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Seasonal Variability of Hydrological Parameters and Estimation of Circulation Patterns: Application to a Mediterranean Coastal Lagoon

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Abstract: Coastal lagoons are among the most important, but also threatened, marine systems of our planet. Rainfall, wind, seawater, and freshwater discharges control water circulation in lagoons, determining the water properties that are vital for the lagoon's biodiversity. The present work is the first study on the circulation patterns and seasonal variability of hydrological parameters in Antinioti lagoon in western Greece, building a reference level on our knowledge of the hydrodynamic functioning of this marine ecosystem. This study shows that the lagoon's water properties' fluctuations and circulation variability are affected by an antagonistic effect between freshwater (river discharge, underground spring, rainfall) and seawater inputs. This effect, influenced by atmospheric forcing (rainfall, atmospheric temperature), controls the heat and salt budgets of the lagoon. Nevertheless, the lagoon keeps an almost balanced annual cycle, returning from June 2020 to June 2021 to similar values for all parameters.

Keywords: coastal lagoon; circulation; temporal variability; seawater; freshwater; hydrology

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1. Introduction

Coastal marine systems are among the most exploited and threatened natural systems on our planet. These ecosystems are of great importance due to their contribution to coastal protection, water quality, carbon sequestration, biological productivity, nutrient cycling, maintenance of fisheries, tourism, education, recreation, and research [1]. One of the most important coastal ecosystems is coastal lagoons, constituting about 13% of the world's coastlines [2,3]. Lagoons are of high interest as they provide significant food resources (aquaculture, fishing) and are the habitats of many different species.

Tides, waves, wind, rainfall, river discharges, and buoyancy effects are the natural mechanisms that drive circulation and water renewal in lagoons, controlling the water properties [4–15]. The most important mechanism is tidal mixing, which has a direct and rapid effect, filling the lagoon with seawater during high tide and emptying it during low tide [16]. Also, morphology plays an essential role in the circulation of a lagoon [17].

The biodiversity of lagoons depends on the water quality and the fluctuations of certain physical and chemical parameters that can cause variations in the structure of marine organisms and communities. Natural or anthropogenic stressors can alter the environmental conditions and even lead to catastrophic events, with the reduction in great numbers of individuals [18–20].

Knowledge of the basic hydrodynamic functioning of a lagoon's system and of the different processes that interact over a wide spatial and temporal range determining the water's quality [21,22] is the first step in understanding the circulation patterns in a lagoon. This assists in estimating its biological productivity and evolution [23] and can render the local authorities able to protect and exploit the ecosystem by taking proper actions.

Antinioti lagoon has been subject to research by biologists in the past studying the invertebrates and marine mammals of the lagoon. To the authors' knowledge, there are only a few studies that have conducted some work measuring the physical parameters of the lagoon by including pH, salinity, and depth measurements. In the study of Botsou et al. [24], the authors investigated the trace metals in various areas of the lagoon's sediments and determined the ecological risk of their release into the lagoon. Differences exist between our depth measurements in similar locations, which is due to the sedimentation and deepening processes that occurred in the interval of 14 years between the two studies. In our previous studies [25–27], we evaluated the influence of environmental parameters on the sustainability of zooplankton and the concentration of microplastic particles, as well as the selection of this habitat by the invasive blue crab species (*Callinectes sapidus*).

To the authors' knowledge, this is the first study with systematic measurements of physical and chemical parameters in Antinioti lagoon, although there are some sporadic measurements in previous studies [24,28]. The scope of this study is to investigate the circulation of Antinioti lagoon and determine the forces that affect its annual cycle. The authors hypothesize that, due to the shallowness of the lagoon, Antinioti lagoon's circulation is controlled by the antagonistic effect of seawater and freshwater inputs, which is influenced by atmospheric forcing. The importance of this study is twofold. (i) Coastal lagoons are the first marine environments affected by the sea-level rise. While the ecosystem and marine organisms can adapt naturally to the effect of the sea-level rise [29], there are still many significant negative effects [30–33]. Thus, this study builds a reference level for the circulation and seasonal variability of hydrological parameters of Antinioti lagoon that can be used in future studies. (ii) Also, knowledge of the circulation patterns of the lagoon could be of great economic importance as dredging due to inundation, excavation, and deepening procedures would be targeted and the costs minimized. Also, the lagoon is subject to significant microplastic pollution, which is probably caused by the transport of microplastic particles in the surface waters of the NE Ionian Sea, and therefore knowledge of the circulation patterns within Antinioti lagoon becomes important for fisheries [25,34,35].

2. Methods

2.1. Study Site

Antinioti lagoon is located in NE Corfu Island, Greece (Figure 1), and covers an area of 1.87 km^2 [26,28]. The lagoon is connected to the sea through a narrow inlet located in the northeast. There is also a connective inlet between the lagoon and the sea in the northwest of the lagoon, but it is currently closed due to sedimentation. The lagoon's water properties are determined by an underground freshwater spring (station 11) and a stream (station 18), as well as precipitation and surface runoff, which mix with the seawater inputs from station 1 (Figure 2).

Antinioti lagoon is the habitat of several rare and protected species of flora and fauna with distinguished plants, mammals, fish, birds, reptiles, and invertebrates [36], which led the lagoon to be listed as an NATURA 2000 site and is therefore protected by the EU [24]. Small-scale aquaculture and local fishermen exploit the lagoon for fish stocks (such as sea bream, sea bass, mullet, and white seabream, among others) distributed to the local market. In addition to fish, the lagoon also provides great numbers of crabs (*Callinectes sapidus*) and occasionally eels and shrimp. Thus, the lagoon plays an important economic role in the local community.

Figure 1. The location of Corfu Island on the map of the Mediterranean region is shown in a red rectangle at the bottom left corner, and the location of Antinioti lagoon on the map of Corfu Island is shown in a red rectangle at the top right corner. The coastline of the lagoon is marked with white color. Images from *Google Earth version: 7.3.6.9796 (64-bit)*, 2017 (accessed on 12 August 2020).

