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Interaction between mussel culture and hydrodynamics: a preliminary study in the gulfs of Thessaloniki and Thermaikos, Greece

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A preliminary study for the interaction between mussel culture and hydrodynamics is presented. The study was based on the use of a mathematical simulation in combination with field data of weather parameters and recorded extreme biological events related to mussel cultures. More specifically, the application of a mathematical model was realized for the calculation of currents that prevailed in the coastal region of north-west Thermaikos Gulf in July 1998, a period with mass mortality phenomena of mussels. The model runs revealed the correlation of unfavorable phenomena with the wind conditions and the hydrodynamics in the coastal area. The use of such models may contribute effectively to the sustainable management of the mussel cultures in relation to the hydrodynamics and the ecohydraulics of the aquatic environment in which they are settled.

Key words: ecohydraulics, hydrodynamics, mussel culture, mathematical model, Thermaikos Gulf.

INTRODUCTION

Greek mussel cultures with a history of 30 years constitute a dynamic activity with productivity of ~30,000 tones of mussels (*Mytilus galloprovincialis*) per year. The 90% of the culture units lies in the gulfs of Thessaloniki and Thermaikos, northern Greece (Fig. 1A, B). The mussel cultures are grouped in three farming areas/positions in the gulfs of Thermaikos and Thessaloniki as it is shown in Fig. 1: a) northwest of the Thessaloniki Gulf next to the region of Chalastra, and northeast of the Axios mouth, b) northwest of the Thermaikos Gulf and next to the region of Loudias mouth, and c) west of the Thermaikos Gulf along the Pieria coasts. The aforementioned areas (positions, 1, 2, and 3 in Fig. 1b) produce 80-90% of the total national harvest. The productivity of the units is directly related to the hydrodynamics of the field where they are placed, since the performance of each unit is associated with the position of the settlement and its extent, the topography of the marine area, the prevailing hydrodynamic and ecohydraulic parameters of the area, as well as the physicochemical and biological parameters of the marine environment.

The study coastal area, consisted of the Thermaikos and Thessaloniki gulfs, is characterized by relatively shallow waters (< 40 m), while the estuaries of the three main rivers Axios, Loudias and Aliakmon, are formed in the littoral zone of the north and west parts of the basins (Fig. 1b). During the recent decades there has been a 50% reduction in the total amount of freshwater inputs to the Thermaikos basin, as a result of extraction of river water for irrigation, and the construction of hydroelectric power dams on the Aliakmon river (Hayder *et al*., 2004). Minimal river discharges were recorded during the summer period between 1997 and 1998 (Karamanos *et al.*, 2000).

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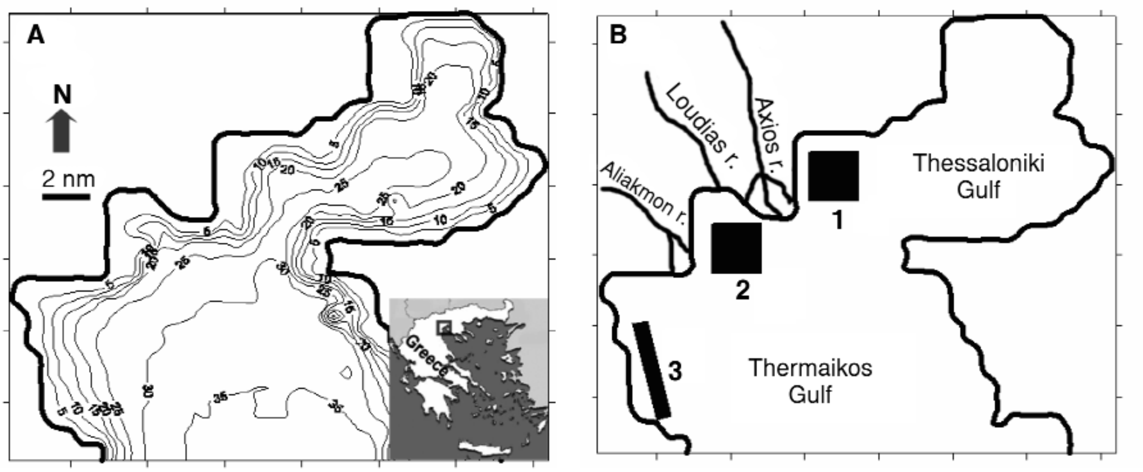

FIG. 1. The study area of Thessaloniki and Thermaikos gulfs with (A) the isobaths, and (B) the positions of the three mussel culture areas.

