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Current Circulation and Water Renewal Time in the Enclosed Marine Area of Pagasitikos Basin, Greece

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Abstract

Greece boasts an impressive closed coastline stretching across 13,676 km, making it the largest in the Mediterranean basin and one of the largest in the world. Given the significant human activities that take place in coastal areas, understanding the behavior of the sea environment becomes crucial. In this study, we delve into the generation and movement of marine currents as well as the retention time and water age within the waters of Pagasitikos Sea inlet, Greece, through numerical simulation of hydrodynamic characteristics. The main examined points of the understudy region are the area of the port of Volos, the Trikeri channel where the ingress and egress of water from the Gulf takes place and the exchange of seawater through circulation of the Pagasitikos Gulf with the North Evian Gulf. In order to evaluate the results, they were compared with real field measurements and with simulation on a laboratory dummy of the same area. The computational simulation was performed with the ELCOM 2.2 numerical modeling tool and the AEM3D latest version and the main factors simulated are the tide, the consequence that Coriolis force, boundary conditions, the topography and bottom geometry of the bay and the actual meteorological conditions of a whole year.

Keywords

Fluid Dynamics Simulation, Current Circulation, Pagasitikos Basin, ELCOM

1. Introduction

Semi-closed sea basins are geographical features characterized by major limited water exchange with the open sea. These basins have very limited water exchange and restricted connections to the open sea, usually through narrow straits or channels. This limited exchange impacts water characteristics such as diffusion, retention, age, temperature, salinity and others and others which are crucial for the human activities that develop around them. The Pagasitikos Gulf is a semi-enclosed marine area where water is hardly renewed and with complex mechanisms that have not been fully investigated. Various studies, physical oceanographic surveys and papers have been carried out in recent years to investigate the status of the Pagasitikos Gulf due to its morphology and its vital importance for the region [1]-[11]. In particular, information on the circulation of the sea masses is mainly available from studies of past years based on direct measurements of currents [12]. There was recently presented a model to simulate the hydrodynamic characteristics and circulation in the bay. This is the first attempt to model the hydrodynamic behavior of the gulf and capture the movement of currents, the age and the time of water renewal. The hydrodynamic attribute of the Pagasitikos basin was simulated computationally using the Aquatic Ecosystem Model-3d (AEM3D) and Estuary, Lake & Coastal Ocean 3d hydrodynamic Model (ELCOM 2.2) [13] [14]. Several relevant numerical simulations of marine areas in other regions that worked on ELCOM 2.2 and AEM3D [13]-[15] have been performed with very good predictions and related papers have been carried out [16]-[27]. The simulation was run with modeling parameters as the bottom geometry, tidal influence, real weather conditions of wind speed and direction, air temperature, rainfall, humidity, sunemission and pressure of the atmosphere [28]. Simulation and record took place for one whole year of the surface and deep water velocity, density, salinity, and age of the water throughout the Pagasitikos Gulf and then qualitative comparison with a laboratory hydraulic model and quantitative comparison with actual recorded values from previously performed field measurements took place [12]. ELCOM utilizes hydrodynamic and thermodynamic models to conduct numerical simulations, aiming to replicate the behavior of stratified water bodies. The hydrodynamic simulation technique employed in ELCOM solves the unsteady, viscous Navier-Stokes equations for incompressible flow, disregarding the non-hydrostatic pressure terms. To address horizontal turbulence, the Reynolds-average Navier-Stokes equations are solved, and the turbulence closure is accomplished through the implementation of horizontal eddy-viscosity. On the other hand, a vertical mixed-layer model is utilized to tackle vertical turbulence [13] [15]. Additionally, the advection of passive and active scalar tracers, including parameters like speed, direction, and retention, is achieved by employing the conservative semi-implicit ultimate quickest discretization method. The simulation results in visualizations of quantities at the surface and various depths and investigates the mechanisms of recharge of the bay waters. Evaluation of results assessment is achieved by comparison with field measured values and not with results or forecasts from other models. Pagasitikos basin gives us ideal simulation conditions as it has no large open sea boundaries, and is enclosed by solid boundaries with two relatively small and bounded open sections where boundary conditions are very well applied (**Figure 1**). The aim of this work is the understanding of the 3D water circulation under the prevailing physical conditions and loads so that the model can be used in longer-time simulations to predict the future behavior of the specific basin.

2. Study Field—3D Computational Domain

For the analysis of marine currents a computational model simulation of the Pagasitikos Gulf has been used, which has already been run and has given important results. The simulation area is the whole Pagasitikos Gulf that is a naturally enclosed basin with a total wider surface of 165 square kilometers basin, with a maximum depth of 101 meters, maximum dimensions of 31 kilometers from arctic to south and 16 kilometers from eastern to westwards (**Figure 1**) and a single point of inlet and outlet of the water South at Trikeri peninsula north of Evia with an aperture dimension of 5.5 kilometers. The simulation area has dimensions of 47.5 kilometers by 31.5 kilometers, a surface area of 1503 square kilometers, two open sea cross-sections at the Artemisio east of the Maliakos Gulf (W.4-4') and at the confined point between North Evia and the southern Pagasitikos coastline west of Skiathos (E.5-5') (**Figure 2**). At these districts, the open boundary conditions of 10 kilometers and 5.2 kilometers length with free water incursion and outflow from each cell were simulated including the existing conditions at each computational step.

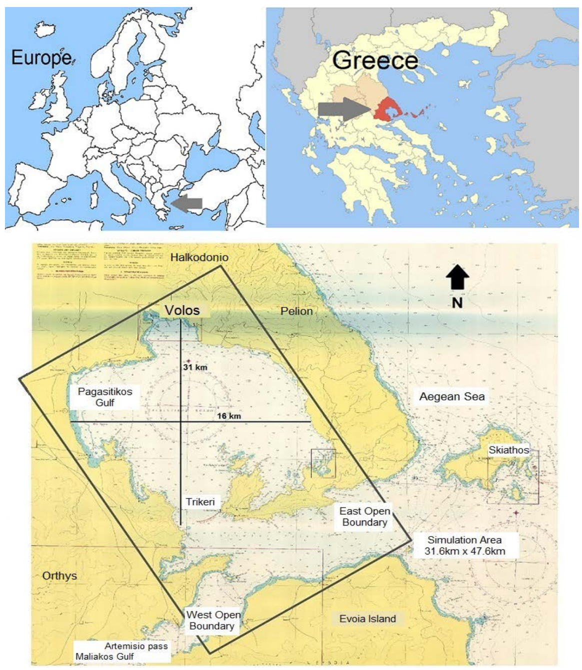


Figure 1. Pagasitikos map plus the simulation field.

All 3D computational domain consists of 394,842 active cells of fixed dimensions of 400 m × 400 m horizontal resolution and fixed height dz = 2.5 meters with 42 horizontal layers covering the entire depth of the bay and a rotation of

32.1 degrees to the right so that the influx and efflux at the open bounds is lying flat (**Figure 2**). The results of the vertical discretization are recorded and displayed at 14 layers every 2.5 meters or 5 meters including surface and bottom. The model has three upright sections that keep data records (curtains) two perpendicular to the Y-axis one near Almyros (section Y.1-1') and one at the water entry of the bay near Trikeri (section Y.2-2') and one perpendicular to the X-axis which passes through the port of Volos (section X.3-3') (**Figure 2**).