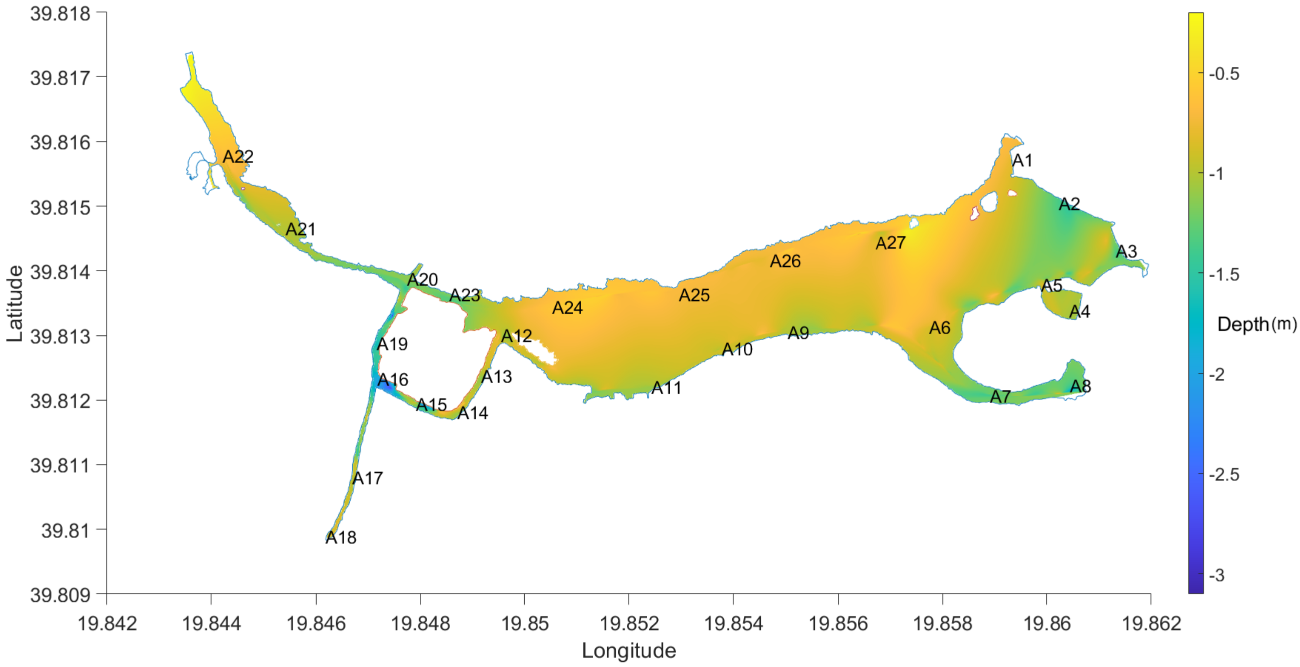

Figure 2. Antinioti lagoon's bathymetry.

2.2. Bathymetry

The lagoon's bathymetry was created by integrating depth measurements made using sonar (also measuring coordinates) in multiple locations across the lagoon's area (Figure 2). Typically, lagoons that exist behind coastal barriers are not affected by the hydrodynamic forcing of the sea and are subject to continued deposition [3]. Therefore, these environments are normally zones of fine sedimentation, which is also the case for Antinioti lagoon. The northern part of the main body of the lagoon is shallow (0.5–0.7 m), while the southern part is characterized by greater depths (1–1.5 m). The main reason for this difference is the deepening operations that occurred several years ago (following the south coastline of the lagoon) from the local fishermen that exploit the lagoon. An underwater embankment (barrier) is formed between stations 6 and 27, extending across from the north to the south coast of the lagoon.

A difference in this pattern of fine sedimentation area is noticed in the channels near the stream in stations 15–16–19 with the presence of scour holes. According to Ferrarin et al. [37], who studied these formations in Venice lagoon, scour holes depend on the characteristics of the flow, salinity gradients, and anthropogenic activities altering the environment. In Antinioti lagoon, there is a stream flow from station 18 (where a stream is located) toward the north and it may be generating the conditions for the maintenance of this scour hole.

2.3. Sampling

Monthly sampling occurred from June 2020 to June 2021, covering 27 sampling stations within Antinioti lagoon, to provide a fine spatial resolution. The sampling dates were between the 12th and 18th of each month between 8 a.m. and 1 p.m. In situ measurements covering the whole water column from the lagoon's surface to the bottom occurred at each station with a Hanna (HI98194) Multiparameter (Hanna Instruments, Woonsocket, RI, USA) probe calibrated beforehand. The parameters measured were temperature (°C), salinity (P.S.U.), density (σ_t-kg/m^3), dissolved oxygen (mg/L), and pH, which were selected as they consist the principal physical properties of fresh and seawater (temperature, salinity, density), the most significant indicator for marine biodiversity (dissolved oxygen), and a great variable for distinguishing fresh and seawater penetrations (pH). Measurements were taken at a rate of 1 scan/s and measurements were obtained at about 5 cm intervals. The raw data were objectively analyzed in Matlab 2021a. Daily meteorological data (atmospheric temperature (°C), rainfall (mm), and wind (m/s)) were obtained from the National Observatory of Athens (www.meteo.gr). The specific station is the closest site of meteorological data for Antinioti lagoon at a distance of 18 km. The station is at the same elevation level as the lagoon and near the sea, and despite the differences in the absolute values that may exist due to the distance from the lagoon, we assume that they relatively well represent the synoptic scale variability. Furthermore, comparisons of wind data taken in the field during the measurements were of great relevance to the station's data (Figure 3). More specifically, performing a simple Pearson correlation showed that the correlation is statistically significant (r = 0.75, p = 0.004).

2.4. Heat and Salt Content

The heat and salt content in each sampling date were estimated using all the sampling stations, to account for monthly changes and investigate the effect of the meteorological changes on the lagoon's properties. For the estimation of the heat content, the authors used the following equation:

$$H = c_p * T * \rho * V \tag{1}$$

where H is the heat capacity of the lagoon in joules, c_p is the specific heat capacity (J/kg°C), T is the median of the temperature measurements (°C), ρ is the average of the density measurements (kg/m^3), and V is the lagoon's volume (m^3). Also, for the salt content, the authors used the following equation:

$$S = s * \rho * V \tag{2}$$

where S is the salt content of the lagoon (in grams) and s is the median of the salinity measurements (in grams).

