer where it rises 4 - 5 psu and the formation of halocline is evident in this layer. In the upper layer salinity differences are on the order of 1 - 2 psu and in the lower layer salinity remains almost unchanged. **Figure 15** shows the comparison of the vertical variation of the seasonal mean salinity in the Pagasitikos at the same time of the year between a) salinity measurements carried out—vertical variation of the seasonal mean salinity during the period 1998-1999

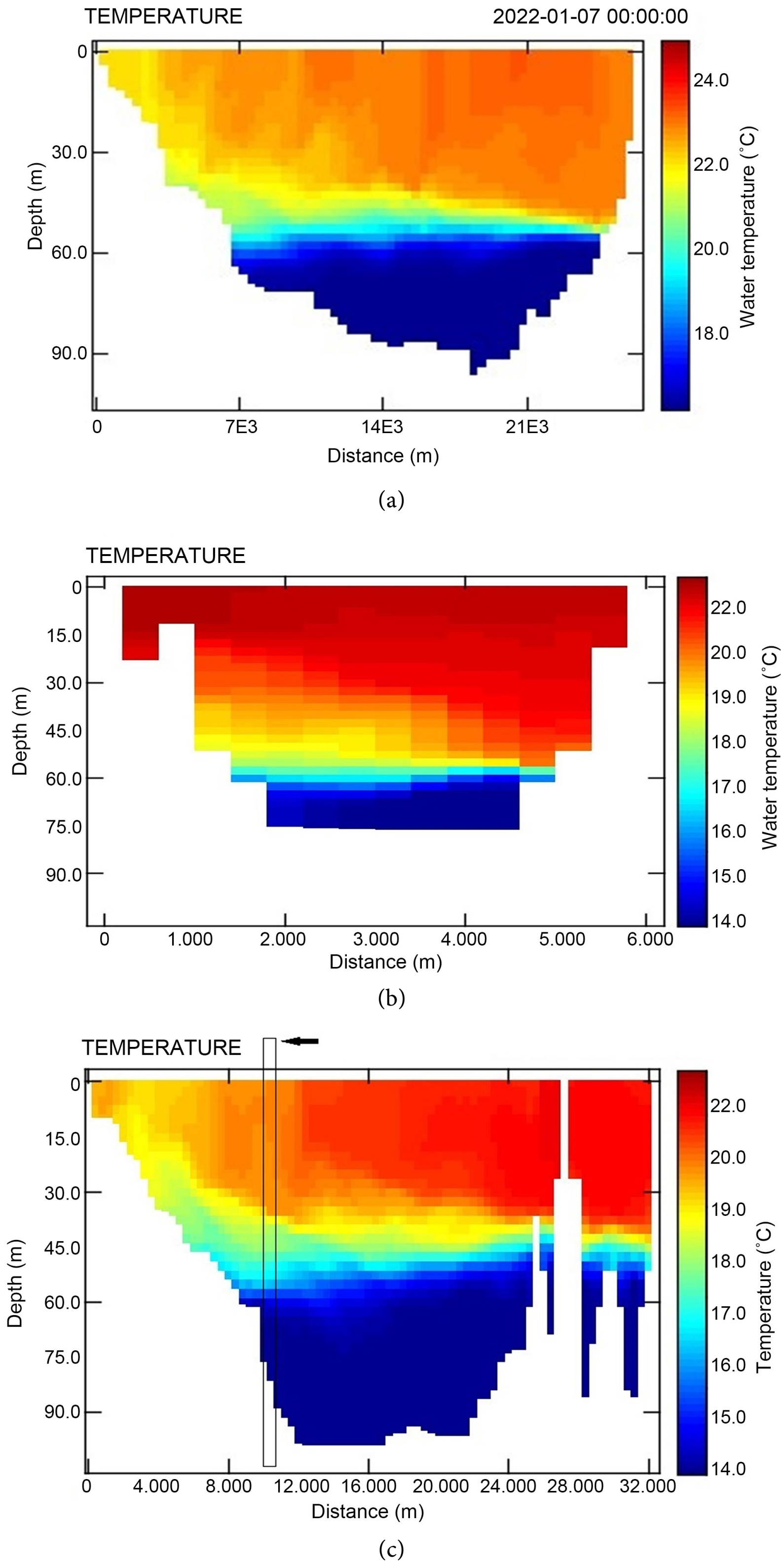


Figure 12. Depth distribution of water temperature (250 days): (a) Vertical section of the bay at the height of Almiros Y.1-1', (b) Vertical section at the height of Trikeri Y.2-2', (c) Vertical section of the bay X.3-3' (with column comparing water temperature from simulation with measurements).

