Case Report

The Role of Hydrodynamics on the Sustainable Mussels' Culture Activity. The Case of the Chalastra Basin (NW Gulf of Thessaloniki)

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Abstract: In line with the framework of strategic guidelines for marine aquacultures, mussel cultures have to be operated in Areas of Organized Aquaculture Development (AOAD). Forty per cent of the national mussel culture production, which is based in Chalastra (NW Gulf of Thessaloniki, part of the Thermaikos Gulf), uses pole and longline systems. Due to legislative changes, both farmers and the authorities are in the process of reforming the existing units and planning processes based on the principles of sustainability, as defined in AOAD. The aim of this study is to estimate the appropriate orientation lines on which the mussel socks are to be placed in the mussel culturing units, in relation to the direction of sea currents for optimum water circulation in AOAD. The hydro-dynamics of the Chalastra basin is mainly wind driven and affected by prevailing northerly and southerly winds during winter and summer periods, respectively. When placed perpendicular to sea currents, the socks in the mussel production lines form an obstacle. Thus, the appropriate orientation of pole and longline units based on natural current directions can comprise a useful tool for sustainable mussel cultures. The benefits arising from the application of the proposed scheme are twofold: (a) productivity through the appropriate circulation and regeneration of nutrients can be maximized and (b) the environmental impacts of mussel culture activity can be minimized, as byproducts can more easily be dispersed of and biodegraded. In the present study, two basic schemes are proposed: (a) the division of AOAD is being researched into three sub-areas for pole and long-line units respectively and (b) the placement of the shortest possible length of production lines parallel to sea currents.

Keywords: AOAD; coastal water circulation; mussel units; pole and long line orientation; hydrodynamic modelling; sustainability; Thermaikos Gulf

1. Introduction

European shellfish aquaculture is based mainly on the production of mussels and oysters in coastal and intertidal environments. The majority of production takes place in Spain (63%), France (17%) and Greece (6%) [1]. One of the most significant constraints in the expansion and development of mussel culture in Europe is the designation of suitable culturing sites.

Mussel culture has been developed in Greece for more than half a century, with the most important mussel farming areas situated in the NW Gulf of Thessaloniki (Chalastra, Figure 1A) and the NW Thermaikos Gulf. The Thermaikos Gulf is a long semi enclosed gulf with three sub-divisions based on the coastline from north to south. The Chalastra basin, located in the NW part of the central area of the Thermaikos Gulf, named the Thessaloniki Gulf, has a number of longline and pole mussel units at depths of >10 m and <4–5 m respectively (Figure 1A,B). The establishment and operation of AOAD (Areas of Organized Aquaculture Development) based on European and National legislation

are widely sought after by both public and private institutions. In parallel with the new AOAD, the requirements of the WFD (Water Framework Directive) 2000/60 EC have to be met in order to identify the potential impact of mussel cultures upon aquatic ecosystems, such as nutrient and organic matter inputs. High quality waters are required for mussel cultures, and if properly managed by sustainable practices, they may have positive effects on the natural environment such as retention of water in the landscape, flood control and protection of biodiversity. Implementing sustainability principles in mussel culture planning requires the correlation of many environmental and technical factors in order for maximum productivity to be achieved while minimizing the environmental impact.
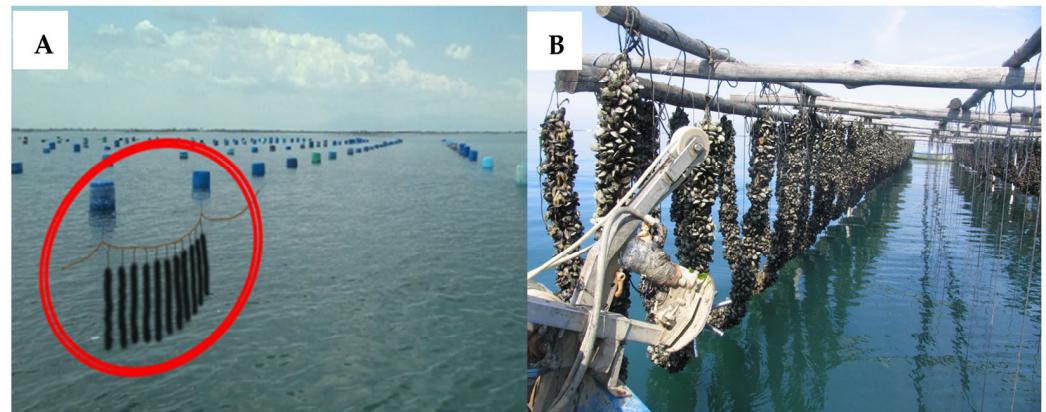

Figure 1. (**A**) Longline farm where the hanging socks were added by drawing on the production line, (**B**) pole farm hung socks.

The application of various models can be of significant importance when deciding on a suitable site, mode of culture and assessment of production and carrying capacity. Moreover, such models could be useful in environmental impact predictions. Various models have been developed and applied to specific areas [2–7], since the environmental conditions specific to each area make them unique. A crucial parameter to be taken into consideration is the hydrodynamic circulation in the area, and whether the current practices applied to long-line or pole orientation are sustainable and compatible with legislation. A number of studies have proven the impact of water movement and circulation [8–10], with numerous studies stressing the importance of water flow, movement and circulation concerning mussel culture activities [10–16]. However, depending on the particular characteristics of the area, the results obtained from mathematical models can vary substantially. Thus, it is of the outmost importance that extensive case-specific studies be carried out. Nevertheless, an integrated approach should be conducted in each case involving parameters such as food availability (in terms of nutrients and chlorophyll–concentrations), oxygenation and possible hypoxic incidents and waste by-products or biological waste due to culture activity [16]. Moreover, different culture arrangements, materials, and structures may have different effects on the mode of circulation.