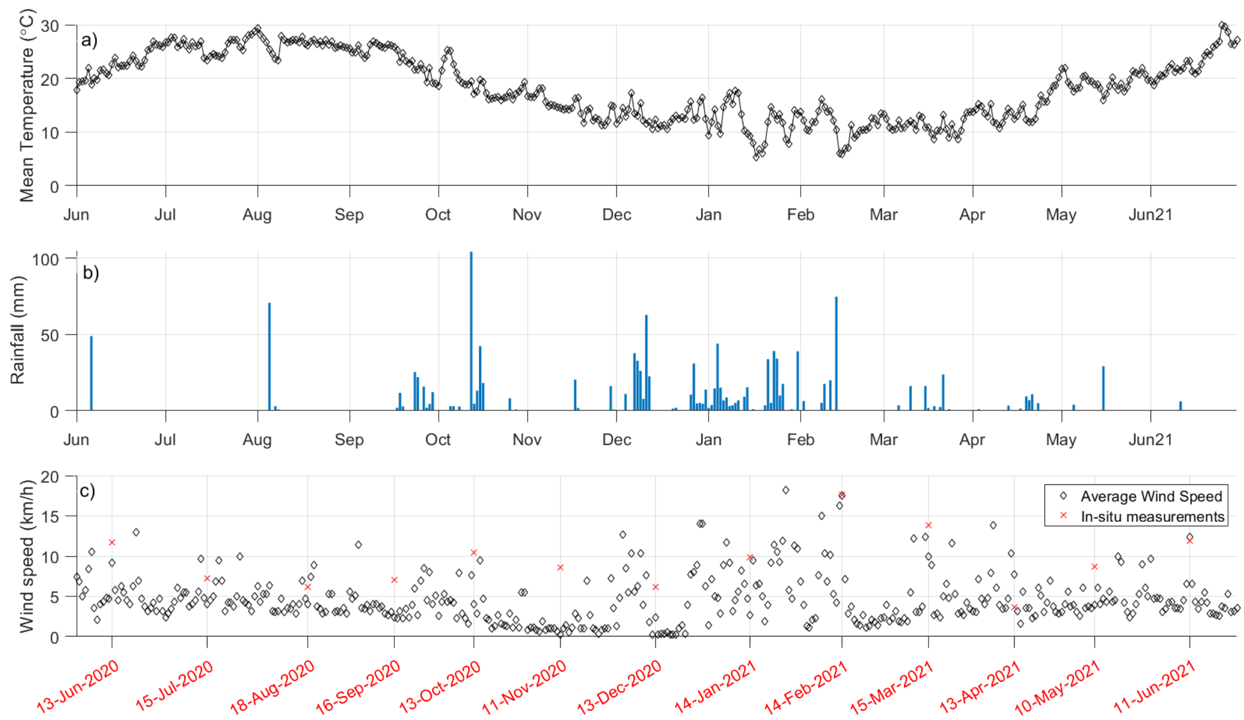

Figure 3. Daily air temperature (**a**), rainfall (**b**), and wind data (**c**) from a national weather station located near Antinioti lagoon. The wind data are compared with wind measurements that took place in Antinioti lagoon. In (**c**), the sampling dates that match the in situ data are shown with red color.

3. Results

Stations A1, A8, A11, A18, A22, and A26 were selected as representatives of important locations to understand the variability of hydrological parameters and circulation (Figure 2). Station A1 is near the inlet that connects the lagoon to the sea. Stations A8 and A22 cover the southeastern and northwestern edges of the lagoon. Station A11 is located near an underwater spring. Station A18 is near the river that supplies the lagoon with freshwater, and station A26 represents the shallow north part of the lagoon.

3.1. Meteorological Data

Atmospheric data extracted from the database of the National Observatory of Athens (NOA) show the daily average values of atmospheric temperature, rainfall, and wind speed between June 2020 and June 2021 (Figure 3). Atmospheric temperature follows a sinusoidal curvature, with high temperatures from July to September and low temperatures from December to March. Rainfall is sporadic, with higher frequencies from September to mid-October and from mid-December to mid-February. The wind speed and direction (NW) compared between the lagoon's field measurements and the station's data show great relevance.

3.2. Profiles

The monthly profiles of salinity (P.S.U.), temperature (°C), dissolved oxygen (mg/L), density (σ_t), and pH at the six selected stations are presented in Figure 4. In the measurements within a year, salinity in the lagoon ranges between 2.9 and 35.3 P.S.U., water temperature ranges between 7 and 30 °C, dissolved oxygen ranges between 2 and 11.6 mg/L, density ranges between 1.5 and 24 kg/m^3, and pH ranges between 7 and 8.3.

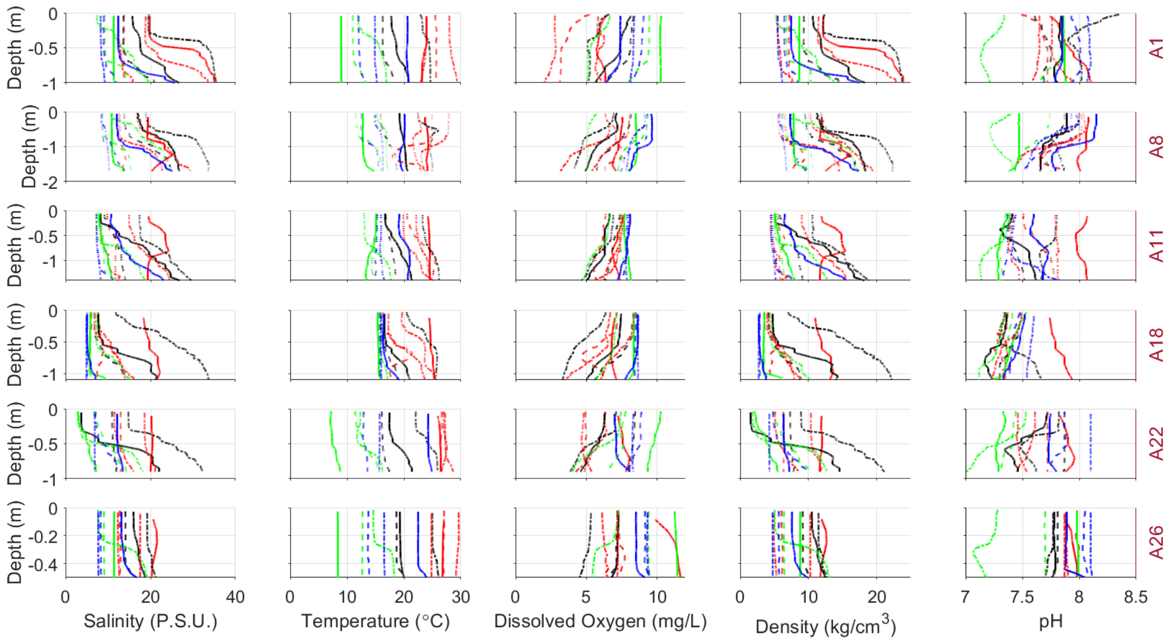

Figure 4. Multiparameter monthly profiles in the 6 selected stations of Antinioti lagoon. Summer months are marked with red, autumn months are marked with black, winter months are marked with green, and spring months are marked with blue.

In the salinity diagram of station 1, a clear halocline is observed during the summer months, indicating a stratified water column. Winter and spring months show a homogenized water column, while October and November have a deeper halocline. Little variation in the water column indicates well-mixed waters. The same pattern is observed in the density diagram of station 1. Temperature increases with depth for most months, with winter profiles characterized by the lowest and summer profiles by the highest temperatures, exhibiting a weak thermocline. pH is higher during spring months, showing values between 7 and 8.2, while in December, the lowest pH values are encountered for all stations. Dissolved oxygen is higher during winter and spring and lower during summer and autumn months, with profiles that show a homogenized water column.

Station 8 also shows an increase in salinity with depth and a halocline layer in most profiles. The highest salinity values are observed during summer and autumn and the lowest values during spring and winter months. Density profiles are similar to the salinity ones. Temperature profiles exhibit a smaller range in station 8 to in station 1, showing the highest temperatures in summer and the lowest in winter months. The summer and autumn months show a strong thermocline layer, while the spring and winter months show a weak thermocline layer. pH decreases with depth, showing the highest values during spring and summer and the lowest in December, also seen at station 1. Dissolved oxygen decreases with depth, with the highest values during winter and spring and the lowest during summer and autumn months.

The next two stations (stations 11 and 18) are close to the freshwater sources. Station 11 is located near an underwater spring, and station 18 is near the stream. In terms of salinity and density, there are no haloclines and pycnoclines observed, and salinity increases steadily with depth for most months, indicating stratified water columns. During the summer months and September, the highest salinity values are observed, while in the winter and spring, salinity drops to its lowest values. The temperature range is smaller than in the previous stations, with station 18 exhibiting the smallest monthly variations. The highest values are encountered in the summer and autumn, while the lowest are in the winter and spring months. As noticed at other stations, the temperature increased with depth. A very weak thermocline is observed. pH values at station 11 are lower than stations 1 and 8 and exhibit a smaller range, while in station 18, pH is between 7 and 7.5 and decreases with depth. In both stations 11 and 18, dissolved oxygen decreases with depth, and the range is smaller than in stations 1 and 8, with the highest values encountered during the winter and spring months.