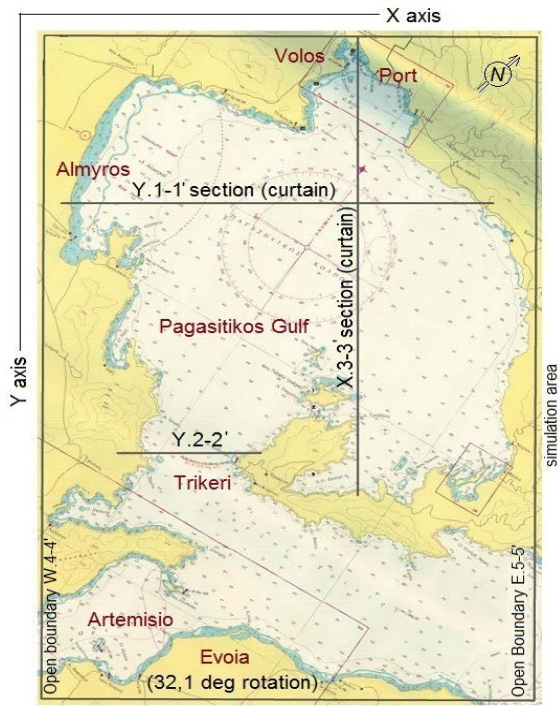
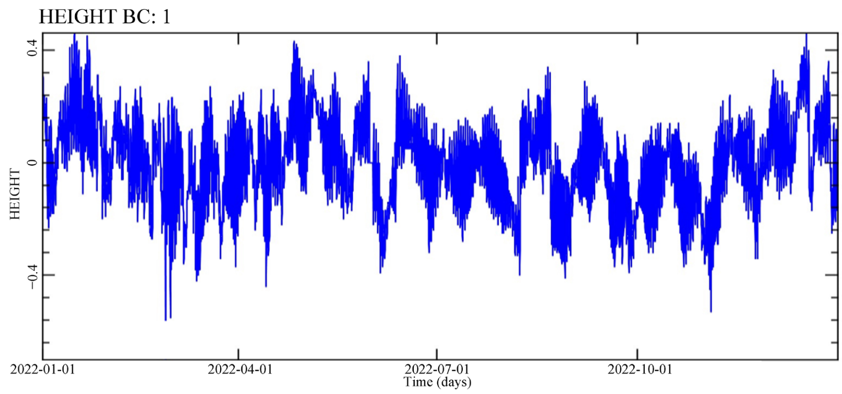


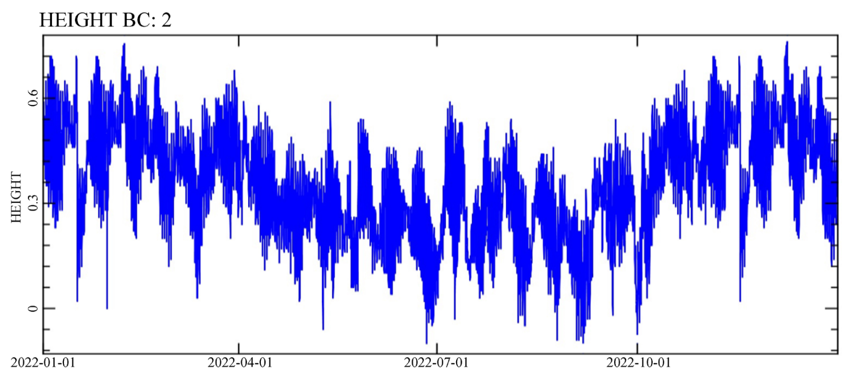
Figure 2. Simulation area (32.1˚ rotation), vertical sections and open boundaries.

3. The Numerical Modeling Process

With the two hydrodynamic models [14] [15], modeled and simulated processes include stratified water flow simulated in time and velocity results at the surface and in several depths and directions of water currents. The residence and rejuvenate time were obtained. Visualization was performed on surface images and vertical sections in the computational domain and the validity of the simulation was affirmed after comparison with measurements and published sampling results. Introductory salinity and temperature settings at the beginning of the simulation in all cells were 16.10 degrees Celsius (˚C) and salinity of 37.40 practical salinity units (psu), which are typical measurements taken outside the estuary. In order to simulate the open boundary conditions and tides, the sea surface variation at the eastern boundary (E.5-5') for a full year and was entered using data from the Poseidon system of ELKETHE which has systematic measurements, among other field data, and sea level values from the measuring station in Skopelos from 24-5-2021 to date [29] with location of latest transmission latitude: 39.1238—longitude: 23.7297. Two records were selected for a full calendar year and a combined time series import in Julian form of the sea level difference at the eastern open boundary was performed, which is summarized in **Figure 3(a)**. The model then automatically generated the water velocities due to sea level difference and produced all the corresponding sea level changes at the western open boundary which is also summarized in **Figure 3(b)**, so there is a complete and real tide simulation. In order to select the optimal time step (dt), a sensitivity analysis was performed with short-duration test simulations for various time step values from which the main ones were selected 60 sec, 120 sec, 180 sec and 240 sec. Tests with dt shorter than 60sec were rejected because they eventually produced files with too large a volume of stored data and were difficult to process subsequently. Tests with dt greater than 240 sec were also rejected because the simulation exhibited instabilities. A recycling time step of 180 sec was selected as the subsequent velocities most closely approximate the real published measurements [12]. The simulation was performed for one year, using full actual recorded meteorological data for one year [29] and recording and visualization of age, retention time and water refresh results at the surface and in the vertical field transects. The simulation yields visualizations of results at the surface and



(a)



(b)

Figure 3. Annual sea water level change: (a)sea level values from the Skopelos measuring station at the East open boundary E-5-5', (b) sea level values generated by the model at the West open boundary W-4-4'.

at selected depths and shows the structure form of estuary water renewal. The main criterion was to make comparisons of results with real values and not with results or predictions of other models. The points of the field measurements were simulated after being converted from latitude and longitude to coordinates and were placed in the computational field accurately. The simulation of the depths of the measurements was made through vertical curtains that were created in the point cells giving us vertical velocity distributions throughout the depths.

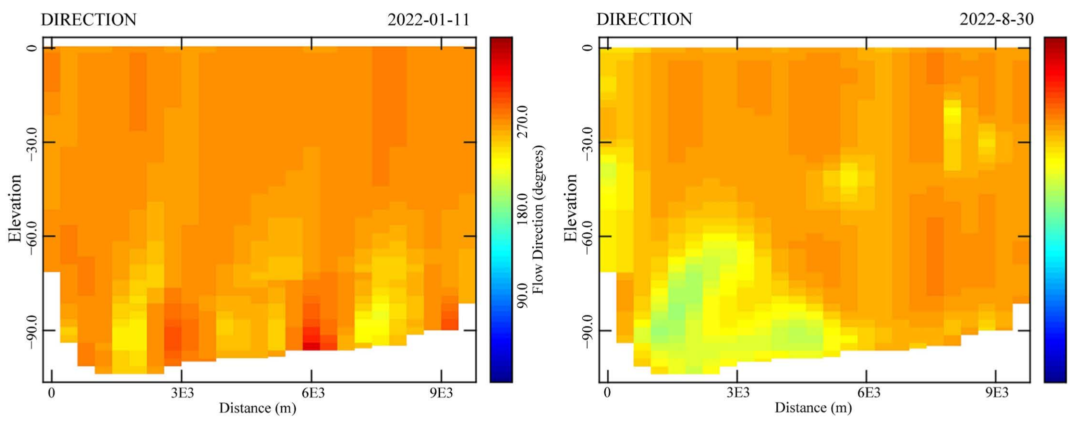
4. Results and Analysis of Hydrodynamic Circulation

4.1. Water Circulation outside the Pagasitikos Gulf

The water circulation in the area outside the Pagasitikos is first examined in order to determine how the bay communicates and interacts with the adjacent marine area from which it is fed with seawater.