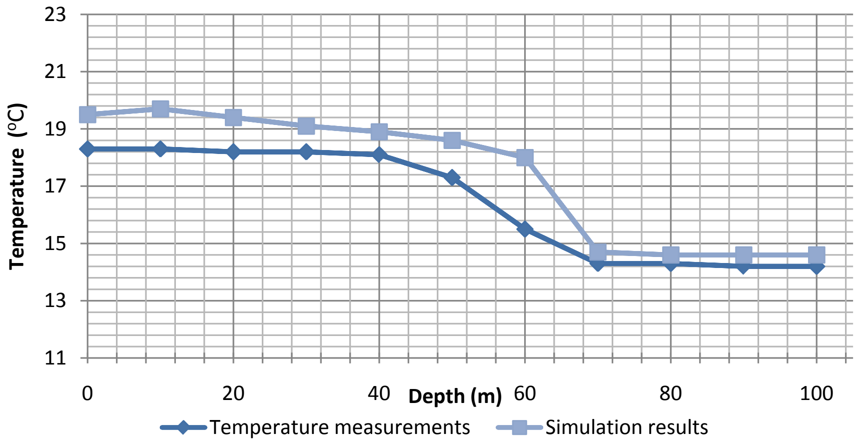
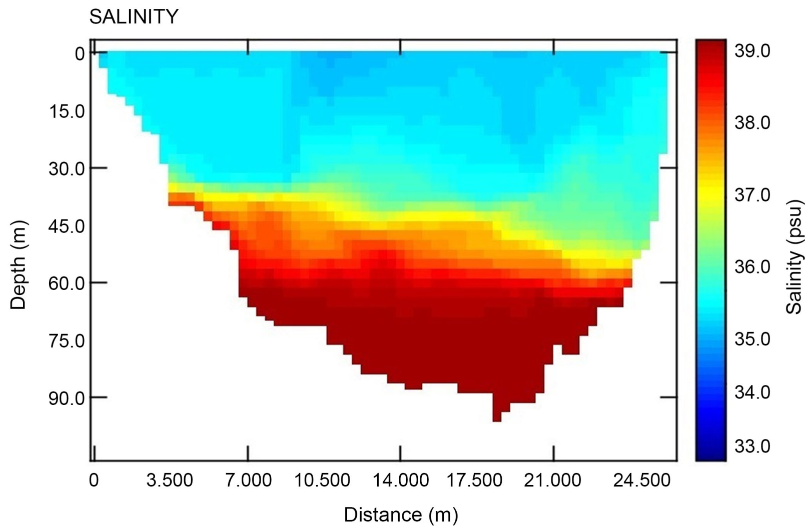
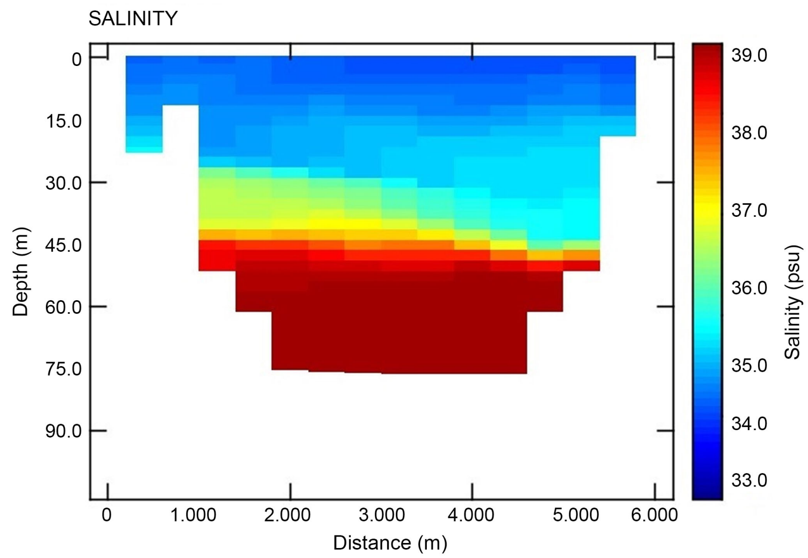