In station 22, salinity increases with depth and shows the highest values during the summer and autumn months, with strong haloclines appearing in September and October. Density shows similar curvatures to salinity. The water column is stratified in terms of temperature, with the highest values during summer and the lowest during winter months. Temperature ranges to a greater extent than in stations 11 and 18 and shows similarities with station 1. pH values range between 7 and 8.2, and the profiles decrease with depth. Dissolved oxygen decreases with depth and shows the highest values during winter and spring and the lowest during summer and autumn.

Station 26 is the shallowest station selected located in the northern part of the main body of the lagoon. The water column is homogenized for most months in terms of all parameters. Salinity and density show the smallest range variations, without exceeding 21 P.S.U. The highest values are observed during summer and autumn and the lowest during winter and spring months. Temperature shows the highest values during summer and the lowest during winter and spring months, with large range variations among the months. pH shows the smallest range of variations of all stations, with most months being between 7.7 and 8.2, except December, where values lower than 7.3 are encountered. Dissolved oxygen is greater in the winter and spring months, with an exception in June, where high values are also observed.

Overall, salinity in Antinioti lagoon is highest in the summer and autumn months, with the appearance of haloclines, and lower in the winter and spring months. Locations near freshwater inputs show smaller amounts of salty water and a more stratified water column. Temperature is highest in summer and lowest in winter and increases with depth. Dissolved oxygen is highest in the winter and lowest in the summer months and decreases with depth. Density is mainly controlled by salinity, showing similar profiles and curvature patterns. In terms of pH, the highest values are encountered during spring and summer and the lowest in winter months.

3.3. Spatial Interpolation

The number of sampling stations (27) for a lagoon of small area coverage (1.87 km^2) offers the ability to create a fine spatial resolution of the parameters' variations in every corner of the lagoon. Spatial interpolation was performed in Matlab 2021a to integrate the in situ measurements and make an estimate of the parameters' values over the whole extent of the lagoon. More specifically, the authors used the discrete data points from the field measurements (e.g., surface salinity at each station) and fitted a continuous surface of the form $v = f(x, y)$ to the scattered data in vectors (x, y, v). The surface always passes through the data points defined by x and y, which, in this study, are the coordinates (longitude and latitude) of the sampling stations. This was achieved using Matlab's "griddata" function, and by performing a triangulation-based natural neighbor interpolation. This method is an efficient trade-off between linear and cubic interpolation. Thus, surface and bottom horizontal diagrams were created, showing the monthly values of each parameter in every location on the lagoon. Due to the possibility that presenting 24 diagrams showing similar results might be overwhelming, the authors selected the months of November 2020 and June 2021 as representatives in order to discuss the circulation of the lagoon.

3.4. November 2020

Surface salinity does not exceed the 15 P.S.U., with values decreasing gradually from the sea connection to the stream. Low temperatures are observed near the stream and sea, while the main body of the lagoon shows higher values. Dissolved oxygen shows high values in the greater extent of the lagoon with a small decline in the area near the spring. Density follows the salinity pattern. pH shows small variations in most areas and a significant decrease in the area of the spring (Figure 5).

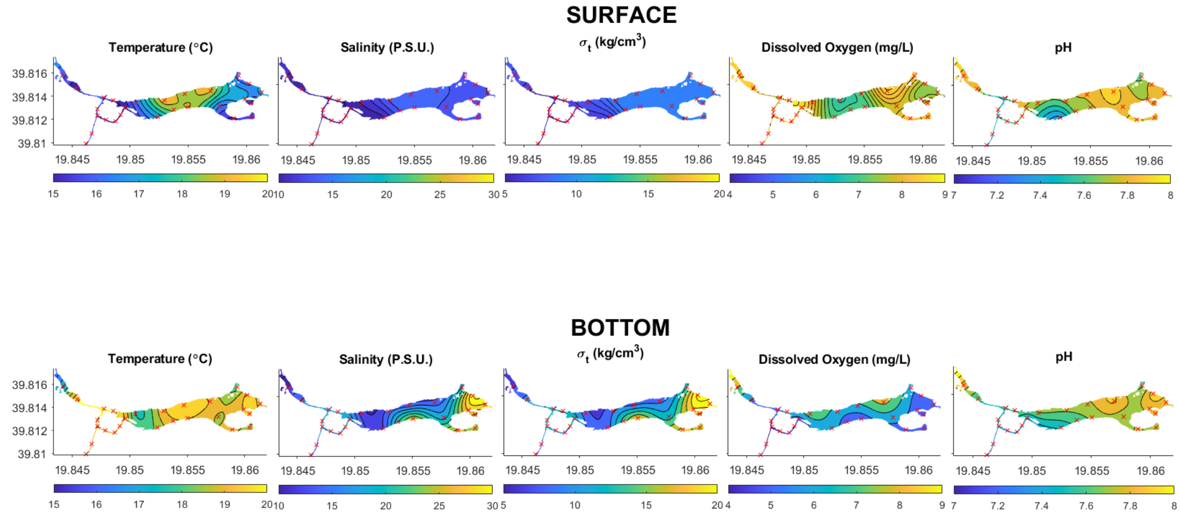

Figure 5. Spatial interpolation of parameters in the surface and bottom of Antinioti lagoon on November 2020.

Bottom salinity ranges between 10 and 30 P.S.U., with the highest values near stations 1–5, which are closer to the inlet that connects the lagoon to the sea, and the lowest values near stations 11–23, which are closer to the stream that supplies the lagoon with fresh water. The northwest channel of the lagoon also shows low values in terms of salinity (Figure 5). Temperature shows a warm bottom in the greatest extent of the lagoon with variations between 15 and 20 (°C). The less warm areas are observed near the underwater spring, the connection to the sea, and the northwestern area. Density follows patterns similar to salinity, while dissolved oxygen follows the bathymetry pattern, with the highest values in the shallowest areas and lowest in the deepest parts. pH shows small variations, with gradually decreasing values from the areas near the sea to the areas near the mouth of the stream.

3.5. June 2021

During the summer months, salinity and temperature show greater values than in November. In terms of salinity, the horizontal patterns are similar to November, with low salinity at the surface and higher salinity at the bottom (Figure 6). Salinity in the bottom plot shows maximum values near the connection to the sea. As seen in November, the saltwater masses pass south of the barrier at stations 6 to 27 entering the main body of the lagoon. Although in November this salinity "tongue" stops around station 11, in June it reaches as far as station 12 and into the channels. This phenomenon could be related to the smaller freshwater inputs of the summer due to the absence of rainfall.

pH shows greater values than in November and is gradually decreasing from the areas near the sea to the areas near the stream. Temperature is higher at the bottom than at the surface but with smaller differences than in November (24–26 (°C)), and is gradually increasing from the areas near the sea to the areas near the stream. A significant difference compared to November is the >4 °C increase in the stream area (station 18). Dissolved oxygen shows greater values on the surface and decreases with depth, while density follows the salinity pattern, as observed also in November (Figure 6).