Established mussel units in Greece were at their height from 2000 to 2007. According to Eurostat, the annual Hellenic mussel production rose steadily in the eighties and nineties, with a slight drop between 1994 and 1998, before reaching a peak of 27,000 t in 2005 and then dropping to 20,000 t in 2010, where it plateaued (Figure 2). Chalastra's coastal area (NW Thermaikos Gulf) is one of the three main mussel culture areas in the Thermaikos region [17] contributing significantly to the national production with an annual mussel harvest of 40% of the national production (~8000 t).
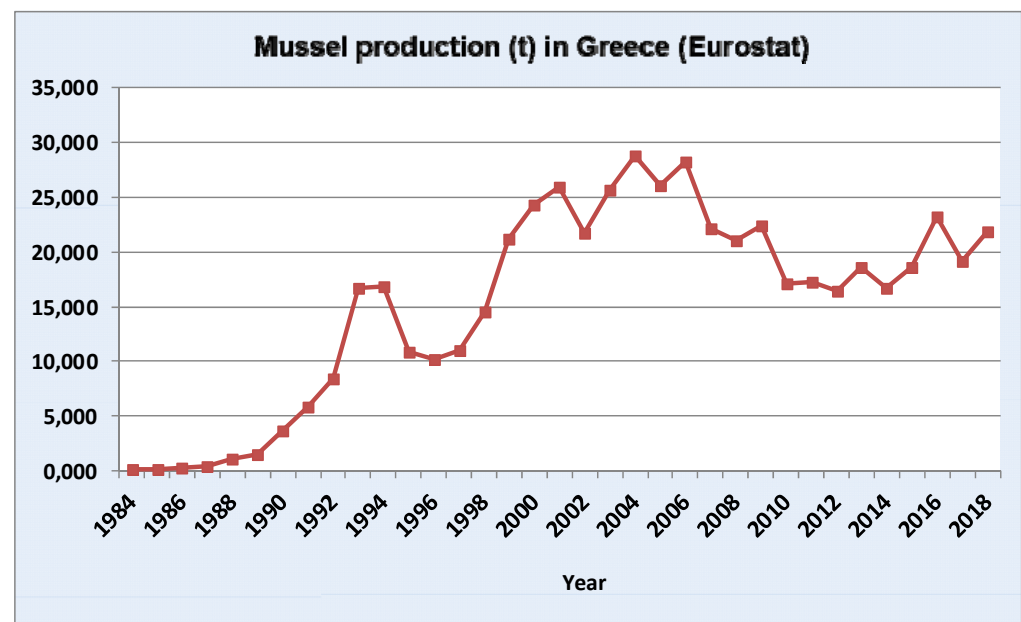
Figure 2. Greek mussel production, tons/per year (EUROSTAT).

Increased human activity in the region has affected the hydrodynamic characteristics of this particular ecosystem. According to Savvidis et al. [18] and Galinou-Mitsoudi et al. [19], the presence of mussel units has resulted in a 30% reduction in the intensity of currents in the region, where production is mainly conducted in longline farms (made up of 11 production lines of 100 m length with a 10 m gap between them, and 0.5 m between mussel socks). The water flow in the area of Chalastra, as in the wider area of the Thermaikos Gulf, is generated mainly by north-westerly winds [20,21], with tidal effects almost negligible [22]. Although the thermohaline circulation in the Thermaikos is mainly affected by the water masses flowing in from the north Aegean Sea, as well as the rivers that flow into the gulf and solar radiation, the river inflows have negligible effects on the area of Chalastra. Southerly winds occur mainly during the summer, a period when the flow of rivers is minimized. Previous research studies in the area have concluded that the river Axios is the major contributing factor to the changes occurring in the area, as it is able to alter not only the salinity concentrations, but also allows the flow of increased nutrients into the area [23]. Notwithstanding, the past decades have witnessed a significant decrease in these inflows.

Seasonal changes in hydrodynamics may favorably influence the inflow of nutrients from rivers into the sea basin. Tsiaras et al. [24] have also reported seasonal increases of nitrate due to agricultural runoffs, while phosphate has had a decreasing trend. The significant role of the Axios river in the transportation of nutrients was also highlighted by Nikolaidis et al. [25] through a watershed management model, predicting that a 40% reduction in nutrient loads from the Axios river would have similar patterns of reduction on nutrients in the Gulf. During the last decade, the most important mussel-farming area in Greece, that of Chalastra, has been facing severe problems due to decreasing levels of mussel production and mussel quality [11,19]. Since mussel cultivation depends primarily on phytoplankton, production may dwindle if natural food resources are depleted.

In this present study, winds and currents have been taken into account and fitted into a mathematical model in order to determine the optimal orientation of the mussel lines. Moreover, a monitoring scheme of the environmental conditions in the area regarding the nutrient and chlorophyll-a profile was conducted, in order to integrate the findings of the hydrodynamic model along with environmental impacts and thus comply with sustainability principles.

2. Materials and Methods

2.1. Hydrodynamic Model and Simulation

A 2D-depth averaged hydrodynamic mathematical model has been applied for the description of the hydrodynamics in the area of mussel cultures cultivated in the Chalastra coastal basin. The hydrodynamic model is based on the following equations of momentum and mass conservation, as applied by Savvidis et al. [18].

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

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

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

where:

h: the depth of the water column,

U, V: vertically averaged horizontal current velocities,

ζ: surface elevation,

f: Coriollis parameter,

τ_{sx}, τ_{sy}: wind surface shear stresses,

τ_{bx}, τ_{by}: bottom shear stresses,

ν_h: dispersion coefficient (Smagorinski, 1963),

ρ: seawater density, and

g: gravity acceleration.

The equations of the aforementioned hydrodynamic model were numerically solved by the finite difference method. The reported work consisted of two basic successive steps: (a) the application of a two-dimensional, depth averaged, hydrodynamic model for the simulation of the water circulation in the area of the inner Thermaikos and the Gulf of Thessaloniki with discretization step dx = 1000 m, and (b) the application of a two-dimensional hydrodynamic, depth averaged, model for the simulation of the circulation in the Chalastra Coastal Basin, with discretization step dx = 50 m. This nesting approach is depicted in Figure 3.
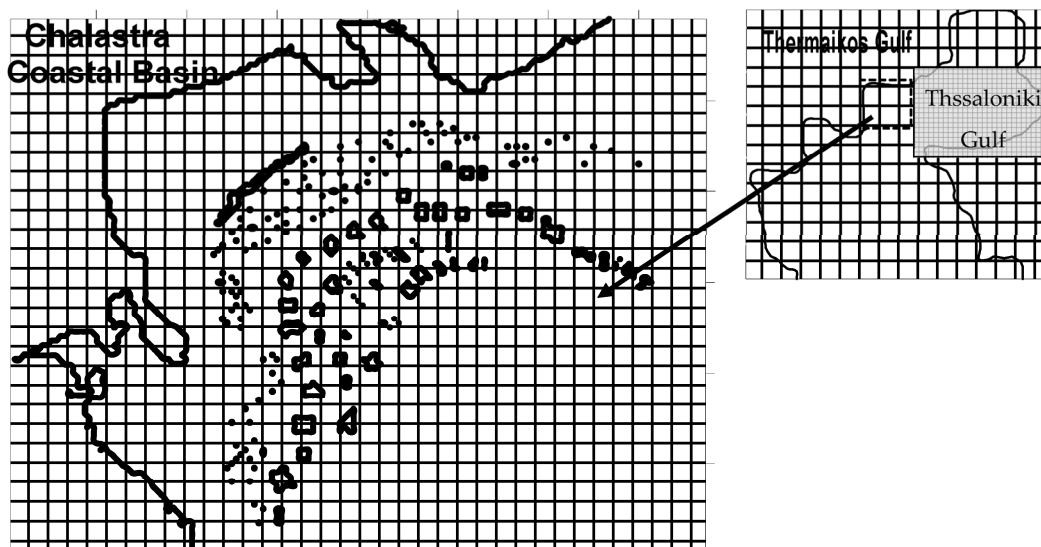

Figure 3. Discretization of the field in orthogonal segments for the model application.