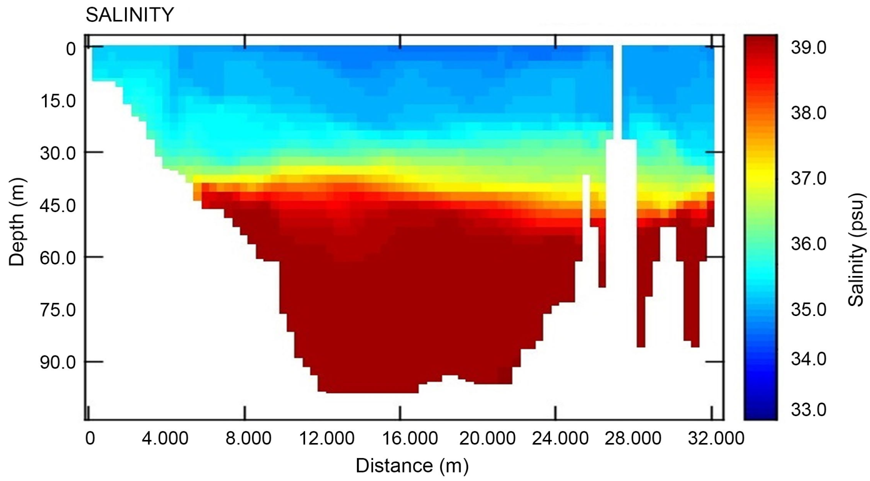
Figure 13. Comparison of the water temperature variation in a vertical section as results of measurements and simulation.



(a)



(b)



(c)

Figure 14. Depth distribution of water salinity at 6 months: (a) Vertical section of the bay at the height of Almiros Y.1-1', (b) Vertical section at the height of Trikeri Y.2-2', (c) Vertical section of the bay X.3-3'.

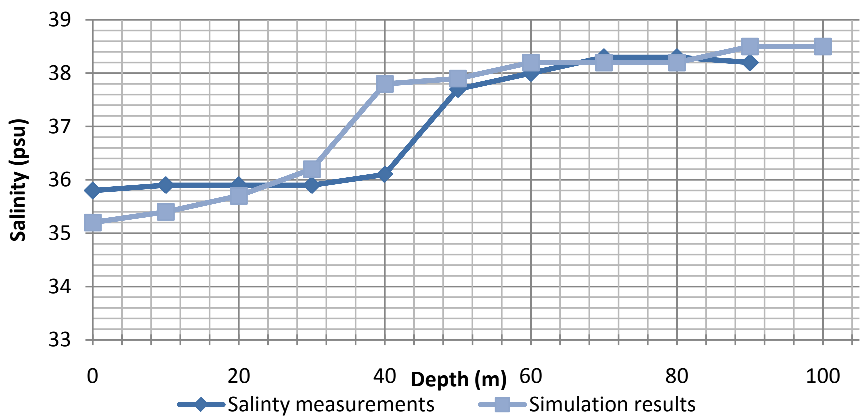


Figure 15. Comparison of the water salinity variation in a vertical section as results of meaurements and simulation.

in the Pagasitikos [21] and the results of the simulation of the present study in the central area of the Pagasitikos Gulf. The comparison of the two curves shows that the simulation gives water salinity values that vary like the actual values and the difference in values is due to the influence of meteorological loadings. According to research, it has been found that in the surface layer the seasonal distribution of surface salinity indicates anticyclonic circulation over the entire surface of the bay [25] [26]. **Figure 16** shows the salinity at the surface of the bay at 120 days of simulation (end of April) where anticyclonic circulation occurs towards the northwestern part of the bay, which is consistent with the previous finding.

3.5. Density Results

Figures 17(a)-(c) depict vertical variation of water density (180 days) in the three vertical transects Y.1-1', Y.2-2' and X.3-3' with respect to depth. There is again a strong stratification of density in three layers: 1) 0 - 30 m, 2) 30 - 60 m, 3) 60 - 100 m. The density shows a more pronounced change in the intermediate layer where it increases sharply by 4 - 5 kg/m^3. In the upper and lower layers the density differences are of the order of 1 kg/m^3.