Thessaloniki and Thermaikos gulfs, the recorded current speed was very low (NCMR, 2001), since 57% of the currents were less than 2 cm sec^{-1} (Galinou-Mitsoudi *et al*., 2002). In related cases, polluted organic matter with a height of 7-30 cm year $^{-1}$ is accumulated on the seafloor, just under the mussel cultures. This accumulation can be prevented by a current speed between 50 and 200 cm s^{-1} (www.fao.org/docrep/T0697E/t0697e04.htm).

In this paper, the interaction between mussel cultures and hydrodynamics, as an environmental expression of ecohydraulics, is primarily studied with the use of a mathematical simulation. The application of the model was realized for a specific summer period with extreme living conditions and intense biological phenomena for the mussel production. This is one of the most new approaches on the subject and the results may contribute to the prognosis of unfavourable biological phenomena as well as to sustainable management of the mussel culture areas.

MATERIALS AND METHODS

The study is based on the application of a 2-D, depth averaged, hydrodynamic mathematical model (Savvidis & Koutitas, 2000; Savvidis *et al.*, 2005). The equations describing the hydrodynamic circulation are the well-known equations of momentum and mass conservation:

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

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

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

where h is the water depth, U and V the vertically averaged horizontal current velocities, ζ the surface elevation, f the Coriollis parameter, τ_{sx} and τ_{sy} the wind surface shear stresses along the x and y axes, τ_{bx} and τ_{by} the bottom shear stresses along the x and y axes, ϱ the density of the water, g the gravity acceleration and ν_h the dispersion coefficients according to the following Smagorinski's formula (Smagorinski, 1963; Mellor, 1998):

$$\boldsymbol{vh} = C \cdot \Delta x \cdot \Delta y \cdot [(\frac{\partial u}{\partial x})^2 + 0.5 \cdot (\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y})^2 + (\frac{\partial v}{\partial y})^2]^{1/2}$$

with Δx and Δy the grid sizes along x and y directions, respectively (here $\Delta x = \Delta y$), U and V the horizontal velocity components along the x and y directions, respectively, and C a coefficient for the horizontal dispersion. The value of constant C was set to 0.10. The above relationship was also used by Karambas & Koutitas (1998) for the simulation of the sub-grid eddy viscosity terms in a 2-D horizontal model, for wind-generated flows in coastal waters. The method of finite differences was adopted for approaching the terms of the mathematical equations used for the simulation.

For the field topography, a hydrographic map of the gulfs of Thessaloniki and Thermaikos was used, where bathymetric information concerning the mussel culture areas was also included (Fig. 1a). After the drawing of the coastline, the discretization of the field with a square grid of $\Delta x = 1000$ m was followed. The time step used for the application was $\Delta t = 25$ sec. The assumptions for the application of the mathematical model as well as the initial and boundary conditions are described in detail in Koutitas (1988).

During July 1998, an amount of more than 50% of the total annual production was destroyed (Galinou-Mitsoudi & Petridis, 2000). The influence of the river water discharges is not important especially to the summer water circulation in the Thermaikos basin and is therefore neglected in the present study. The wind speed and direction values from the Meteorological Station of AUTH (Aristotle University of Thessaloniki) were used. Concerning the tidal influence, a signal of approx. 25 cm was taken into account on the south open sea boundary of the basin of the gulf. This value corresponds to the mean tidal height in the Mediterranean and the Aegean Seas (Krestenitis *et al*., 1997; Dodou *et al.*, 2002; Savvidis *et al*., 2004).

RESULTS AND DISCUSSION

The application of the model for tidal circulation showed that, the effect of the tide on the circulation is insignificant for the specific area. More specifically, the simulation, based on this weak tidal forcing, led to quite small values of the current velocities (< 5 cm s^{-1}) apart from the water entrance from the open sea to the Thessaloniki Gulf. These results are in line with previous work (Ganoulis, 1994).

The application of the model for wind circulation was based on two discrete numerical experiments, focused on the study of the hydrodynamic circulation in the gulf and the computation of the time series of the current speed (in the center of each area of mussel cultures):

a) without the mussel cultures, and

b) with the mussel cultures in the three areas of the aquacultures (Fig. 1). In this case, the simulation was based on the following numerical approach of the physical phenomenon: in the mussel culture areas, the blockage of water circulation was simulated with the increase of the momentum dispersion coefficient ν_h related to the turbulence (and the development of shear stresses causing increased internal friction). This increase causes reduction of the current speed, and the value of that increase is found by repeated numerical tests based on the values of current's reduction, recorded from field measurements in position 1 (NCMR, 2001). In the present application, the values of the dispersion coefficients taken into account in the area of the mussel cultures are 100 times larger than the values computed for the case without the mussel cultures. This approach leads to current's reduction by 30% (NCMR, 2001; Krestenitis *et al*., 2003). The choice to adopt the technique of increasing the momentum dispersion coefficients is very close to the physical phenomenon of the evolution of the shear due to turbulence, causing reduction to the currents' velocity. This approach is considered much more close to the physics than the increase of an external friction factor, like bottom friction. Besides, the increase of the dispersion coefficients leads to a consequent increase of the internal friction to the fluid's motion.