In particular, the model, a coarser two-dimensional hydrodynamic model applied to the Chalastra Coastal Basin nested along the south open sea boundary, was primarily applied over the extended area of the Gulf of Thessaloniki. The velocity values, computed by the application of the model to the Thermaikos domain, were appropriately applied to the open sea boundaries of the Chalastra basin. The influence of mussel units to the flow was simulated by a decrease in the current velocities of the cells corresponding to mussel units. This decrease was based on the field data. In addition, the applied model considers the cultivation socks as areas with negligible porosity. The above model was applied to a mussel culture unit, as shown in Figure 4.
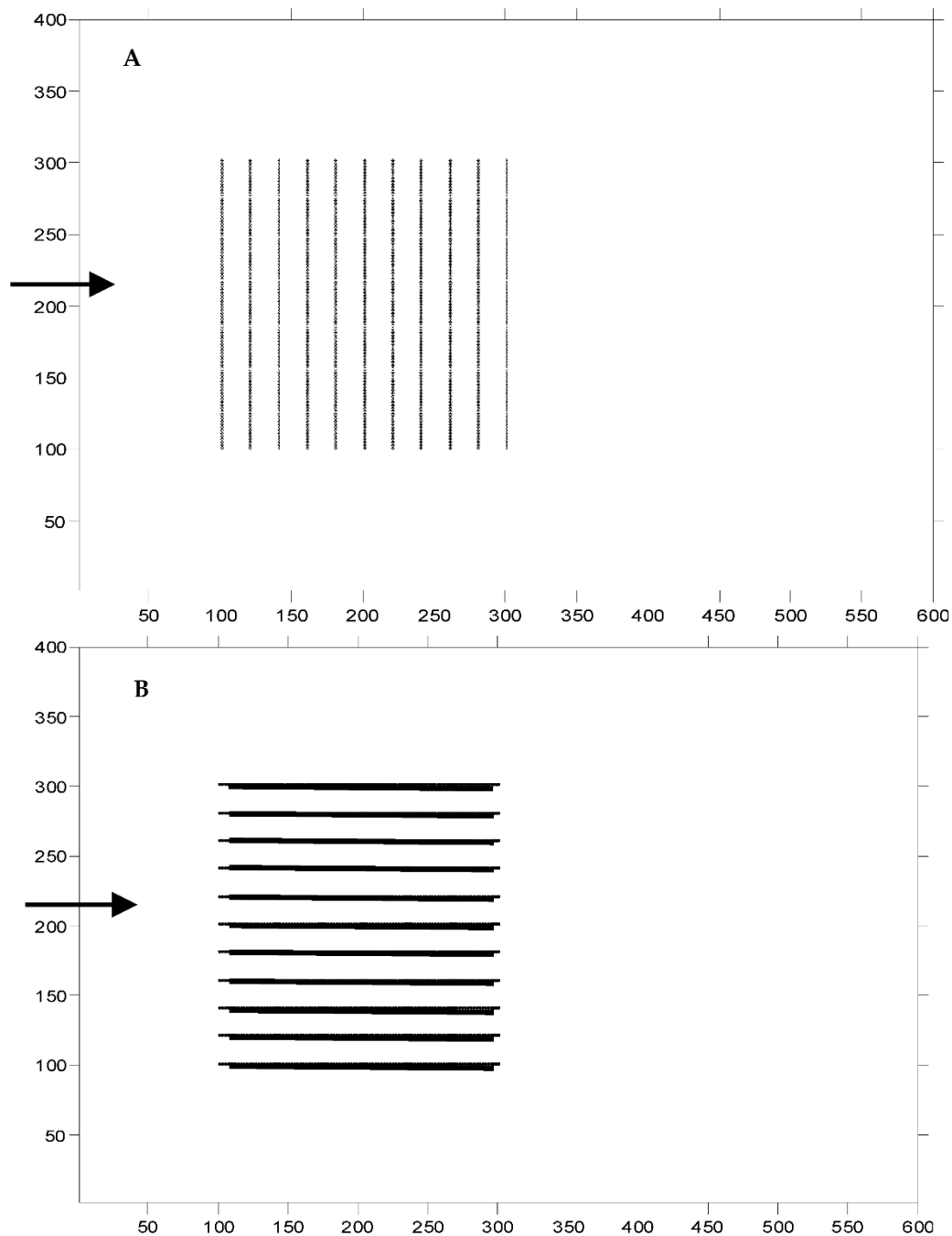

Figure 4. Simulation outlay of a mussel culture in the case of currents (**A**) perpendicular to the longlines unit, and (**B**) parallel to the longlines. The arrows indicate the velocity of inflowing current. Axes are defined as numbers of Δx. Each line consists of 100 socks with a max diameter of 0.5 m and 0.5 m space between the socks.

The minimization or degree of impeded or unobstructed flow was studied both in the field and with the help of mathematical modeling. In particular, it should be noted that the flow for the study was initially determined in a hypothetical channel length, where Lx = 300 m (in the x direction) and width Ly = 200 m (in the y direction). Hence, the computational field is characterized by a grid of 600 × 400 square cells-loops, where the spatial step is Δx = 0.5 m. Subsequently, the unit has been designed as follows: every meter in the y direction (i.e., in width) accounts as an obstacle to the flow. Thus, over a width of 100 m of the unit (corresponding to the length of 200 grid cells, i.e., 200 Δx), a group of 100 hanging mussel socks is created on the same production longline. Every ten meters in the x direction of the channel (lengthwise) the presence of a new longline is taken into account. Thus, in 100 m of the unit (lengthwise) 11 longlines are created. The lateral boundaries of the channel are solid, while the boundaries at the entrance and the exit areas are open. An inflow of water of velocity acts as a boundary at the entrance to the channel (u = 0.10 m/s). The structured hydrodynamic mathematical model (where the average velocity values are obtained) is based on the known equations of conservation of momentum and mass; Equations (1)–(3) which describe the hydrodynamic two-dimensional circulation. The forms of the mussel farms, the hydrodynamic modeling and the attempted study are depicted in Figure 4.