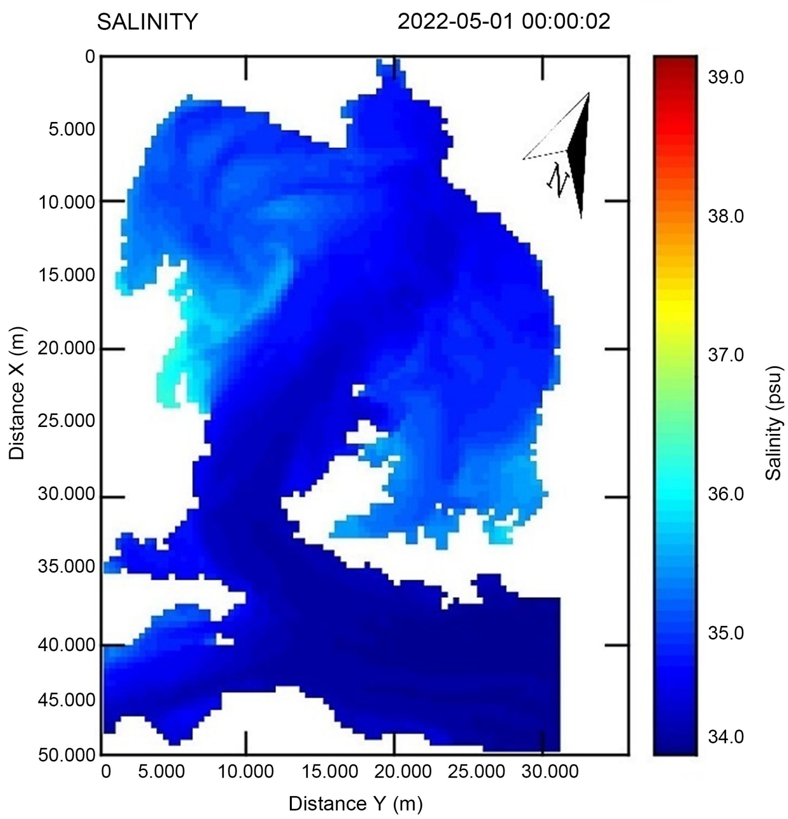
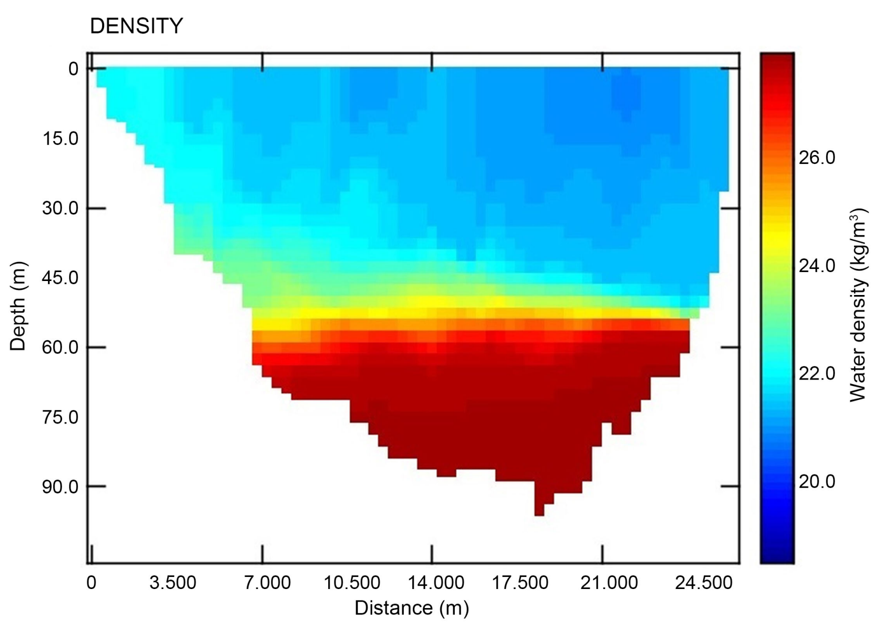
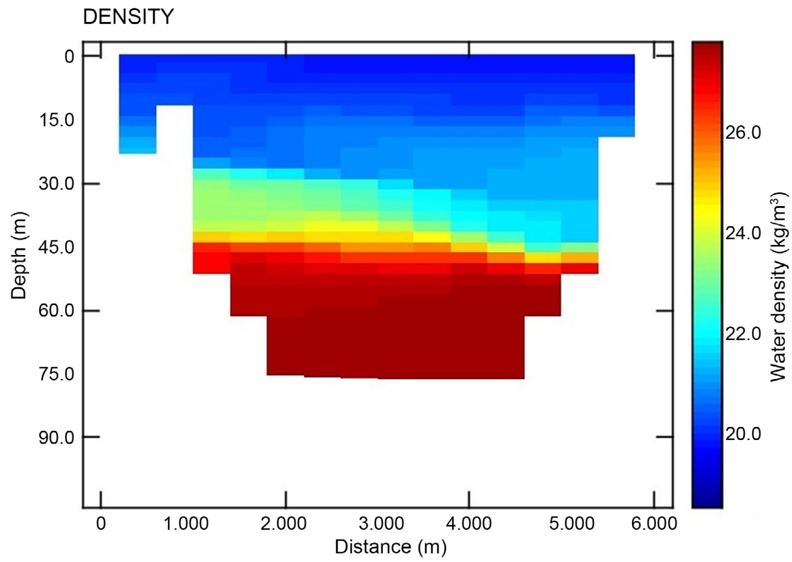