In Fig. 2, the temporal variability of the wind speed during the period of July 1998 over the field is given. The correlation of Figs 3a-c to Fig. 2 is characteristic. The Figs 3a-c show the variability of the current speed during the same period, with or without mussel cultures (model results). The intensity of currents in the study regions, according to the wind conditions recorded in July 1998, is presented in Table 1. The results of simulation (Figs 2, 3 and Table 1) showed that the current speed is proportional to the intensity of winds, and decreases through the mussel culture areas. The regions of positions 1 and 2 are presented with even lower currents which make them more prone to unfavorable phenomena. The currents calculated in the areas of mussel cultures are characterized, according to Inglis *et al*. (2000), as very low (< 5 cm s^{-1}), even without the presence of the units, which leads to lack of food in the central units of a mussel culture, while currents of mean speed

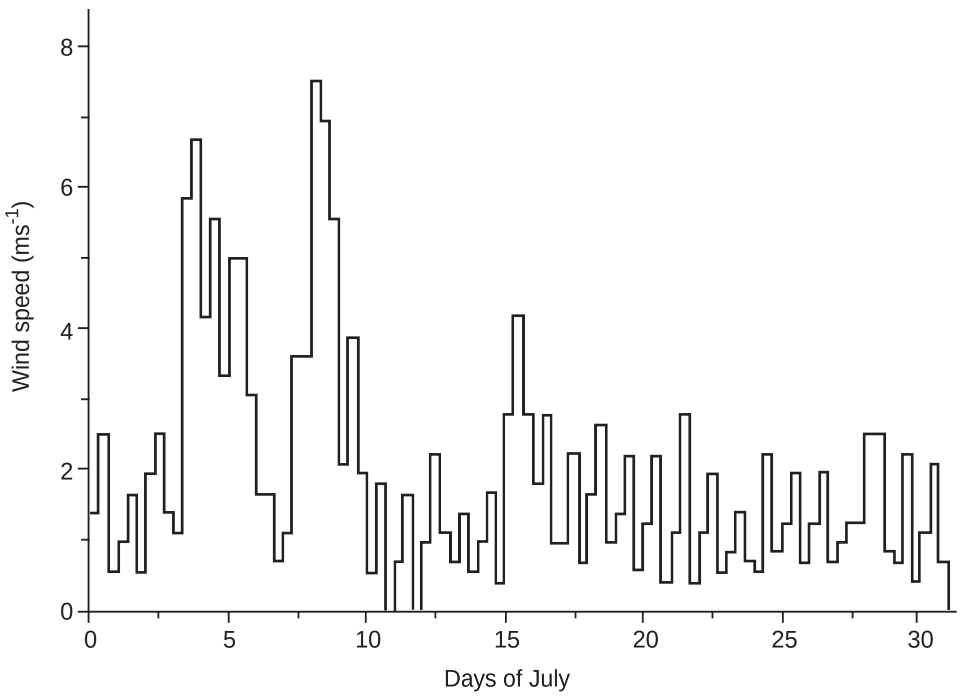

FIG. 2. Temporal variability of the wind intensity (data from station).

TABLE 1. Current velocity in the gulfs of Thessaloniki and Thermaikos corresponding to the winds in July 1998

Area of mussel culture	**Current speed: variance / mean ± SD** Without mussel culture	With mussel culture
Position 1 (Chalastra)	0 - 10 / 2.2 cm s^{-1} ± 0.015	0 - 8 / 1.5 cm s^{-1} ± 0.011
Position 2 (Loudias)	0 - 15 / 3.3 cm s^{-1} ± 0.029	0 -10 / 1.9 cm s^{-1} ± 0.015
Position 3 (Pieria)	0 - 10 / 1.8 cm s^{-1} ± 0.015	0 - 8 / 1.5 cm s^{-1} ± 0.011