2.2. Monitoring of Nutrients and Chlorophyll-a

Seawater samples, together with current and wind data, were collected monthly or bimonthly via a van Dorn type water sampler from the water column. Sampling was duly performed at a site within the mussel farms, and a reference site 2.5 km away from mussel farming activities (Figure 5).
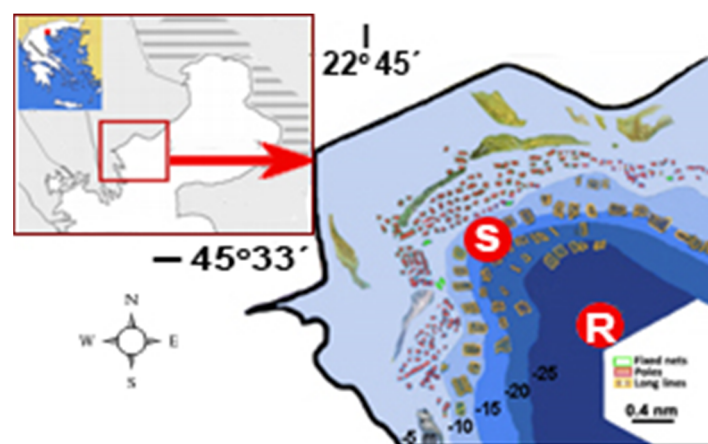

Figure 5. Map of the sampling area where R: reference site and S: sampling site.

Seawater samples were filtered on-board through 0.45 μm membrane filters and stored at −18 °C until their analysis. Nitrate and phosphate values were measured spectrophotometrically [26]. Analyses of ammonium were performed by means of the phenolhypochlorite method [27], and dissolved oxygen was measured using the Winkler method on board while chlorophyll-a was determined after its extraction with acetone on a double beam spectrophotometer [26].

3. Results
3.1. Hydrodynamic Model Simulations

The NW winds blowing at speeds of >4 Bf generate sea currents of 5–10 cm/s, which are satisfactory for a sustainable mussel culture activity [28]. These winds are the most common ones in the area throughout the year, and especially during the winter months. Furthermore, SE winds seem to be quite frequent during the summer months. Figure 6

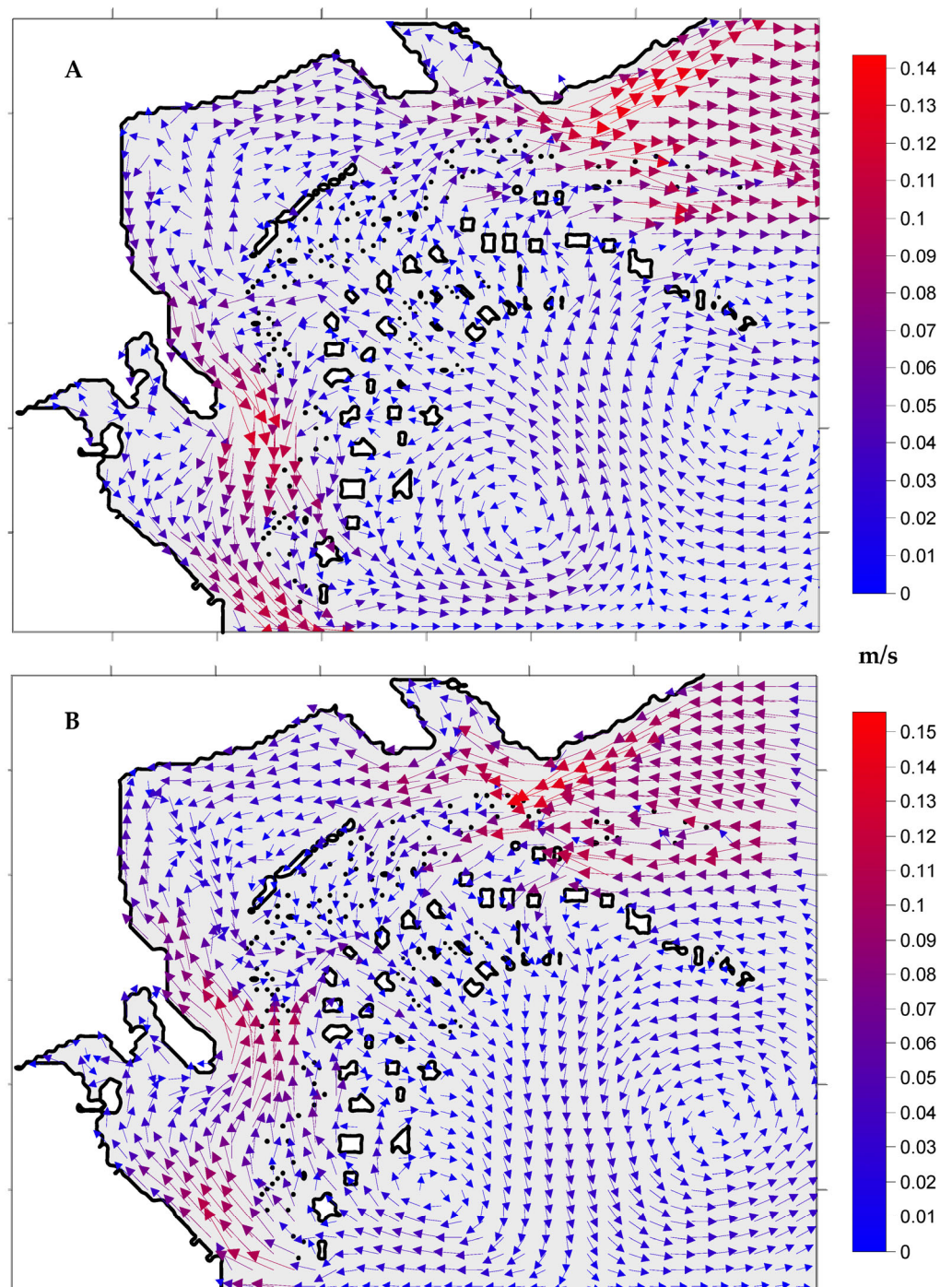below depicts the patterns of sea water circulation in the area of Chalastra due to NW and SE winds of 7 m/s.

Figure 6. Hydrodynamic circulation in the area of Chalastra during NW (**A**) and SE (**B**) winds. The X and Y axes represent the discretization of the field in orthogonal segments.