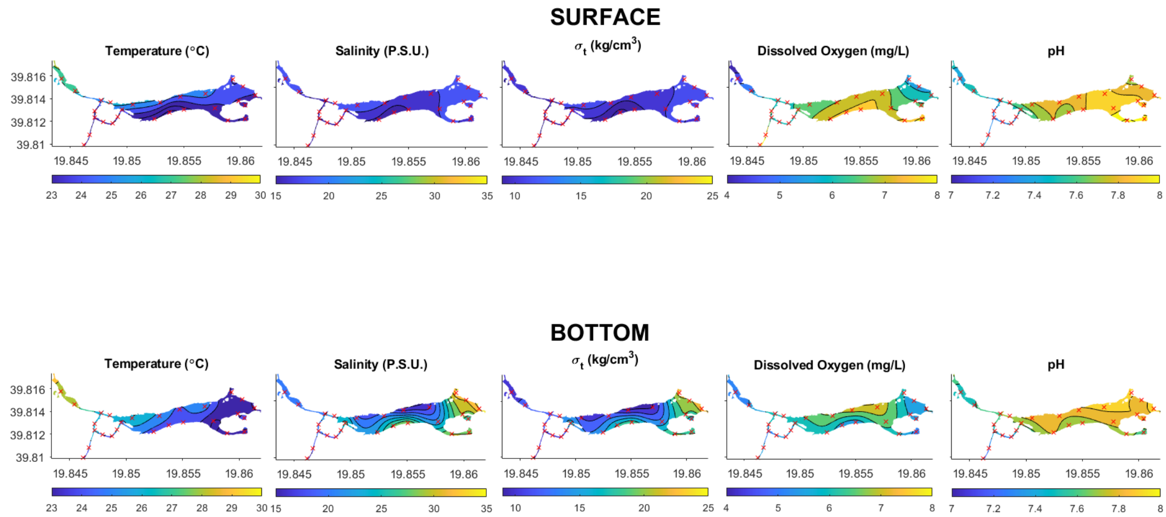

Figure 6. Spatial interpolation of parameters in the surface and bottom of Antinioti lagoon in June 2021.

4. Discussion

The monthly field measurements presented in this study provide a dataset of physical and chemical parameters characterized by fine spatial resolution that assists in understanding the circulation and seasonal variability of Antinioti lagoon. Considering that this work is the first study on Antinioti lagoon's hydrodynamics, this dataset could be used as a benchmark for future studies on the annual variability of Antinioti lagoon's circulation, the seasonal cycling of water properties, and mathematical modeling.

4.1. Seasonal Variability of Water Properties

The lagoon's water properties show temporal evolution within the year (Figure 7). Temperature oscillates between 7 and 30 °C, with greater values in summer and lower values in winter. Due to the lagoon's shallowness, atmospheric temperature variations affect the whole water column. pH ranges between 7 and 8.2, influenced by the freshwater input that is low in pH and the stable seawater inputs that have higher pH values. Dissolved oxygen varies inversely with temperature between 2 and 11 mg/L, with higher values in the winter and lower values in the summer. This could be a result of physical (higher wind magnitude and rainfall seen in the winter months, less solar radiation influences the lagoon during the winter) or biochemical processes (photorespiration, microbial activity that depend on the water temperature) [38]. Salinity and density distributions are similar, indicating that salinity is the main force affecting the lagoon's density, with temperature having a smaller effect on density. Salinity is higher in June and September, with a sudden drop between the two months, and then gradually decreases until the minimum values are reached in spring. In April, its values start to increase rapidly. The decrease in July and August could be an effect of heavy freshwater inflow to the lagoon related to rainfall amounts that have occurred in the previous months and have influenced, with a temporal gap, the effectiveness of the stream to drop the salinity levels.

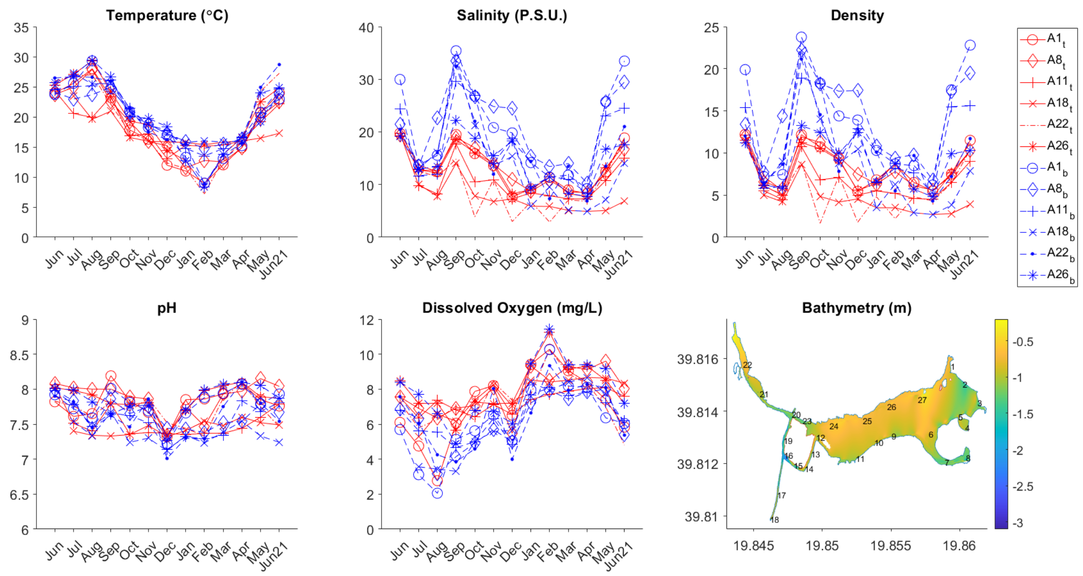

Figure 7. Monthly surface (t) and bottom (b) values of physical parameters in 6 stations of Antinioti lagoon. The bottom values are colored blue and the surface values are colored red.

4.2. Heat and Salt Budgets

Similar to the seasonal variability of salinity in Antinioti lagoon (Figure 7), the heat and salt budgets show the highest values in both June 2020 and 2021 and in September. In July and August a sudden decrease in both heat and salt budgets is observed, while after September, the values are steadily decreasing until April when the budgets start increasing again. Both budgets are influenced by the same factors since they exhibit similar curvatures (Figure 8). As discussed previously, the main factor controlling the variability of these parameters is rainfall which influences the stream inflow.