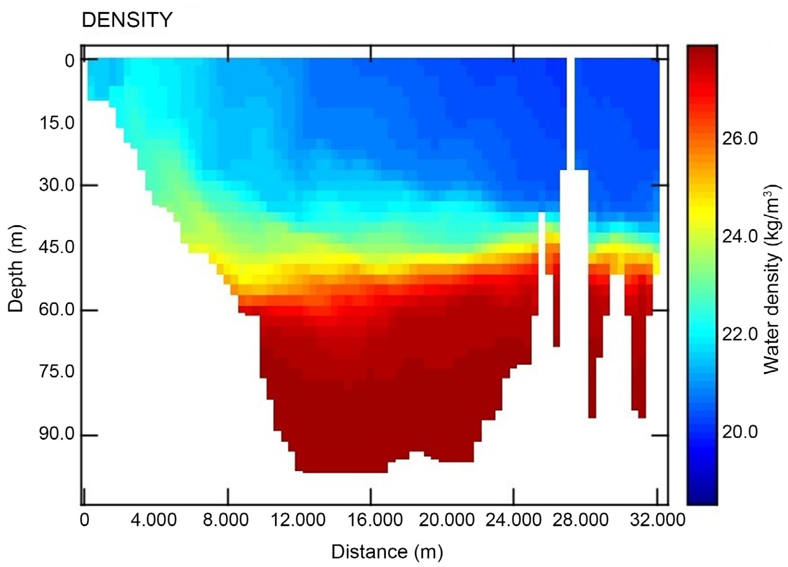
Figure 16. Water salinity at the surface of the bay at 120 days.



(a)



(b)



(c)

Figure 17. Depth distribution of water density at 6 months: (a) Vertical section of the bay at the height of Almiros in the Y direction, (b) Vertical section at the height of Trikeri in the Y direction, (c) Vertical section of the bay at the height of the port of Volos in the X direction.

4. Discussion

Regarding the water velocities, it has been found that they are weak, vary smoothly and the phenomena generally within the bay are mild and slow evolving. Surface velocities in the eastern part of the bay appear slightly higher with values between 0.10 m/sec and 0.50 m/sec, while in the western part they are between 0.05 m/sec and 0.30 m/sec. Velocities in the vertical distribution start from 0.70 m/sec at the surface and are clearly reduced towards the bottom with values between 0 and 0.10 m/sec. In the eastern part of the bay the currents have surface values: mean 10 cm/sec and maximum 38 cm/sec and near the bottom: 6 and 32 cm/sec respectively, while in the western bay the surface currents are: mean 6 cm/sec and maximum 29 cm/sec and near the bottom: 5 and 24 cm/sec respectively. A sea current is observed entering from the Aegean Sea moving from the eastern open sea boundary towards the western open sea boundary and consequently towards the Malian Gulf. Part of this current enters the Pagasitikos Gulf through the Trikeri Channel and then diffuses in the form of a vortex throughout the basin, a phenomenon which seems to be maintained over time. In the western open boundary, generally higher velocities develop due to the smaller cross-section and the water is mainly directed towards the Evian Sea. At the entrance to the bay, the velocity field initially shows a linear flow, which then changes to a north-westerly and south-easterly flow in direct correlation with the morphology of the area (bottom topography, coastline). Water enters the bay along the eastern shoreline of the Trikeri Channel and exits along the western shoreline of the channel. Meteorological conditions also play an important role in shaping the flow as the circulation in the Pagasitikos is mainly influenced by atmospheric loading, with wind action being the main factor.