4.1.1. Water Movement through Eastward and Westward Open Bounds, Direction of Currents, Communication with the North Evian Gulf

Almost throughout the entire evolution of the phenomenon, the water flow in the section between the open boundary (E.5-5') at the East and the open boundary (W.4-4') at the West occurs in a constant direction from East to West. This is clearly illustrated in two characteristic snapshots (**Figure 4(a)** & **Figure 4(b)**) where the water direction at the open boundary (E.5-5') is shown in color for winter and summer to be West-Southwest from 270 degrees to 230 degrees. Also correspondingly in two winter-summer snapshots (**Figure 5(a)** and **Figure 5(b)**) from open boundary (W.4-4') the water direction is West-Southwest from 270 degrees to 230 degrees with small changes in flow in the northern part of the transect due to the small cross-section in the area of the island of Argyronisos. The water direction is consistently West in the upper layers (orange) and more rarely slightly Southwest (yellow) in the deeper layers. This pattern prevails throughout the year, thus confirming an inflow of water from the Aegean Sea with a steady movement towards the (W.4-4') boundary (North Evian) and



(a) (b)

Figure 4. Direction of water currents at the East boundary (transect E.5-5'): (a) in January, (b) in August.

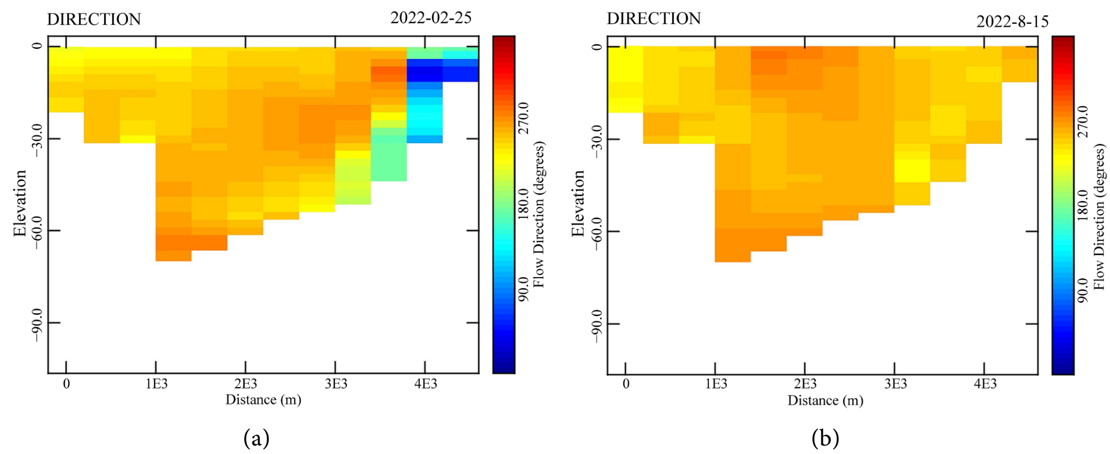


Figure 5. Direction of water currents at the West boundary in (Section W.4-4'): (a)in February, (b) in August.

through the entrance of the Pagasitikos (Trikeri). There is also no reverse movement of water from the Euboean to the Aegean and the Pagasitikos, so the North Euboean Gulf is fed with water mainly from the Aegean Sea and to a small extent from the outgoing waters of the Pagasitikos Gulf, while no water from the Euboean Gulf enters the Pagasitikos Gulf.

4.1.2. Water Velocities in both Sections E.5-5' and W.4-4'

Water flow velocities entering the Eastern open boundary are in the range of 0.3 m/sec - 0.4 m/sec in the upper layers and decrease with increasing depth with an average value of 0.2 m/sec at depths above 60 meters (**Figure 6**).

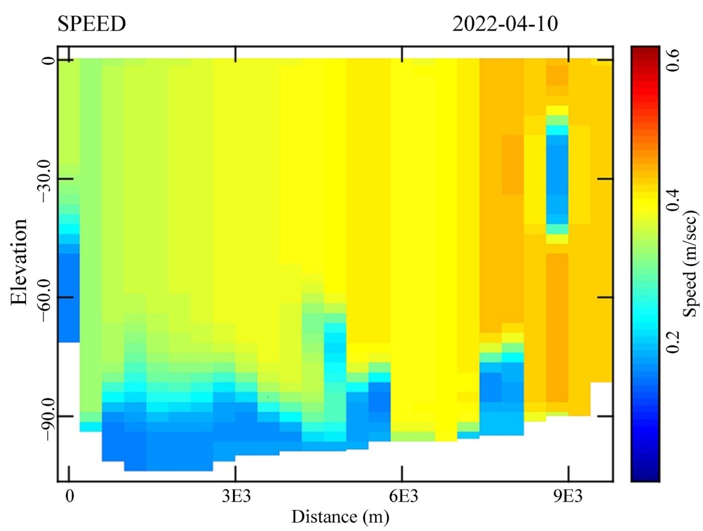


Figure 6. Vertical velocity distribution in section E.5-5'.

Water exit velocity results at W.4-4' boundary are in the range of 0.9 m/sec - 1.2 m/sec and decrease in the deeper layers. Higher velocities evolve at W.4-4' boundary than those prevailing at E.5-5' boundary due to a shorter flowprofile and shallower depth (**Figure 7**).