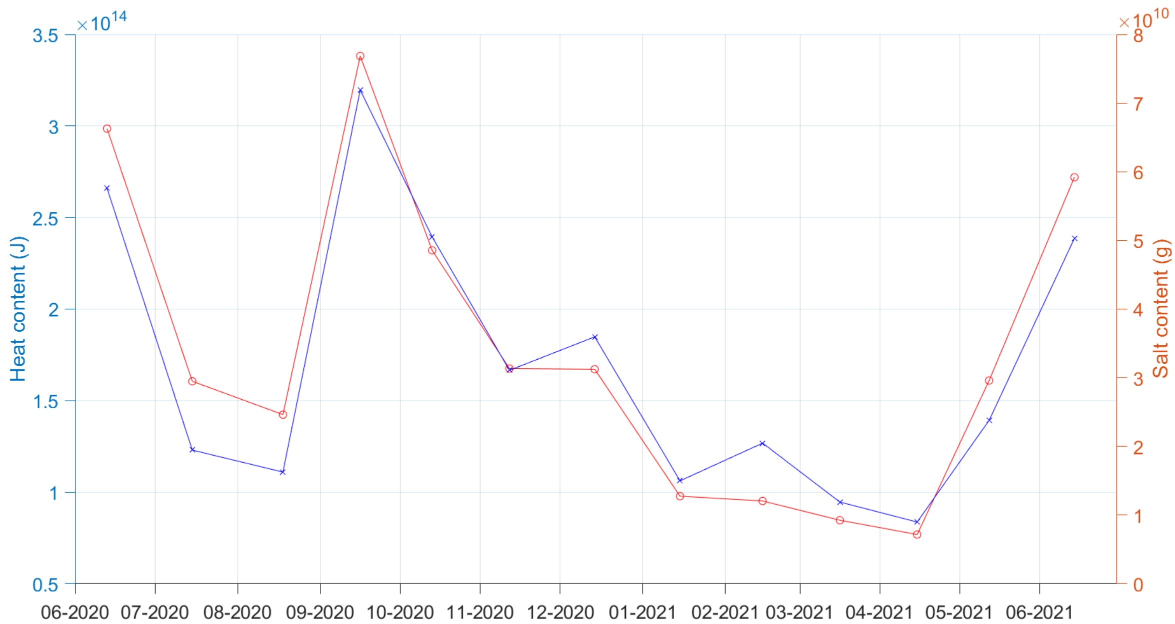

Figure 8. Heat and salt content of Antinioti lagoon per month.

4.3. Circulation

Coastal lagoons are confined environments that display wide spatial and temporal variations in their physical and chemical properties [39]. Temperature variations on the whole water column are affected by the temperature of water inflow from the sea and the stream and atmospheric temperature due to the shallowness that characterizes Antinioti lagoon. Although atmospheric temperature influences the entire water column, its highest impact is observed in the upper layer. The formation of a submerged temperature maximum in several locations within the lagoon (invert temperature stratification) is possibly explained by the solar pond effect, which has been reported in other shallow lagoons as well [40,41]. Salinity, on the other hand, depends on the antagonistic effect between seawater inflow from the sea and freshwater inflow by streams, rainfall, and springs. The temperature and salinity temporal and spatial variability are the main factors driving the circulation of shallow lagoons, such as Antinioti, and are magnified by the restricted character of these marine systems [42]. Therefore, Antinioti lagoon's circulation is controlled by the antagonistic effect of seawater and freshwater inputs, which is also the case for other lagoons in the current literature [43–45]. Seawater inputs from the inlet located at station 1 fill the eastern part of the lagoon, following the south coastline to pass through the underwater barrier that extends from station 6 to 27 (Figure 2), and then moving toward the main body of the lagoon. Freshwater inputs from station 11, and in greater amounts from station 18, fill the channels and the western part, moving toward the main body of the lagoon. Depending on the weather conditions, the rainfall, and freshwater runoff, the freshwater amounts are increased or decreased, moving the mixing region between stations 9 and 12. Typically, at the location where the two water masses of different densities meet, the freshwater will ascend, filling the surface level, and the seawater will descend, filling the bottom level (Figures 4–7).

Another way of showing the circulation patterns in Antinioti lagoon is by investigating the presence of seawater within it and monitoring the antagonistic effect between seawater and freshwater. The water masses in station 1 are considered the closest to seawater and taken as the seawater reference and the water masses in station 18 as the freshwater reference. Then, following the procedure for determining the percentage of specific water masses within each of the lagoon's stations, we were able to determine the percentage of seawater from the water properties of each station within the lagoon [46]. If a station's water masses are a product of the intrusion of seawater, then the percentage will be 100. If the station's water masses are a product of freshwater, then the percentage will be 0. Due to the mixing of seawater and freshwater, as well as the shallowness of Antinioti lagoon, the percentages varied, but clearly showed the pattern of seawater intrusion and its circulation within the lagoon.

In Figures 9 and 10, the spatially interpolated percentage of seawater in Antinioti lagoon is presented between the surface and bottom in October 2020 and April 2021. In October, we noticed that the signals of seawater and freshwater masses were strong in the areas closer to the sea and the stream, respectively. Both inputs control their regions and exhibit a gradual mixing in the center of the lagoon. On the surface, the lagoon shows freshwater masses in the western region and seawater masses in the eastern region. At the bottom, seawater prevails from the sea towards the deeper south region of the lagoon, reaching stations A20 and A23. In station 2, contrary to the expected seawater type, we notice freshwater masses. This can be the drainage of rainwater related to a day of heavy rainfall seen in Figure 3 a few days before sampling occurred. In April, a higher level of mixed water masses is observed. In both the surface and bottom, seawater masses prevail, following the south part of the lagoon toward stations A20 and A23. Therefore, we can determine that Antinioti lagoon exhibits a stable circulation pattern. Still, its extent is largely influenced by the supply of fresh water from the stream (due to rainfall).