Regarding the recharge and residence of water throughout the bay area it is observed that the Northwestern part of the bay and a small part in the inner South-Eastern area remains without significant recharge while there is moderate to low recharge in the Volos harbour area and better recharge on the Eastern beaches. Full water renewal is consistently observed in the area near the Trikeri channel (entrance to the bay). Water age is generally lowest at depths from the surface to about 30 m and increases with depth. The renewal at depths of 70 metres and above is very small. The average renewal time of the water is between 100 and 145 days in one year. In relation to depth, it is observed that the recharge at the surface is much better and decreases significantly with increasing depth. The difference in age of the water from the surface to the deeper layers in the same places is as much as 130 days.

The water column is highly stratified and is divided into three layers of varying thickness: the surface layer (10 - 30 m), the intermediate layer (30 - 50 m), in which both thermocline and halocline formation is evident, and the deep layer (in areas deeper than 50 m). The seasonal vertical distributions of temperature, salinity and density clearly follow this stratification, particularly in the summer months. Stratification is maintained throughout the year.

Water temperature varies seasonally, decreasing from the surface to the bottom and always maintaining a difference of 2˚C to 3˚C between the three strata observed. In early summer, water temperatures in the surface layer are between 21˚C and 19˚C, in the intermediate layer between 19˚C and 17˚C, and in the deeper layer between 17˚C and 14˚C. The overall temperature difference between the surface and the bottom is 6˚C or more depending on the local depths. Seasonal temperature variations are more pronounced in the upper layer of the individual areas of the bay and are almost non-existent at depths of more than 50 m.

Salinity follows the same phenomenon and also always maintains a 2 to 3 psu difference between the three layers, *i.e.* in the corresponding season in the surface layer water salinity is between 34 psu and 36 psu, in the intermediate layer it is between 36 psu and 37 psu, while in the deeper layer it is between 37 psu and 39 psu. Salinity in the surface layer is lower than in the intermediate and deep layers by 3 to 4 psu depending on the depth of each region. The highest salinity values are observed in the eastern basin of the bay during most seasons of the year, especially in winter. The western area of the Pagasitikos shows slightly lower salinities compared to the eastern area and the Trikeri Channel.

Water density increases significantly with depth and shows an increase from the surface to the bottom between 4 kg/m^3 and 7 kg/m^3 depending on the local depths. Similarly, in the early summer the water density in the surface layer is between 20 kg/m^3 and 22 kg/m^3, in the intermediate layer between 22 kg/m^3 and 25 kg/m^3 and in the deeper layer between 25 kg/m^3 and 27 kg/m^3. This results in an intense linear density stratification with depth, which prevents vertical mixing of the sea masses.

5. Conclusions

In this paper, a computational simulation of the hydrodynamic circulation of the Pagasitic Gulf waters was carried out with ELCOM 2.2 AEM3D models for one year. The hydrodynamic behaviour of the bay, water circulation, velocities at the surface and in depth, water recharge and residence throughout the bay area, and changes in temperature, density and salinity were investigated. The validity of the present simulation is confirmed by a number of measurements and published results from realised sampling exercises as detailed and significant convergence of magnitudes is obtained. The simulation resulted in visualizations of magnitudes at the surface and at various depths and investigated the mechanisms of recharge of the bay waters.

The main finding that came out from the simulation is that the circulation in Pagasitikos is mainly influenced by atmospheric loads, mainly by wind action, as well as by the exchange of water with the Aegean Sea. The influence of tides seems to be small. Phenomena generally within the bay are mild and relatively slow developing. The inflow of water into the Pagasitikos appears to take place only from the eastern open boundary (Aegean Sea) and not from the Evian Gulf. The predominant movement of water in the northern Evian is from east to west and part of the flow enters the Pagasitikos, while the rest moves westwards. Higher velocities develop at the western open boundary and the water is mainly directed towards the Evian Sea. The prevailing velocities within the bay are generally weak (average velocity values of 0.40 m/sec to 1.0 m/sec). It is observed that the north-western part of the bay and a small part in the inner south-eastern area remain without significant recharge, while there is moderate to low recharge in the Volos harbour area and better recharge on the eastern beaches. Full water renewal is consistently observed in the area near the Trikeri channel (entrance to the bay). The age of the water is generally lowest at depths from the surface to about 30 metres and increases with increasing depth. The renewal at depths of 70 metres and above is very small. Water temperature decreases with depth and thermocline formation is observed at depths between 40 m and 70 m. The salinity of the water also decreases with depth and haloclines are observed at depths between 30 m and 50 m. A roughly linear density stratification with depth occurs, which prevents vertical mixing of the sea masses.