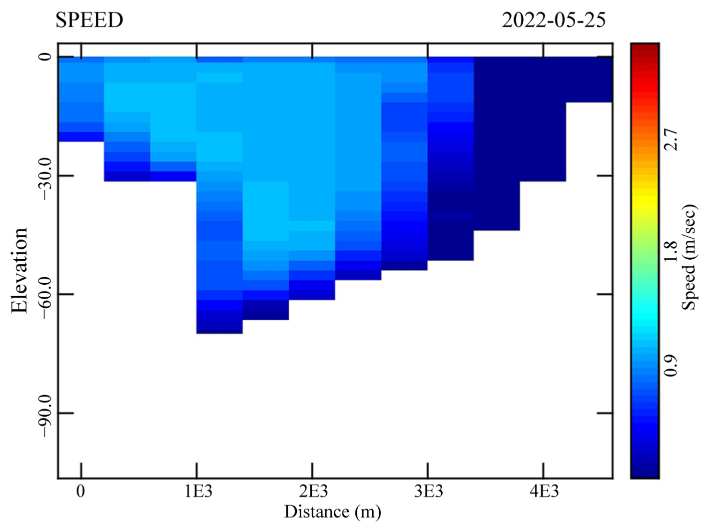
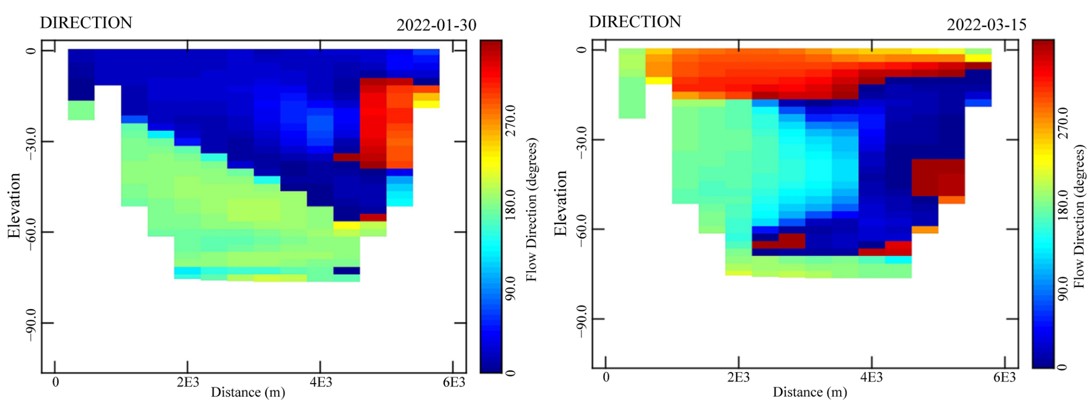


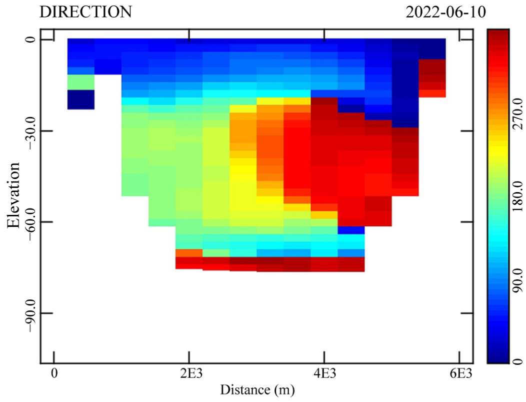
Figure 7. Vertical velocity distribution in section W.4-4'.

4.2. Water Ingress and Egress to the Pagasitikos Gulf at Trikeri Canal

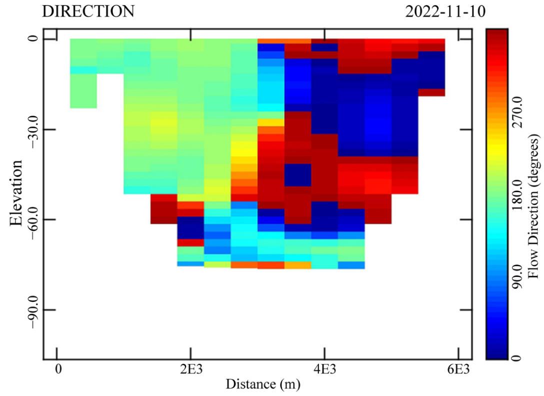
The area of the Trikeri Canal is the natural inlet and outlet of the water masses of the semi-enclosed sea basin being simulated and the results are recorded in cross section W.2-2'. **Figure 8** show the color representation of water currents direction in cross-section Y.2-2' (Trikeri) with distribution. It is observed that the flow often alternates during the simulation but the main flow pattern is that the upper layers with depth up to 50 meters have a direction North-Northwest from 330 degrees to 60 degrees, meaning they enter the bay, while the lower layers with depth of 50 meters and above have a direction South-Southwest from 180degrees to 220 degrees meaning they exit the bay. The results are consistent with the measurements conducted, which demonstrate that the waters from the North Euboean are strengthened on the left side of the Trikeri Canal by surface flow originating from the Aegean [1] [12]. The above water masses enter the bay through the surface layers, while relatively warmer and more saline waters exit in the deeper layers among 50 meters.



(a) (b)



(c)



(d)

Figure 8. Color representation of water currents direction in cross-section Y.2-2' (Trikeri) with depth distribution: (a) on January-winter, (b) on March-spring, (c) on June-summer, (d) on November-Winter.

Therefore, it is confirmed that the water recharge takes place with water entering from the Aegean Sea along the left side of the Trikeri canal and water exiting to North Eubian along the right side of the channel.

4.3. Water Circulation within the Gulf

In the period February-November 1999 a research study was carried out to measure the currents in the Pagasitikos Gulf using an acoustic tomography [12]. Although the water diffusion in the Pagasitikos is complex and controlled by both wind force, exchange of water with the Aegean Sea and tidal action, it appears that a constant dipole is observed in the bay. An anticyclone in the eastern region and a cyclone in the central region mixed with minor eddies. The computer simulation has given exactly this picture of the movement of currents throughout the evolution of the phenomenon. In three characteristic snapshots-graphs of the main velocity vectors (**Figure 9(a)**, **Figure 9(b)** and **Figure 9(c)**) the direction of the sea currents in the interior of the Pagasitikos Gulf is very well captured. **Figure 9(a)** illustrates the velocity vectors at the beginning of the event showing the main velocity vectors and the water direction from the outside towards the interior of the bay. The entry and diffusion of water from the Trikeri Channel into the bay towards the coastal areas and the formation of the cyclone dipole in the eastern and western inner bay area with higher velocities in the central and northeastern areas are captured. It also shows the direction of water flow between the two open boundaries with higher velocities at the western end. **Figure 9(b)** shows after three months of simulation the strengthening of the cyclonic flow within the bay where the East and West vectors depict a stable double anticyclone in the interior of the bay and the stabilisation of the water movement and the stabilisation of the water movement between the two open cross-sections from east to west. **Figure 9(c)** shows after 10 months during a day with strong northerly winds the reversal of water movement from North to South and the partial exit from the Trikeri Channel to the North Euboean. The Coriolis force explains this counter-meteorological movement as it deflects the wind direction to the right and consequently the currents within the bay.

From the set of velocity vectors given by the simulation, the main picture of the developing currents with their directions in and out of the bay is obtained, which is illustrated in Figure 10.