As far as easterly winds are concerned, although of similar frequency, they tend to be weaker and thus of minor significance to the water circulation.

It should be noted that for the two cases of hydrodynamic circulation under the influence of NW and SE winds, water masses move in opposite directions. Thus, although NW winds generate currents that enter a mussel farm from a specific direction, SW winds generate currents that exit from the same direction as the previous mussel farm. According

to Konstantinou et al. (2015) [11], this circulation pattern is in an accordance with the pattern of circulation defined by NW winds of 10 m/s.

The application of the mathematical model at farm level is demonstrated in Figures 7 and 8, with production lines perpendicular and parallel to wind direction, respectively.
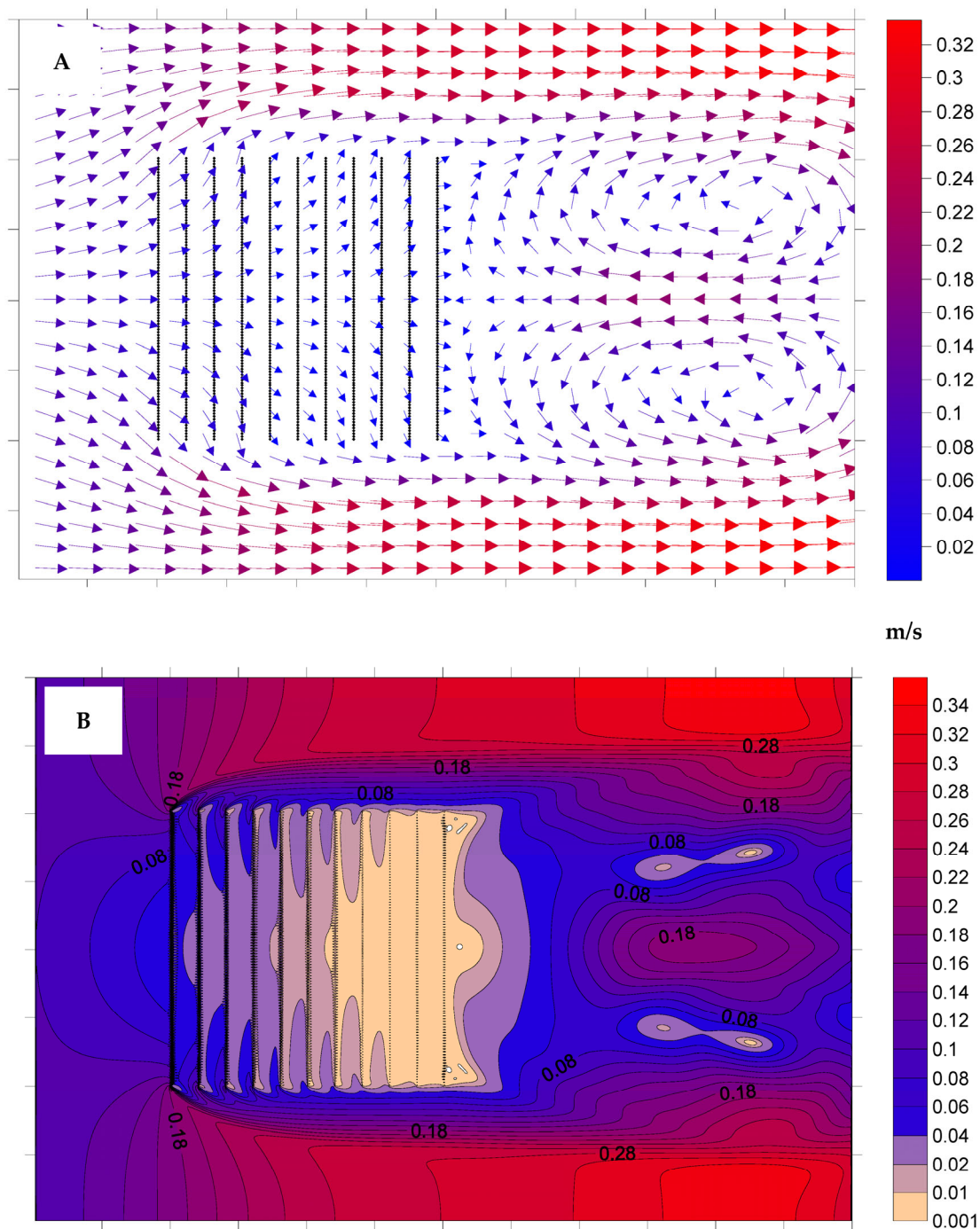