In the present study, the hydrodynamic behaviour of the Pagasitikos Gulf, the velocities at the surface and in depth, the recharge and residence of water throughout the gulf and the variation of temperature, density and salinity were examined by simulation. The resulting conclusions contribute to the understanding of the bay behaviour and can be used for further environmental simulation of the diffusion and dispersion of pollutants in this marine region, which is a typical semi-enclosed sea basin with a complex mechanism for water renewal.

Conflicts of Interest

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

References

[1] Karageorgis, A.P., Kanellopoulos, T., Mavromatis, V., Anagnostou, C., Koutsopoulou, E., Schmidt, M., Pavlopoulos, K., Tripsanas, E. and Hallberg, R.O. (2012) Authigenic Carbonate Mineral Formation in the Pagassitikos Palaeolake during the Latest Pleistocene, Central Greece. *Geo-Marine Letters*, **33**, 13-29. https://doi.org/10.1007/s00367-012-0306-y

[2] Kormas, K.A., Karayanni, H., Christaki, U., Giannakourou, A., Assimakopoulou, G. and Gotsis-Skretas, O. (2014) Microbial Food Web Structure and Its Impact on Primary Production in a Meso-Oligotrophic Coastal Area (Pagasitikos Gulf, Aegean Sea). *Turkish Journal of Fisheries and Aquatic Sciences*, **14**, 527-537.

[3] Karagitsou, H., Siapatis, A. and Anastasopoulou, A. (2000) Development of an Integrated Policy for the Sustainable Management of the Pagasitikos Gulf. Final Report, ESTE.

[4] Karageorgis, A.P., Sioulas, A.I. and Anagnostou, C.L. (2001) Use of Surface Sediments in Pagassitikos Gulf, Greece to Detect Anthropogenic Influence. *Geo-Marine Letters*, **21**, 200-211. https://doi.org/10.1007/s00367-001-0086-2

[5] Korres, G., Triantafyllou, G., Petihakis, G., Raitsos, D.E., Hoteit, I., Pollani, A., Colella, S. and Tsiaras, K. (2011) A Data Assimilation Tool for the Pagasitikos Gulf Ecosystem Dynamics: Methods and Benefits. *Journal of Marine Systems*, **94**, S102-S117. https://doi.org/10.1016/j.jmarsys.2011.11.004

[6] Petihakis, G., Triantafyllou, G., Pollani, A., Koliou, A. and Theodorou, A. (2005) Field Data Analysis and Application of a Complex Water Column Biogeochemical Model in Different Areas of a Semi-Enclosed Basin: Towards the Development of an Ecosystem Management Tool. *Marine Environmental Research*, **59**, 493-518. https://doi.org/10.1016/j.marenvres.2004.07.004

[7] Petihakis, G., Tsiaras, K., Triantafyllou, G., Korres, G., Tsagaraki, T.M., Tsapakis,

M., Vavillis, P., Pollani, A. and Frangoulis C. (2011) Application of a Complex Ecosystem Model to Evaluate Effects of Finfish Culture in Pagasitikos Gulf, Greece. *Journal of Marine Systems*, **94**, S65-S77. https://doi.org/10.1016/j.jmarsys.2011.11.002

[8] Raitsos, D.E., Korres, G., Triantafyllou, G., Petihakis, G., Pantazi, M., Tsiaras, K. and Pollani, A. (2012) Assessing Chlorophyll Variability in Relation to the Environmental Regime in Pagasitikos Gulf, Greece. *Journal of Marine Systems*, **94**, S16-S22. https://doi.org/10.1016/j.jmarsys.2011.11.003

[9] Triantafyllou, G., Hoteit, I., Korres, G. and Petihakis, G. (2005) Ecosystem Modeling and Data Assimilation of Physical-Biogeochemical Processes in Shelf and Regional Areas of the Mediterranean Sea. *Applied Numerical Analysis & Computational Mathematics*, **2**, 262-280.

[10] Tsangaris, C., Kaberi, H. and Catsiki, V. (2012) Metal Levels in Sediments and Transplanted Mussels in Pagassitikos Gulf (Aegean Sea, Eastern Mediterranean). *Environmental Monitoring and Assessment*, **185**, 6077-6087. https://doi.org/10.1007/s10661-012-3008-z

[11] Hodges, B. and Dallimore, C. (2010) a. ELCOM User Manual, CWR, University of Western Australia, Crawlwy, 62 p.