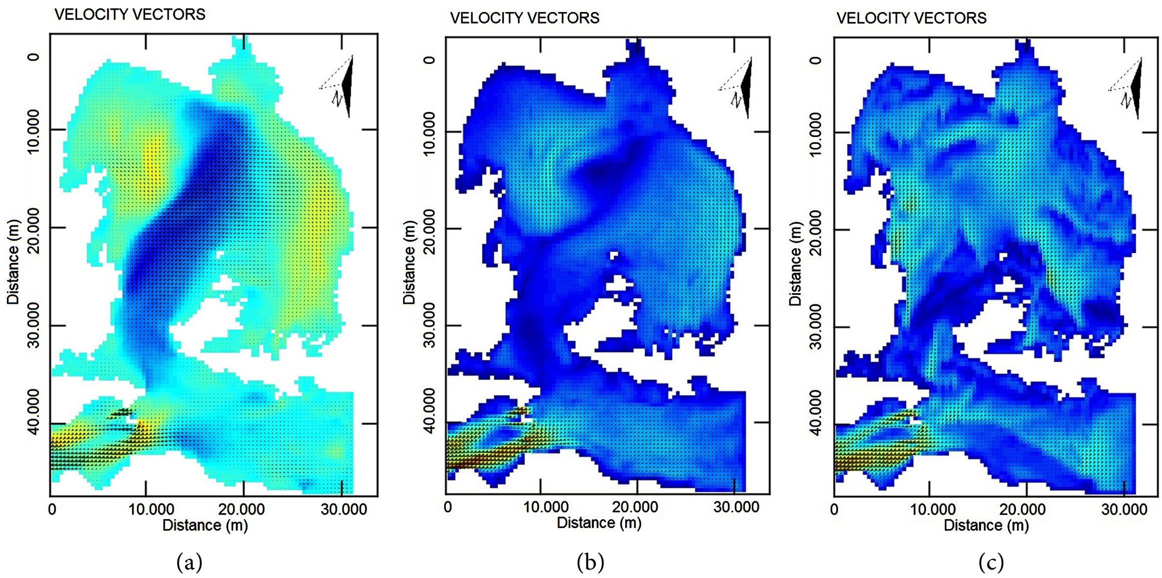


Figure 9. Plots of the main velocity vectors in the study area: (a) at the beginning of simulation, (b) after three months of simulation, (c) after 10 months of simulation.

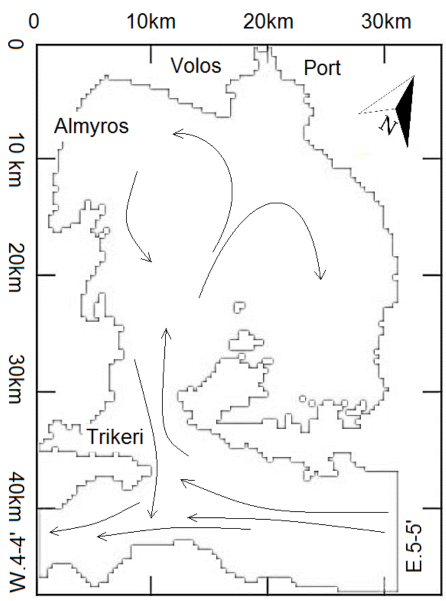
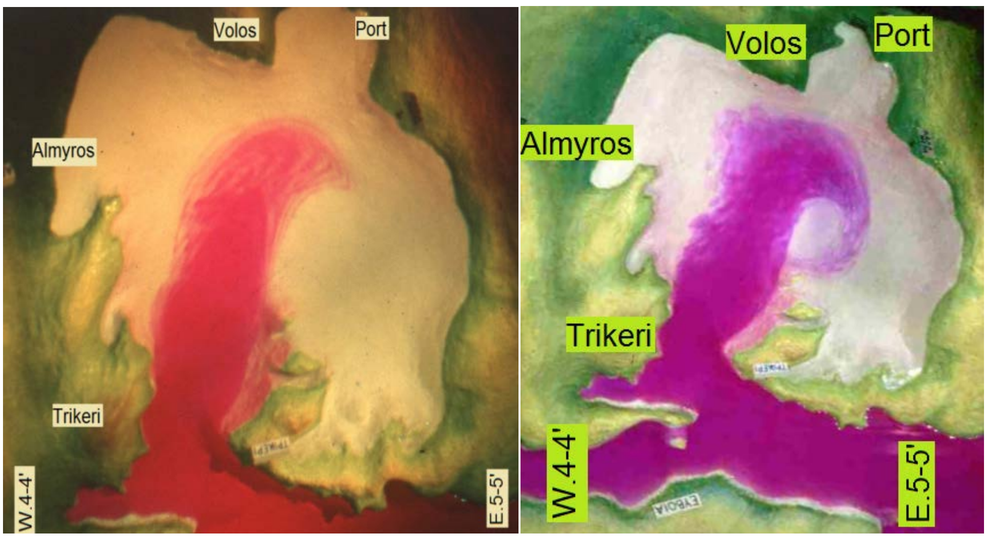


Figure 10. Schematic representation of water circulation and currents directions in and out of the Pagasitikos Gulf.

4.4. Qualitative Comparison with Laboratory Model—Model Evaluation

The laboratory modeling of water diffusion in the Pagasitikos basin was initially examined by constructing a hydraulic dummy in the Laboratory of the Hydraulic Works of the DUTH. The whole project was under the supervision of Professor Nikolaos Kotsovinos who collaborated in the construction of the numerical model and with his agreement we used the results of the experiment in this paper for evaluation. A study of the water diffusion among the North Evian Gulf and the waters of the Pagasitikos took place. The dummy was constructed on a warped scale, and without layering, with dimensions of 1.5 meters wide, 1.5 meters long and 0.40 meters deep, and the phenomenon was recorded photographically. The two characteristic photographs of the evolution of the laboratory phenomenon **Figure 11(a)** and **Figure 11(b)** show in red the water entering the bay from the North Euboean Gulf and show the thinning of the water and the direction of the current created at the beginning and in the middle of the experiment respectively. This macroscopic record of the Euboean-Aegean inlet into Pagasitikos is interesting as it shows the creation of a large eddy that initially moves northwards and then turns east and south towards the eastern shores of the bay. This eddy is mainly due to the topography of the area simulated in the laboratory.



(a) (b)

Figure 11. Photographic illustration of the laboratory hydraulic model of the Pagasitikos Gulf: a) at the beginning of the experiment, b) in the middle of the experiment.

In order to have a qualitative comparison and evaluation of the computer simulation, the entry of water from the outer ocean into the east boundary E.5-5' was simulated with a conservative tracer that enters consistently along the entire length and depth of the open boundary. As the simulation progresses, several snapshots are recorded and compared with the images of the laboratory model at corresponding time points. Two typical of them at corresponding times with those of the experiment are **Figure 12(a)** at the beginning and **Figure 12(b)** in the middle of the numerical simulation. In the computer model in addition, the Coriolis force, meteorological data, salinity, tides, accurate bay bottom geometry and the overall topography at real scale were simulated, which are crucial for the hydrodynamic circulation. Under the influence of these additional conditions, phenomena are also more pronounced in the computational simulation. The laboratory procedure has significant resemblance with the numerical simulation in terms of water circulation, mixing, and flow direction. While the computational simulation shows a more pronounced and precise representation of the phenomenon, the overall depiction closely mirrors that of the laboratory model. The same inlet current is generated in the bay and the same large eddy with a similar direction. It is observed that the incoming current from E.5-5' moves westward, a part of it enters the Pagasitikos Gulf and a part of it continues westward to the North Eubian and then to the rest of the Eubian Gulf. The current entering the Pagasitikos also moves North initially and then proceeds in the form of a vortex moving East and South towards the Eastern shores of the bay.