Figure 7. Circulation modeling at culture level with production lines perpendicular to the wind direction (**A**) current velocity speeds (velocity vector) and (**B**) contours of the current intensity (current speed, m/s).
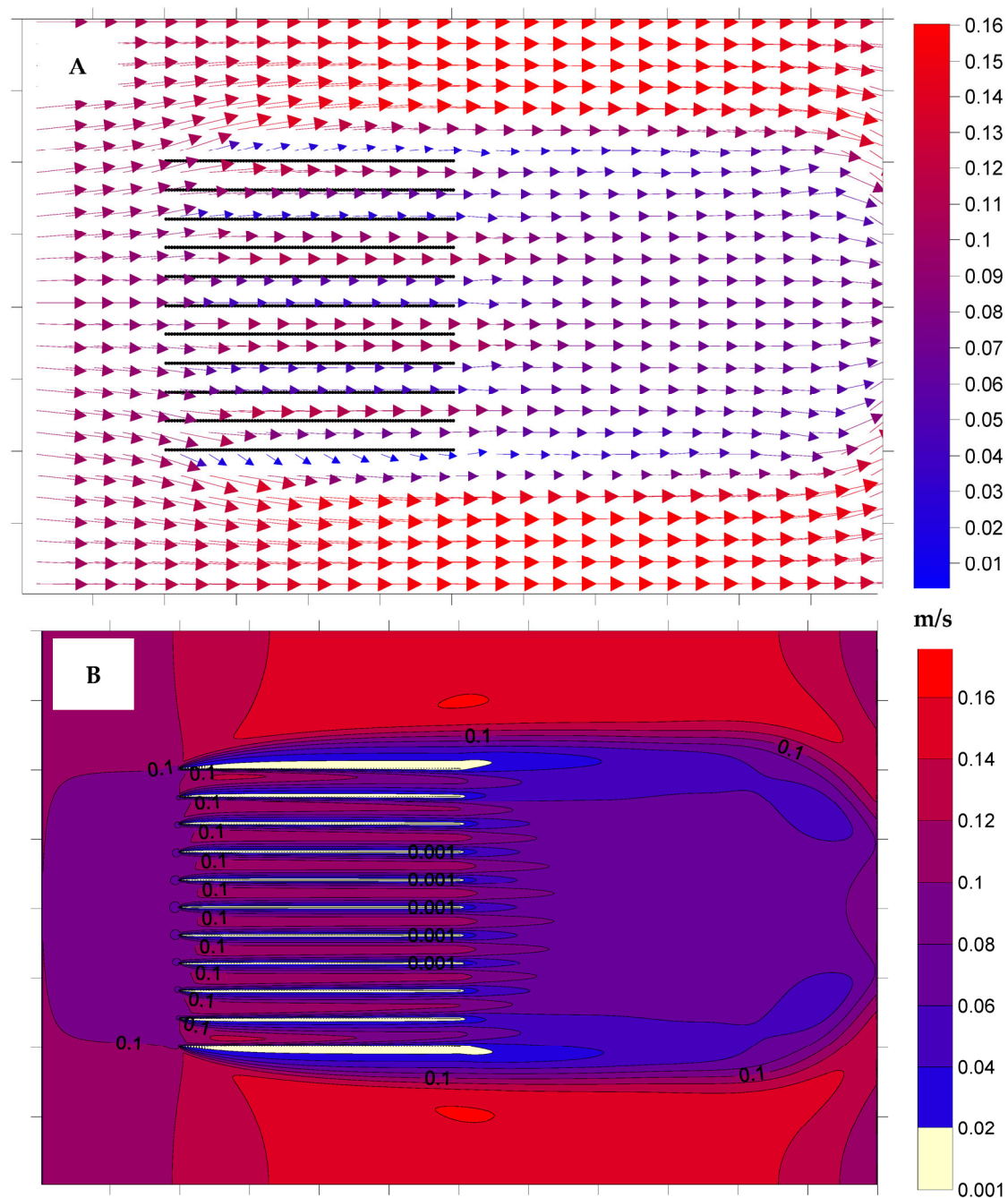
Figure 8. Circulation modeling at culture levels with production lines parallel to the wind direction (**A**) current velocity field (velocity vectors) and (**B**) contours of the current intensity (current speed, m/s).

More specifically, filed measurements showed that the presence of a mussel unit acts as if a breaker to the currents' intensity [29]. This is in line with the results of the hydrodynamic mathematical models, that can be summarized in the following two important points: (a) in the case of water flow perpendicular to culture lines, with currents of 10 cm/s at the entrance to the farm, flow velocity is reduced by one or even two orders of magnitude (Figure 7). This major reduction seems to occur from the middle of the farm all the way up to the exit. Moreover, the outflow from the mussel culture farm is characterized by a pattern of two symmetrical eddies and a return flow between the eddies, and (b) in the case of currents parallel to the culture lines, with currents of 10 cm/s at the entrance of the farm, the flow velocity is reduced laterally to the culture lines, up to one order of magnitude, but reaching two orders of magnitude on the outskirts of the culture lines

(Figure 8). In this case, the reduction in the flow intensity is distinctively lower than that of the flow perpendicular to the culture lines. Moreover, the currents seem to recover their initial intensity when flowing out of the culture unit.

3.2. Monitoring of Nutrients and Chlorophyll–a

The results from the physicochemical analysis showed variations in the concentration of nutrients, with ammonium being the dominant form of nitrogen around the mussel culture area throughout the year. However, high levels of all nitrogen forms (ammonium, nitrates and nitrites) were observed during early spring and early summer, both within the units as well as in the reference site (Figure 9). Phosphate concentrations were limited throughout the year (Figure 9), with even lower concentrations in winter (Figure 9).
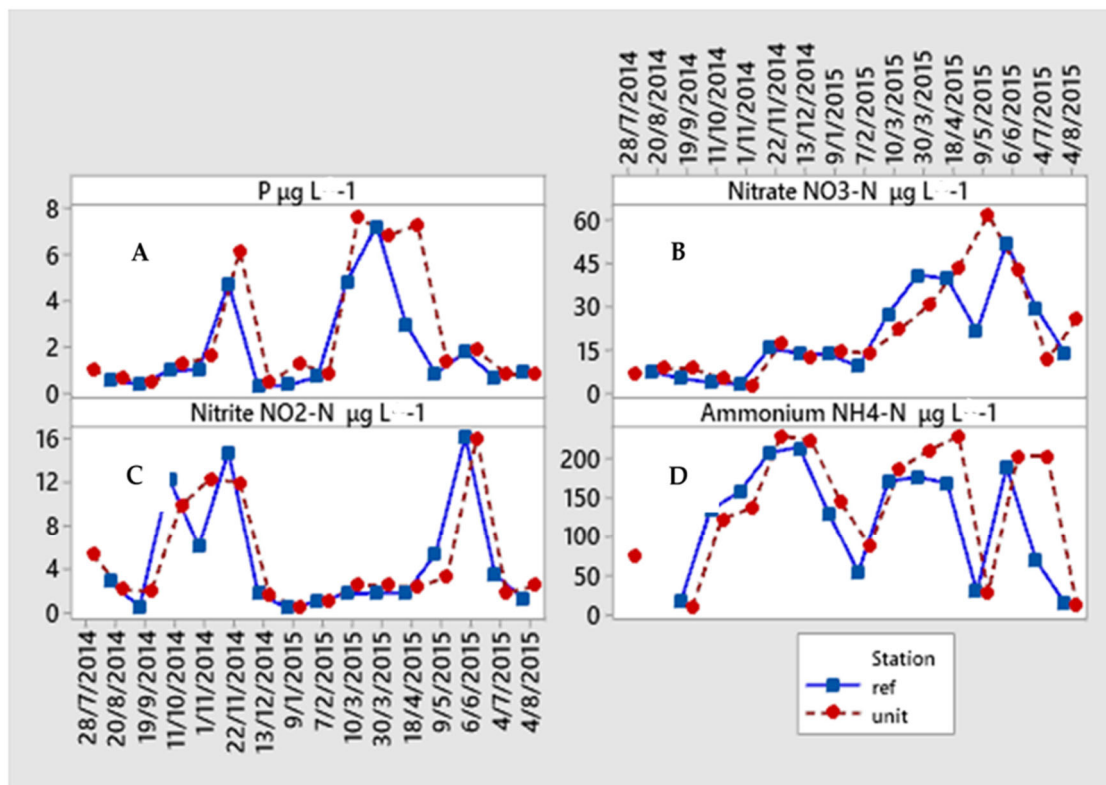
Figure 9. Phosphates (**A**), Nitrate (**B**), Nitrite (**C**) and Ammonium (**D**) profiles as μg L^{-1} throughout a one year period for the reference site (ref) and sampling site within the culture unit (unit).