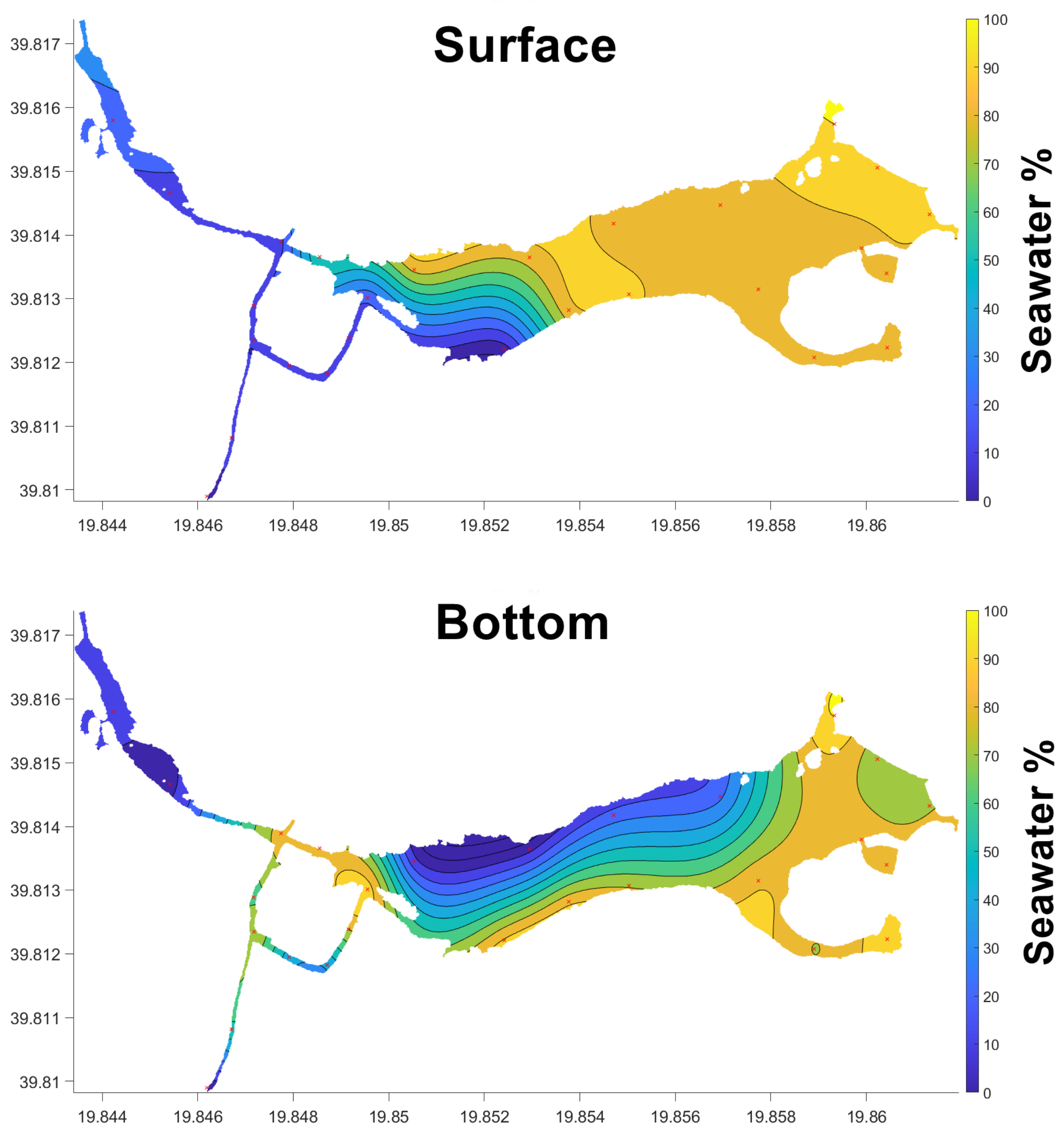

Figure 9. Percentage of seawater forming the lagoon's surface and bottom water properties in October 2020.

In summary, we have shown that Antinioti lagoon's circulation is controlled by the antagonistic effect of seawater and freshwater inputs, which is influenced by the atmospheric forcing, and this was presented using (i) a discussion of the lagoon's hydrological properties (mainly temperature and salinity), and (ii) a mathematical approach of determining the penetration of seawater (by its percentage) within the lagoon at different seasons. The findings of these approaches exhibit a similar behavior of water circulation patterns in Antinioti lagoon that is mainly affected by atmospheric forcing (due to its shallowness) that controls the freshwater and seawater inputs. Over the year, the lagoon exhibits similar circulation patterns, except for early summer, when the freshwater inputs are negligible and seawater spreads all over the lagoon's extent.

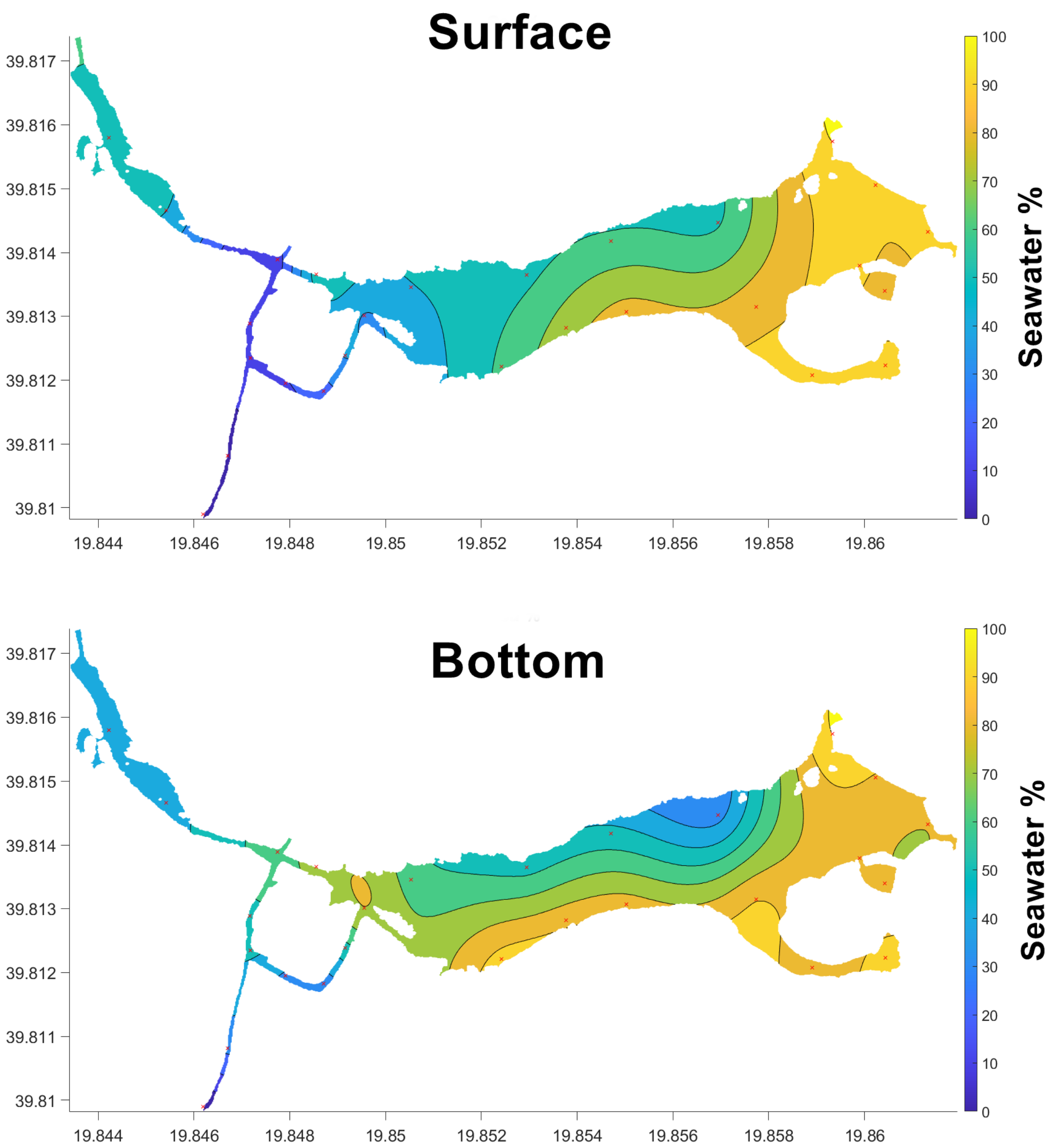

Figure 10. Percentage of seawater forming the lagoon's surface and bottom water properties in April 2021.

4.4. Comparison with Investigations of Other Coastal Lagoons

In Table 1, the authors provide a review of studies in coastal lagoons, with a similar scope of investigating the circulation patterns of these marine environments. The studies are categorized as experimental (studies that involve field measurements), numerical (studies that involve simulations), and remote sensing (studies that involve satellite data). Similarly to Antinioti lagoon, in the majority of the other studies, researchers concluded that the water circulation in coastal lagoons depends on the fresh and seawater inputs and their antagonistic effect, as well as the atmospheric forcing and the lagoon's topography. The novelty of the present study is that for the first time, the extent of fresh and seawater masses within the lagoon was investigated using the mathematical approach described in the previous subsection. Also, the influence of wave activity and wind speed are also presented as important factors influencing the lagoon's circulation in several studies. However, in the case of wave activity, this only appears to be significant in studies of coastal lagoons that exhibit greater depths (5–50 m) and do not have a high barrier separating them from the open sea (which is the case in Antinioti lagoon). Hence, wave activity should not be considered a possible factor affecting Antinioti lagoon's circulation. In the case of wind speed, studies have shown that wind-driven circulation occurs for wind speeds averaging (6–18 km/h) that last for at least a few hours to days [16,44,47–49]. However, as seen in Figure 3, the daily average wind speed in Antinioti lagoon does not exceed 2–3 km/h. Therefore, it is difficult for Antinioti lagoon to exhibit wind-driven circulation patterns. Nevertheless, in the case of a severe storm, there is a possibility of temporarily measuring wind-driven circulation.