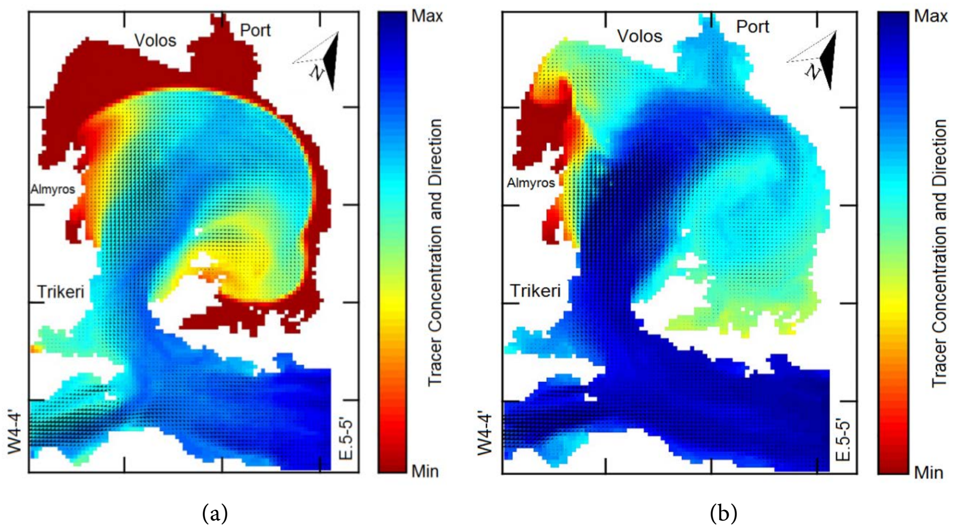


Figure 12. Tracer concentration and direction during hydrodynamic simulation: a) at the beginning of the numerical simulation, b) in the middle of the numerical simulation.

The Coriolis force and all the additional conditions simulated computationally enhance the effect, which as seen in the laboratory dummy is generated without them. Therefore, the correctness of the computational simulation is confirmed and evaluated as correct qualitatively compared to the laboratory simulation.

4.5. Water Renewal and Residence Time—Investigation of Water Renewal in the Volos Port Area

Current measurements carried out in the Pagasitikos Gulf and a recent hydrodynamic Simulation of the same basin [30] showed that water renewal occurs with the inflow of water from the Aegean Sea onwards east shore of the Trikeri canal and the outflow of water from the Aegean Sea along the western shore of the channel with a typical water renewal time of 105 days with an average deviation of 51 days [1] [12]. **Figures 13-16** show water age in the inner bay at 3 months (90 days), 6 months (180 days) and 9 months (270 days) as derived from the present study, in hypsometric contour curves. The analysis of the contour curves shows that after 90 days in the areas where the lines have a value of 70,80 days the recharge is almost zero or very small as the water age is very close to the time of the evolution of the phenomenon. In contrast, in areas where the isobaths

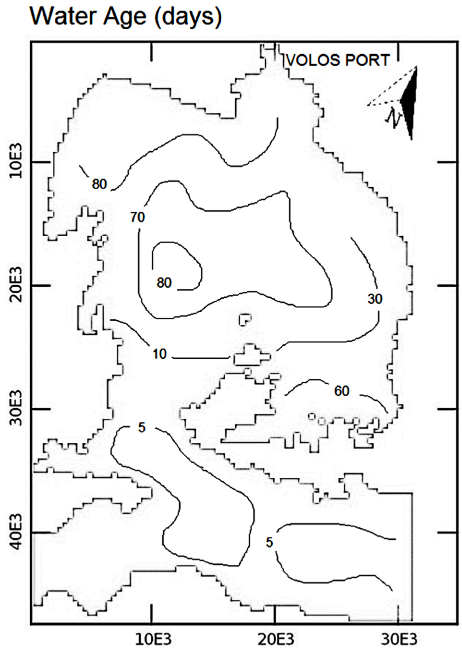


Figure 13. Water age contours at 90 days (March).

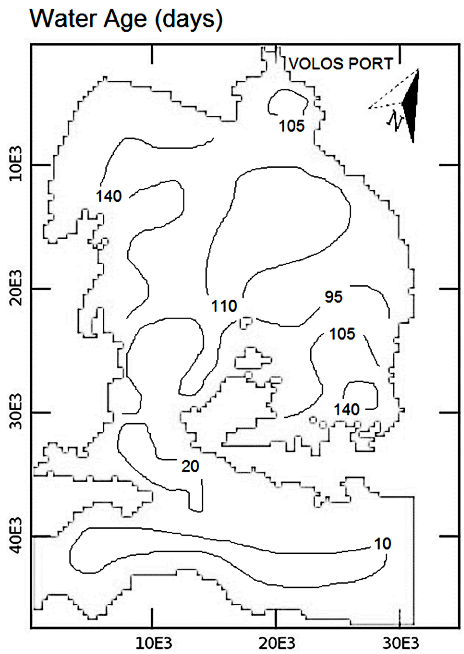


Figure 14. Water age contours at 180 days (June).

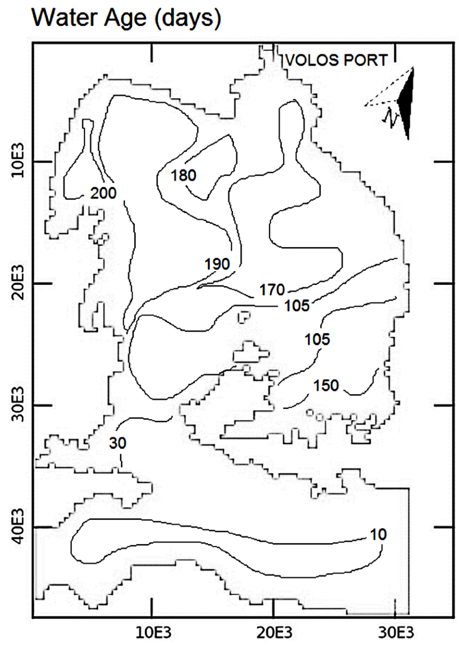


Figure 15. Water age contours at 270 days (September).

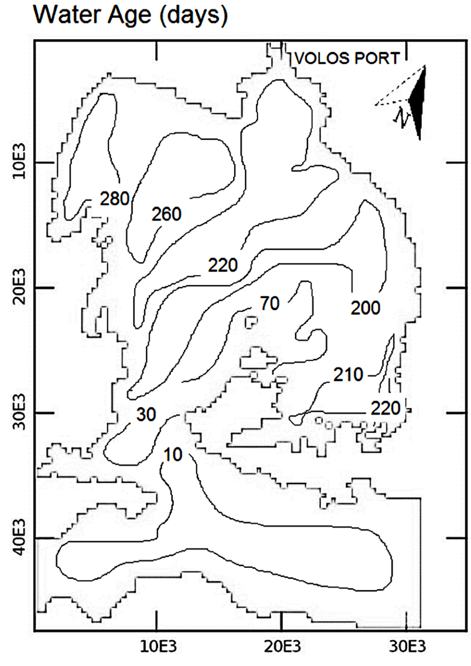


Figure 16. Water age contours at 360 days (December).

have lower age values such as 60, 30 or 10, the water recharge is greater. Thus we see that on the eastern shores of the bay water is renewed faster while in the northern and northwestern areas, the renewal is significantly delayed. The picture is similar to the evolution of the phenomenon (180, 270 days) and at 360 days when the simulation is completed we see that in the Northwestern areas, the water is 260 - 280 days old (so the renewal has taken place 80 to 100 days ago) and in the Eastern areas the water is 200 - 220 days old (so the renewal has taken place 140 to 160 days ago). In the other central regions, the age is much lower because renewal has been achieved for the 2nd and 3rd time. Therefore, we conclude that by the completion of the simulation the renewal time shows a lower value of 80 days and a higher value of 160 days, the average renewal time is 110 days with a maximum standard deviation of 50 days. This agrees with the recharge time given by the stream measurements, which quantitatively evaluates the computer simulation and confirms its reliability. In the region of Volos Port, according to the analysis of contour curves and the residence times recorded by the simulation in section X.3-3' which starts from this point, the water age ranges from 140 to 160 days which means that the renewal of the water takes place every 4 to 5 months.