While chlorophyll-a values were low (about 0.2 mg m^{-3}) in summer and autumn (Figure 10), a peak was observed during early spring with the chlorophyll being marginally sufficient for sustaining both the mussel feeding activity and phytoplankton production, both at the reference and sampling site. Dissolved oxygen concentrations, on the other hand, showed well oxygenated waters in all cases [30].

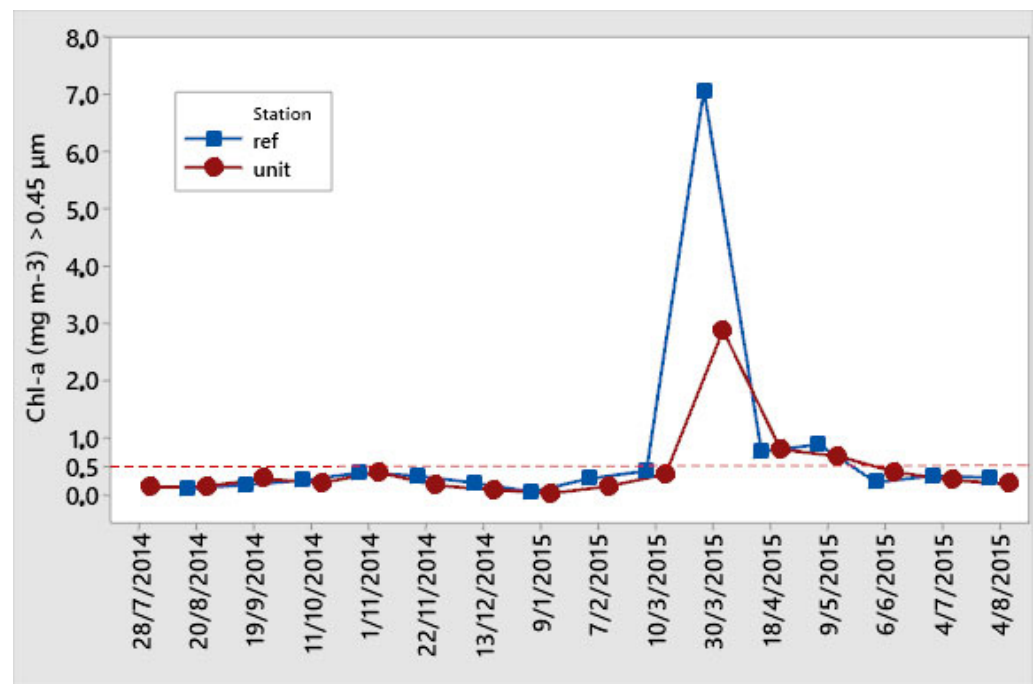**Figure 10.** Chlorophyll–a (>0.45 μm) as mg m^{-3} throughout a one year period for the reference (ref) and sampling sites within the culturing unit (unit). The horizontal line indicates the lowest optimal concentration for mussel growth.

4. Discussion

4.1. Hydrodynamic Model Simulations

The wind constitutes the highest determining factor for water circulation in the study area, while the influence of river flows has decreased in the past few decades [17] and the tidal effect is almost negligible. The prevailing winds blow from north-westerly directions mainly during the winter, and south-easterly directions during the summer. Consequently, the prevailing current flow is a result of the dominant NW winds as well as the SE winds that influence the water circulation in the mussel cultures basin (Figure 11 and field works [20,31]. According to a recent study [32], the majority of the recorded currents in the central area of the basin were 0–5 cm/s for winds ≤4 Bf, while the water masses in this area flowed towards the production lines at an angle. A significant percentage of sea current movements occurred in a perpendicular direction, while a small percentage of the currents flowed along the lines.

The general pattern of the water circulation in the area is determined by the prevailing direction of moderate and strong NW winds. Flow hindrance is strongly dependent on the angle at which the currents approach the production lines, as shown by field data and mathematical models. The mathematical model showed a significant reduction in the center of the unit when water masses flowed perpendicular to the longlines, however flow velocity shows little reduction when the current enters at a parallel angle to the longlines. Similar results were obtained in modeling studies by Konstantinou (2013) [31]. Furthermore, the mussel units were found to cause a reduction of more than 30% in current speeds, as a consequence to the flow rate, and even reaching 70% in some units. Nevertheless, according to the research results, mussel units did not cause major changes to current directions [29].
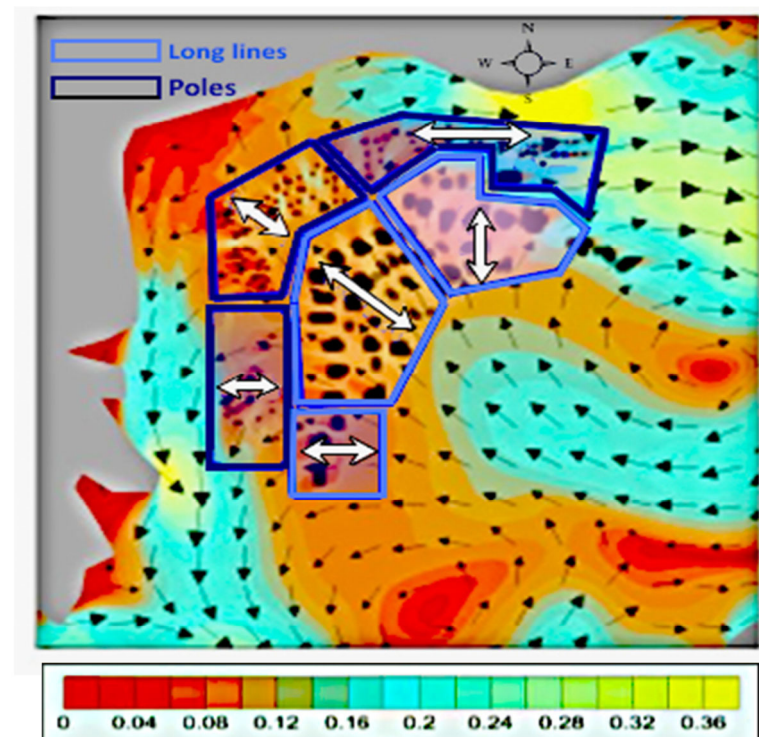
Figure 11. The proposed delimitation of subareas in Chalastra AOAD based on currents resulting from the dominant NW winds. The white arrows indicate the direction of mussel production lines. The proposed scheme is superimposed on the map of the hydrodynamic circulation, velocity field (m/s) by Konstantinou (2013).