[12] Hodges, B. and Dallimore, C. (2010) b. ELCOM Science Manual, CWR, University of Western Australia, Crawlwy, 54 p.

[13] Hodges, B. and Dalimore, C. (2016) Estuary, Lake and Coastal Ocean Model User Guide. https://www.researchgate.net/publication/237814096_Estuary_Lake_and_Coastal_Ocean_Model_User_Guide

[14] Konidaris, A., Georgoulas, A., Angelidis, P. and Kotsovinos, N. (2006) Computational Simulation of the Outflow from the Hellespont in B. Aegean. 10*th Panhellenic Conference of the Hellenic Hydrotechnical Association on* "*Water Resources and Environment Management—Contemporary Problems and Perspectives*", Xanthi, 13 December 2006, 315-322.

[15] Konidaris, A., Georgoulas, A., Angelidis, P. and Kotsovinos, N. (2008) Simulation of the Discharge of Brackish Waters from the Dardanelles into the North Aegean. *International Conference*: "*Studying, Modeling and Sense Making of Planet Earth*", Mytilene, 1 June 2008, 101-108.

[16] Kopasakis, K. (2012) Simulation of the Hydrodynamic Transport and Diffusion of Pollutants Form from the Black Sea into the North Aegean Sea with the Use of Hydrodynamic Models and Study of the Effect of Their Long Term Accumulation to the Environment of the North Aegean Coastal Area. Ph.D. Thesis, DUTH, Xanthi.

[17] Kopasakis, K., Georgoulas, A., Angelidis, P. and Kotsovinos, N. (2012) Numerical Modeling of the Long-Term Transport, Dispersion and Accumulation of Black Sea Pollutants into the North Aegean Coastal Waters. *Estuaries and Coasts*, **35**, 1530-1550. https://doi.org/10.1007/s12237-012-9540-9

[18] Kopasakis, K., Georgoulas, A., Angelidis, P. and Kotsovinos, N. (2012) Simulation of the Long-Term Fate of Water and Pollutants, Transported from the Dardanelles Plume into the North Aegean Sea. *Applied Ocean Research*, **37**, 145-161. https://doi.org/10.1016/j.apor.2012.04.007

[19] Mousidis, A., Kopasakis, K. and Angelidis, P. (2015) Impact of Salt Wedge on a Coastal Mediterranean Lagoon Using a 3-D Numerical Model. *IWA Balkan Young Water Professionals* 2015, Thessaloniki. https://www.researchgate.net/publication/281006049_Impact_of_Salt_Wedge_on_a

_Coastal_Mediterranean_Lagoon_Using_a_3-D_Numerical_Model

[20] Tsirogiannis, E., Angelidis, P. and Kotsovinos, N. (2019) Hydrodynamic Circulation under Tide Conditions at the Gulf of Evoikos, Greece. *Computational Water*, *Energy and Environmental Engineering*, **8**, 57-78. https://doi.org/10.4236/cweee.2019.83004

[21] Tsirogiannis, E., Angelidis, P. and Kotsovimos, N. (2019) Mixing Characteristics under Tide, Meteorological and Oceanographic Conditions in the Euboean Gulf Greece. *Computational Water*, *Energy*, *and Environmental Engineering*, **8**, 99-123. https://doi.org/10.4236/cweee.2019.84007

[22] Tsirogiannis, E. and Angelidis, P. (2023) The Impact of Climate Change on the Stratification of Coastal Areas of the Euboean Gulf and the Diffusion of Urban Wastewater in Them. *Computational Water*, *Energy*, *and Environmental Engineering*, **12**, 1-26. https://doi.org/10.4236/cweee.2023.123001

[23] Kotsovinos, N. and Angelidis, P. (2008) Hydraulics of the Environment. 1st Edition, Democritus University of Thrace, Xanthi.

[24] Lagouvardos, K., *et al*. (207) The Automatic Weather Stations NOANN Network of the National Observatory of Athens: Operation and Database. *Geoscience Data Journal*, **4**, 1-13.

[25] Psohiou, E. (2003) Assessment of the Ecological Status of the Pagasitikos Gulf. School of Agricultural Sciences, Volos. http://dx.doi.org/10.26253/heal.uth.6197

[26] Balopoulos, E., Papageorgiou, E., Charalambakis, A. and Papadopoulos, V. (1987) Measurements of Sea Currents in the Western Aegean Sea: Pagasitic Gulf. *Proceedings of the* 2*nd Panhellenic Symposium on Oceanography*, Athens, 318-321.