5. Discussion

In this paper, a numerical modeling of the Pagasitikos Gulf takes place. The basic characteristics that determine the generation and movement of marine currents in the semi-enclosed sea basin of the study area were investigated computationally. The main features of these are (a) the movement of marine currents between North Evia and Pagasitikos between the two open sea districts, (b) the entry and exit of water from the basin and (c) the movement and retention of water within the basin. These three basic characteristics are analyzed below in order to have a complete picture of the hydrodynamic characteristics of the Pagasitikos.

5.1. Movement of Sea Currents between North Evia and Pagasitikos between the Two Open Sea Districts

The mapping of the results between transect E.5-5' East where the area under consideration communicates with the Aegean Sea and transect W.4-4' West where the area communicates with the North Evian Gulf shows that the predominant water movement is from East to West. A stable sea current, in the form of a river, develops, which flows from the Aegean Sea, enters this closed area, a part of it enters the Pagasitikos Gulf and a part of it continues passing through the island of Argyronissos towards the Malian Gulf and then enters the North Euboean Gulf. There is no reverse flow of water in the W.4-4' transect throughout the year, while the water leaving the Pagasitikos Gulf also flows into the North Evian Gulf. Flow velocities are generally between 0.5 m/sec and 1.0 m/sec and increase locally in the Argionissos area due to a significant reduction in the sea cross-section. The main conclusion here regarding the interaction of the North Euboean Gulf with the Pagasitikos Gulf is that the waters from the Euboean do not enter the Pagasitikos but only the reverse occurs. Therefore, the Euboean Gulf does not seem to have a serious environmental impact on the Pagasitikos.

5.2. Inlet and Outlet of Water from the Pagasitikos Gulf

The only point where seawater enters and leaves the bay is the channel at the height of Trikeri. The simulation results as captured in the horizontal cross-section Y.2-2' show that the predominant water movement is ingress to the interior of the bay, in the upper general layers up to 50 m. depth, which alternates with egress to the North Evian mainly at deeper than 50 meters layers. Water renewal takes place with water entering from the Aegean Sea through the eastern shore of the Trikeri canal and water exiting to the Aegean Sea along the western shore of the channel.

5.3. Water Movement and Retentionin the Bay

Within the bay, there is a constant dipole: a clockwise heading cyclone in the eastern bay and a counterclockwise one in the central western bay diffusing with other weaker eddies. The direction of the sea currents is initially from the outside to the interior of the bay, thus reflecting the entry and diffusion of water from the Trikeri Channel to the coastal areas, and then they take the form of the double anticyclone in the interior of the bay under the influence of the Coriolis force, which also determines the wind direction. Upon completion of the simulation, the water renewal time shows a lower value of 80 days and a higher value of 160 days, the average renewal time is 110 days with a maximum standard deviation of 50 days. On the eastern shores of the bay, the water is renewed faster, while in the northern and north-western areas, the renewal is significantly delayed. In the other central areas, the age is much lower because the renewal is achieved more quickly. In the Volos area, where the port is located, water renewal is mainly determined by the sea currents, climatic loadings and the geography of the port. All these three main factors have been simulated in the computer model. The average age of the water in this area is in the range of 140 to 160 days which suggests that the water is renewed every 4 to 5 months.

6. Conclusions

In this study, the numerical simulation of the hydraulic features of the Pagasitikos Gulf was achieved with the use of ELCOM 2.2 and AEM3D models running for one year. The hydrodynamic demeanor of the bay, water diffusion, water enrichment and water residence all through the basin area were analyzed and the precision of the results was achieved by comparing with published measurements and a laboratory dummy. The simulation led to visualizations of quantities at the surface and various depths and analyzed the way of bay water enrichment. The simulation predicted that there is no interaction of the North Evian Gulf as no water from the Evian Gulf enters the Pagasitikos Gulf. The inflow of water into the Pagasitikos flows from the E.5-5' boundary (Aegean Sea) to W.4.4' boundary and not from the Euboean Gulf. This finding is very important as it shows us that the Pagasitikos cannot have an environmental impact on the Evian Sea. The main water flow in the northern Evian is from east to west with a part of the flow entering Pagasitikos basin, while the rest moves westwards. Advancedwater speeds evolve at the western open bound and the water is mainly flowing towards the Evian Sea. This finding is also important as it excludes the possibility that the Pagasitikos can have an environmental impact on the Aegean Sea. As shown by the distribution of mean currents and turbulence in the East but also in the Western Pagasitikos, there is a negative rotation, a tendency counterclockwise anticyclonic circulation, while in the Central Pagasitikos positive rotation prevails a tendency of left-handed (cyclonic) circulation. In the interior of the basin, an almost permanent symmetrical dipole is observed: a clockwise cyclonic flow in the eastern and a counterclockwise cyclonic flow in the central western bay accompanied by small diffusion vortices. The direction of the sea currents is from the outside to the interior of the bay from the Trikeri Channel to the coastal areas and a double anticyclone current prevails in the interior of the bay. The average water renewal time is 110 days with an average deviation of 50 days. Important conclusions are drawn about the time it will take to replenish the water on the different coasts of the bay.

The study of the contour curves reveals that in regions where the lines indicate a value of 70 or 80 days, the recharge of water is nearly nonexistent or minimal due to the water age closely aligning with the duration of the phenomenon's evolution. Conversely, in areas where the isobaths display lower age values such as 60, 30, or 10, the water recharge is more substantial. This discrepancy is evident along the eastern coast of the bay, where water renewal transpires at a faster rate compared to the northern and northwestern zones, where the renewal process is notably delayed. As the phenomenon continues to evolve, we see a comparable pattern at 180, 270, and ultimately 360 days, indicating the end of the simulation. By the end of the simulation, it is observed that in the northwestern areas, the water is approximately 260 - 280 days old, signifying a renewal that occurred 80 to 100 days prior. On the other hand, in the eastern regions, the water age ranges from 200 to 220 days, indicating a renewal that transpired 140 to 160 days earlier. In central regions, the water age is considerably lower due to multiple renewal events. Consequently, the analysis concludes that the average renewal time by the end of the simulation is 110 days, with a minimum of 80 days, a maximum of 160 days, and a standard deviation of 50 days.

On the eastern shores of the bay, the water is replenished faster, while in the northern and north-western areas, the replenishment is significantly delayed. In the other central areas, the age is much lower because the renewal is faster. In the area of Volos, where the port is located, the water is renewed every 4 to 5 months.