The major shortcoming of the present study, compared to others, is the lack of a continuous data stream from the lagoon, which would enable several applications such as the monitoring of environmental parameters, early warning for pollution and/or natural disasters, and decision-making tools for the management of the lagoon. In the future, the establishment of buoys that record and transmit data in real time would be highly significant for monitoring purposes, as well as for the use of data in predictive models for evaluating the sustainability of the lagoon's water properties under future environmental conditions [26].

Table 1. Comparison with hydrological/circulation investigations of other coastal lagoons.

Lagoon (Country)	Method	Forcing	Reference
Antinioti (Greece)	Experimental	Fresh–seawater inputs and atmospheric conditions	Present study
Bizerte (Tunisia)	Experimental	Fresh–seawater inputs	Béjaoui et al. [43]
Ouano (Nea Caledonia)	Experimental	Wave and wind activity	Sous et al. [16]
La Palme (France)	Experimental	Wind speed	Tamborski et al. [47]
Various lagoons (New Caledonia)	Experimental	Atmospheric conditions, freshwater inputs, and internal waves	Bruyère et al. [50]
Ria Formosa (Portugal)	Numerical	Fresh–seawater interactions	Carrasco et al. [51]
Mundaú-Manguaba (Brazil)	Numerical	Freshwater inputs and wind speed	Cunha et al. [52]
Mirim (Brazil)	Numerical	Wind speed	da Silva et al. [48]
Marano, Grado (Italy)	Numerical	Fresh–seawater interactions	Ferrarin et al. [44]
La Pletera (Spain)	Numerical	Bathymetry/topography	Meredith et al. [53]
South-West (New Caledonia)	Numerical	Wind speed	Ouillon et al. [49]
Venice (Italy)	Numerical	Fresh–seawater interaction and atmospheric conditions	Solidoro et al. [45]
Mandinga (Mexico)	Numerical	Fresh–seawater inputs	Gonzalez-Vazquez et al. [54]
RSP (Saudi Arabia)	Numerical	Topography, wind speed, and fresh–seawater inputs	Zhan et al. [55]
Patos (Brazil)	Remote sensing	Freshwater inputs and wind direction	Tavora et al. [56]

4.5. Consequences for Aquaculture

The water properties of the lagoon depend on the distribution of fresh and seawater masses across its entire area. Antinioti experiences periods of heavy rainfall, especially from October to March, and periods where rainfall is absent or sporadic, especially from April to September (Figure 3). This phenomenon impacts the lagoon's properties, as freshwater masses will prevail during the heavy rainfall period and seawater intrusion will increase and expand toward the entire lagoon area during its absence. Considering the oxygen regime, in summer months with the absence of rainfall, some areas of the lagoon experience very low dissolved oxygen concentrations, and may even become anoxic, especially near the sea at station 1. In winter and spring months, the lagoon experiences high levels of dissolved oxygen that may lead to high eutrophication and algae blooms. In terms of the water's pH, it balances between 7.2 and 8.3, depending on the seawater intrusions (Figure 7). Finally, concerning the upper and lower levels of the lagoon, stratification is observed in the salinity and density of the water masses during the summer and autumn months in stations located near the connection to the sea. However, this stratification is absent in winter and spring months, where the water column seems rather homogenized (Figure 4). All these fluctuations may create huge risks for local users and aquaculture, depending on the cultivated species and their sensitivity to sudden changes in the lagoon's water properties, as well as variations between summer and winter months.

5. Conclusions

Coastal lagoons are confined environments that are characterized by vibrant ecosystems located in Earth's frontiers between land and sea. These frontiers are where freshwater, originating from rivers, springs, and rainfall, meets seawater in a restricted area that depends on its water's properties to prosper. Antinioti lagoon, which is part of the NATURA 2000 protection network, is an exceptional example of such a system. The lagoon is the habitat of many marine organisms, from plankton to fish, reptiles, and mammals, and it contains a highly important ecosystem that depends on the lagoon's water properties. In this work, the authors investigated the antagonistic effect between freshwater and seawater, the circulation patterns, and the atmospheric forces that affect Antinioti lagoon. Antinioti lagoon's circulation is directly and indirectly affected by atmospheric forces (atmospheric temperature, rainfall) and influences the lagoon's sustainability. The antagonistic effect between fresh and seawater masses reported here is the major mechanism controlling the water properties of several lagoons worldwide, as seen in Table 1. Wind speed and direction are major drivers of circulation in coastal lagoons; however, in the case of Antinioti lagoon, the stable direction and low magnitude of wind make its contribution to the lagoon's circulation negligible. Moreover, the bathymetry/topography plays a key role in the hydrological cycle of coastal lagoons. In the case of Antinioti lagoon, its shallowness allows the rapid influence of atmospheric conditions. Further research is required to establish a proper knowledge of the fluctuations of the lagoon's water properties and predict its response to future conditions and sudden atmospheric changes.

Although several studies have used several numerical, experimental, and remote sensing techniques to estimate the hydrological/circulation patterns in other lagoons, this study uses an innovative method for estimating the circulation patterns by studying the presence of seawater masses within the lagoon. Monitoring the intrusion of seawater was proven to be a robust method for visualizing the movements of water masses in the spatial and temporal axis. The method tested here can be applied in other lagoons and lakes, as well as the marine environment. Nevertheless, future work should include a comparison with modeling efforts and real-time buoys to monitor the circulation of the lagoon and the method's effectiveness with higher accuracy.

The results of this study will serve as a reference level for future changes in the lagoon due to the sea-level rise and climate change, as well as anthropogenic effects. The authors suggest that future studies on Antinioti lagoon's annual changes will reveal more information regarding the climate change effect on these vulnerable environments. Nevertheless, the authors are encouraged to follow up with a study on the vulnerability of Antinioti lagoon to natural hazards. Moreover, the influence of fluctuations in wind magnitude and direction, especially during storms, should be evaluated in the context of mathematical modeling for a complete evaluation of the stratification and the fluctuations in water properties that can affect marine life. The next step in fully understanding the annual hydrological cycle of Antinioti lagoon is investigating the biogeochemical processes and their influence on the physical parameters. More research is required to evaluate the marine biological activity effect on dissolved oxygen, the potential formation of algae blooms in spring, and the influence on water temperature and dissolved oxygen, sediment processes, and microbial activity, as well as the impact of aquaculture on the ecosystem of the lagoon. This will allow further mathematical modeling research in this lagoon, simulating and predicting fluctuations in the physical parameters and their impact on the water properties and the sustainability of the prosperous and significant local aquaculture marine life.

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