Consequently, the selection of the orientation of mussel production lines should be based on the criterion of minimum flow disturbance, ensuring optimum environmental conditions both for mussel and water quality. The confinement of current flow due to the orientation in both pole mussel cultures and longline cultures is similar. Flow confinement is expected to be even more intense for the pole cultures due to the smaller distances between the mussel socks (in comparison with the distance of the socks of the long line cultures). As such, it is recommended that pole mussel farms be used in shallow waters.

The combined outcomes of the mathematical modelling, together with the fact that prevailing winds in the area are mainly of NW and SE direction, has enabled the designation of subareas that could potentially comply with the AOAD requirements. The proposed layout for the three sub-areas in Chalastra are shown in Figure 11 below.

The proposed orientation scheme is applicable to both longline and pole units. Most of the studies up to date have considered the area as a unifying space to align the longline and/or poles mussel cultures [29,31,33]. The distribution of units in subareas according to the hydrodynamic activity will not only minimize the flow disturbance in the aquatic environment of mussel units, but also allow improved circulation and availability of nutrients and chlorophyll as a food source to the mussels, thereby enhancing their growth potential.

The approach of the present study can be applied to new farms during the licensing application period and the development of an operational scheme.

4.2. Chlorophyll–a and Nutrient Availability

The added value of the proposed scheme would be improved distribution of sea nutrients and the balancing of biochemical cycling and regeneration. Figure 10 indicates that the highest concentrations of nitrogenous compounds, usually originating from biological activity, and decay of organic matter and animal excretions, possibly from the mussel culture, are in the form of ammonium. The nitrates are limited and in low concentrations, indicating reduced upwelling activity. Inorganic phosphorus concentrations were almost depleted in

most of the samples (Figure 9). In previous studies [34,35], a correlation matrix of the effect of wind direction on the concentration of nutrients, dissolved oxygen and chlorophyll-a values in the surface layer was observed. In addition, there was a positive correlation between northerly winds and phosphate values, while the correlation of southerly winds with inorganic phosphorus values is negligible [35]. These southerly winds did, however, affect the concentration of ammonium nitrogen [35]. The wind field in the North Aegean depicts northerlies as the strongest winds year-round, with long periods of southerlies during summer [32,34]. Reduced values of chlorophyll-a have been measured at low to almost depletion levels (<0.5 mg m^{-3}) among the mussel culture socks which are intensely cultivated in the area [18,32]. However, these values increase significantly (up to 70%) compared to average values for a reference area sampling point [32]. Since mussel growth depends on natural sources of food, phytoplankton depletion may negatively affect mussel production and quality. Inglis et al. [28] highlight that Chl-a values <0.5 mg m^{-3} are very poor growing conditions for very slow growth, and the mussel conditions deteriorate if they remain there for a prolonged period. Mussel culture facilities limit the water exchange rate within the area of culture, thus limiting the fluctuation of nutrients. Consequently, the food availability may be limited or even insufficient both for the growth of the mussels as well as for sustaining the surrounding aquatic ecosystem. However, differentiations in the nutrient and thus productivity profiles may be observed at various developmental stages of the mussels. The variations in food particle sizes and food demand follows the biological life cycle of the mussels [36]. In the present study, the chl-a and the phosphates ranged from low to almost depletion levels in all sampling points close to mussel culture activities. Insufficient food supplies in the water may initiate adverse effects on the yield of mussels, a fact that will have an immediate and significant effect on national productivity and enhance the profits gained from mussel culture activities. The limited food abundance of low phytoplankton biomass extends over a very long period in the year, but could be more permanent in cases where the positioning of the mussel cultures inhibits the circulation and regeneration of nutrients. The amount of phytoplankton biomass is not the only factor affecting mussel productivity; the quality of the food supply as well as acclimatization are two additional important factors [36]. Moreover, herbivorous invertebrate organisms can act antagonistically, as far as food resources are concerned, towards bacteria and zooplankton. Consequently, any shifts in the food resources available for the mussels will immediately affect the ecosystem [37]. The inhibition of current velocity within the culture area may affect total biological processes, especially those related to the upwelling of nutrients and the downwelling of biodeposits [38], the latter of which is of particular significance, especially in relatively swallow waters such as those in this present study. Previous studies [39,40] concluded that biodeposits along with low hydrodynamics can also alter macroinvertebrate diversity. Intensive stratification, leading to increased accumulation of organic material derived from biodeposits and minimal water movements, may initiate hypoxia and potentially alter the biogeochemical cycles of nitrogen and phosphorus by extending the retention time in the sediments and thus reduce their bioavailability [41]. The effects of changes in nutrient loading can be seen in the annual variation of chlorophyll-a values, reflecting poor food availability to support mussel farming activities in the area. However, the appropriate positioning of the mussel culture units according to the hydrodynamic models may enable the recirculation of the nutrients and thus initiate their regeneration and availability.

5. Conclusions

The final orientation of mussel farms is based on two important findings: (a) the formation of the water circulation in accordance with prevailing external forces that generate the sea currents, and (b) the angle (the direction) of the mussel production line in relation to current direction. More specifically, the numerical simulations that describe the water circulation in a mussel farm reveals that the pattern of water circulation in the farm for currents entering perpendicular to the longlines (with an initial velocity of 10 m/s) shows

strong reduction in the velocity starting from about the center of the unit; meanwhile, flow velocity shows little reduction when the current enters parallel to the longlines.

The appropriate orientation of pole and longline units based on the natural current direction can comprise a useful tool for sustainable mussel culturing. The benefits arising from the application of the proposed scheme are (a) improved primary productivity through the appropriate water and nutrient circulation, and (b) minimization of environmental impacts of the mussel culture activity, as byproducts are more easily dispersed and thus biodegraded. Therefore, in order to effectively apply the AOAD directive and comply with the enforced sustainability goals, hydrodynamic simulations both on the greater coastal area of mussel farms as well as on a unit level should be applied prior to the positioning of the culture units. Moreover, the present hydrodynamic model of the Chalastra area could serve as a useful tool for future environmental and mussel-production decision making.

Author Contributions: C.A.P. provided the physicochemical data and data concerning the relation between nutrients and the rest of the parameters; Y.G.S. provided the model application and the analysis of the results; S.G.-M. provided data on the current situation and production in mussel culture units; A.M. provided the chlorophyll data. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement: The data can be found in printed form only as project reports.

Conflicts of Interest: The authors declare no conflict of interest.

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