This means that a pollutant entering this area will take at least 5 months to completely leave, relying solely on natural water renewal. In areas closer to the Trikeri seaway, the water's age decreases and the renewal mechanisms are faster. The findings acquired offer enhanced understanding of water diffusion within the basin and precisely ascertain the three-dimensional water circulation under the prevailing natural circumstances and loads. The computational model can be employed in extended time simulations to anticipate the future dynamics of the bay, thereby proving valuable in broader environmental planning efforts for the region and mitigating potential environmental deterioration of the bay. This paper studies the structure, function and dynamics of the Pagasitikos Gulf ecosystem, focusing on factors such as current movement and water retention in order to provide a comprehensive and combined description of the sensitive ecosystem of the Bay and take further measures aimed at sustainable management of the area.

Conflicts of Interest

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

References

[1] Psohiou, E. (2003) Assessment of the Ecological Status of the Pagasitikos Gulf. Master's Thesis, University of Thessaly.

[2] Dimarchopoulou, D., Keramidas, I., Tsagarakis, K. and Tsikliras, A.C. (2019) Ecosystem Models and Effort Simulations of an Untrawled Gulf in the Central Aegean Sea. *Frontiers in Marine Science*, **6**, Article 648. https://doi.org/10.3389/fmars.2019.00648

[3] 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

[4] Kokkinos, K., Roditi, K., Prapa, A. and Vafeidis, D. (2022) Ahp and Fcm-Based Modeling of Socio-Economic and Environmental Factors in Fishing Management: The Case of Pagasitikos Gulf, Thessaly, Greece. *SSRN Electronic Journal*. https://doi.org/10.2139/ssrn.4271287

[5] 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

[6] Papanastasiou, D.K., Melas, D. and Kioutsioukis, I. (2007) Development and Assessment of Neural Network and Multiple Regression Models in Order to Predict PM10 Levels in a Medium-Sized Mediterranean City. *Water, Air, and Soil Pollution*, **182**, 325-334. https://doi.org/10.1007/s11270-007-9341-0

[7] Korres, G., Triantafyllou, G., Petihakis, G., Raitsos, D.E., Hoteit, I., Pollani, A., *et al.* (2012) 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

[8] Lyra, A., Loukas, A., Sidiropoulos, P., Tziatzios, G. and Mylopoulos, N. (2021) An Integrated Modeling System for the Evaluation of Water Resources in Coastal Agricultural Watersheds: Application in Almyros Basin, Thessaly, Greece. *Water*, **13**, Article 268. https://doi.org/10.3390/w13030268

[9] Karageorgis, A.P., Kanellopoulos, T.D., Mavromatis, V., Anagnostou, C.L., Koutsopoulou, E., Schmidt, M., *et al.* (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

[10] 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. https://doi.org/10.4194/1303-2712-v14_2_24

[11] Petihakis, G., Tsiaras, K., Triantafyllou, G., Korres, G., Tsagaraki, T.M., Tsapakis, M., *et al*. (2012) 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

[12] Balopoulos, E., Papageorgiou, E., Charalambakis, A. and Papadopoulos, V. (1987) Measurements of Sea Currents in the Western Aegean Sea: Pagasitic Gulf. *Proceedings of the 2nd Panhellenic Symposium on Oceanography*, Athens, 7-11 May 1987, 318-321.

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

[14] 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

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

[16] Kamidis, N., Sylaios, G. and Tsihrintzis, V.A. (2011) Modeling the Nestos River Plume Dynamics Using ELCOM. *Desalination and Water Treatment*, **33**, 22-35. https://doi.org/10.5004/dwt.2011.2627

[17] Tsirogiannis, E. and Angelidis, P. (2023) The Hydrodynamic Behaviour of Euboean Gulf Coastal Areas and the Mixing of the Physico-Chemical Characteristics of Urban Sewage Discharged into Them under the Influence of Climate Change. *Computational Water, Energy, and Environmental Engineering*, **12**, 27-57. https://doi.org/10.4236/cweee.2023.124002

[18] Rao, Y.R. and Zhao, J. (2010) Numerical Simulation of the Influence of a Red River Flood on Circulation and Contaminant Dispersion in Lake Winnipeg. *Natural Hazards*, **55**, 51-62. https://doi.org/10.1007/s11069-010-9534-5

[19] Missaghi, S. and Hondzo, M. (2010) Evaluation and Application of a Three-Dimensional Water Quality Model in a Shallow Lake with Complex Morphometry. *Ecological Modelling*, **221**, 1512-1525. https://doi.org/10.1016/j.ecolmodel.2010.02.006

[20] Kopasakis, K.I., Georgoulas, A.N., Angelidis, P.B. and Kotsovinos, N.E. (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

[21] Nakhaei, N., Boegman, L., Mehdizadeh, M. and Loewen, M. (2018) Hydrodynamic Modeling of Edmonton Storm-Water Ponds. *Environmental Fluid Mechanics*, **19**, 305-327. https://doi.org/10.1007/s10652-018-9625-5

[22] Kopasakis, K.I., Georgoulas, A.N., Angelidis, P.B. and Kotsovinos, N.E. (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

[23] Bocaniov, S.A., Ullmann, C., Rinke, K., Lamb, K.G. and Boehrer, B. (2014) Internal Waves and Mixing in a Stratified Reservoir: Insights from Three-Dimensional Modeling. *Limnologica*, **49**, 52-67. https://doi.org/10.1016/j.limno.2014.08.004

[24] Tsirogiannis, E., Angelidis, P. and Kotsovinos, N. (2019) Hydrodynamic Circulation under Tide Conditions at the Gulf of Evoikos, Greece. *Computational Water, Ener-*

gy, and Environmental Engineering, **8**, 57-78. https://doi.org/10.4236/cweee.2019.83004

[25] Ulańczyk, R., Łozowski, B., Woźnica, A., Absalon, D., Kolada, A. (2021) Water Quality and Ecosystem Modelling: Practical Application on Lakes and Reservoirs. In: Zeleňáková, M., Kubiak-Wójcicka, K. and Negm, A.M., Eds., *Quality of Water Resources in Poland*, Springer, 173-189. https://doi.org/10.1007/978-3-030-64892-3_8

[26] Tsirogiannis, E., Angelidis, P. and Kotsovinos, 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

[27] Kopasakis, K., Laspidou, C., Spiliotopoulos, M., Kofinas, D. and Mellios, N. (2016) Numerical Investigation of Wind Driven Circulation and Horizontal Dispersion in the Surface Layer of a Re-Flooded Shallow Lake. *Environmental Processes*, **3**, 693-710. https://doi.org/10.1007/s40710-016-0165-z

[28] Lagouvardos, K., Kotroni, V., Bezes, A., Koletsis, I., Kopania, T., Lykoudis, S., *et al.* (2017) The Automatic Weather Stations NOANN Network of the National Observatory of Athens: Operation and Database. *Geoscience Data Journal*, **4**, 4-16. https://doi.org/10.1002/gdj3.44

[29] Poseidon System Monitoring, Forecasting and Information System for the Greek Seas. https://poseidonsystem.gr/platforms

[30] Bousbouras, G. and Angelidis, P. (2024) Hydrodynamic Simulation of the Pagasitikos Gulf, Greece. *Computational Water, Energy, and Environmental Engineering*, **13**, 58-85. https://doi.org/10.4236/cweee.2024.131004