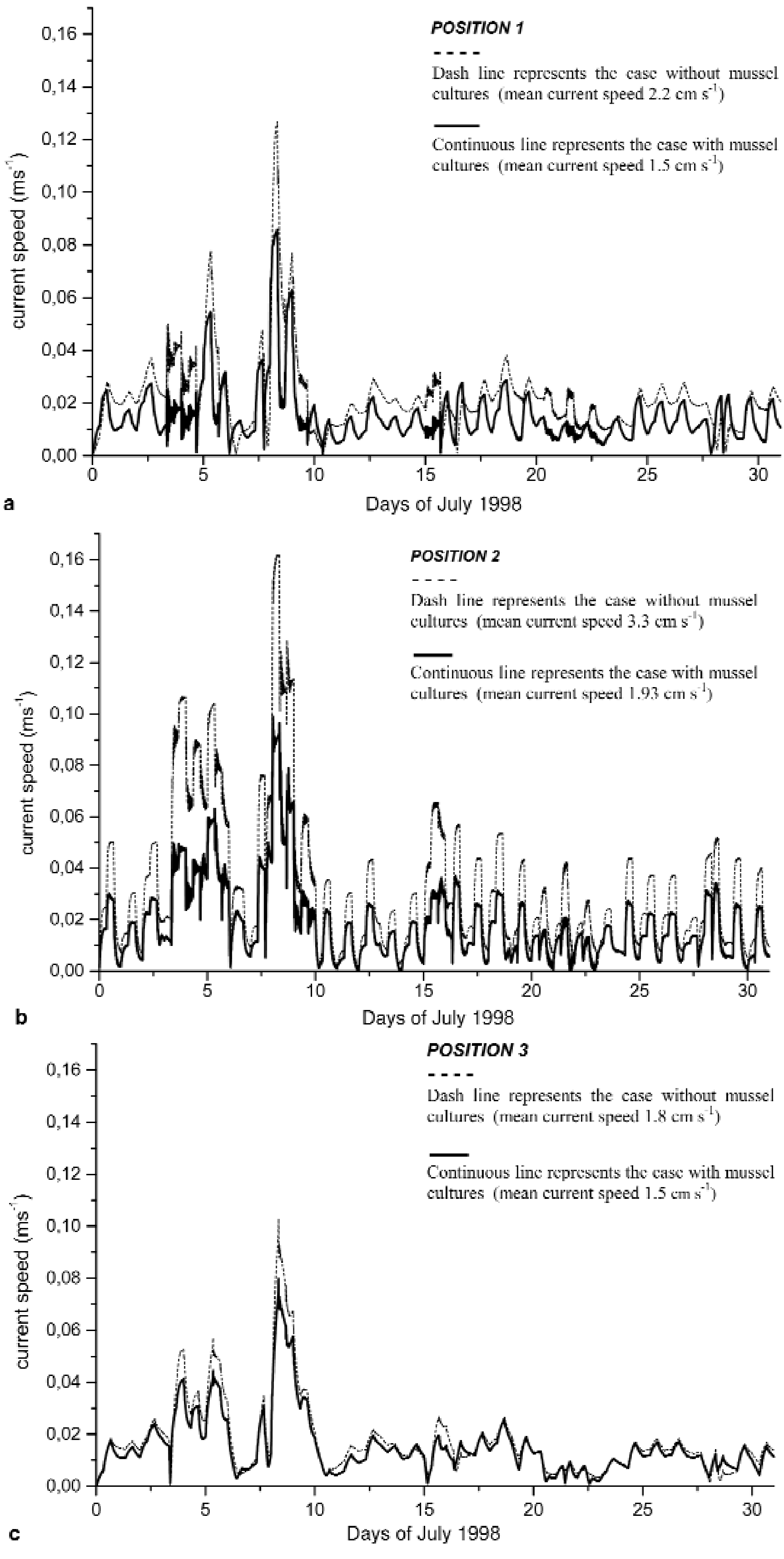

FIG. 3. Temporal variability of the currents without (--) and with (—) mussel cultures at a) position 1, b) position 2, and c) position 3 (model results).

(10-20 cm s^{-1}) were observed very rarely during the particular period. Similar results were observed in mussel cultures of South Africa, where the current speed becomes reduced from 7.5 cm s^{-1} in the outer region to 1.25 cm s^{-1} inside the units (Heasman *et al*., 1998).

As a consequence of the low current speeds, the residence time of the waters in the basin of the mussel cultures increases. Although issues related to the residence time were not included in the simulation, the flow rate is directly related to the intensity of the current velocities, and, consequently, it is obvious that because of the low current speeds, the residence time of the waters in the basin of the mussel cultures becomes gradually longer. This fact, in combination with the high temperatures of July (mean monthly temperature 26.7°C) and the stratification of the water column, led to mass mortality of mussels of the units in the position 1. It is estimated that the mortality occurred after the middle of July, when, for a period of five days, the winds blowing over the area were negligible.

Furthermore, bivalve culture structures modify current velocity and direction of water movements. In turn, these changes may alter patterns of the erosion and sedimentation of particulate matter, as well as food availability for cultured organisms. These phenomena, related to the decrease of the flow currents, may cause a) problems in mussel production and culture management, b) changes in benthic communities (www.fao.org/docrep/T0697E/t0697e04.htm), c) reduction of the food availability with consequent reduction of the mussel harvest (Gosling, 1992), d) decrease in the byssus degree attachment of mussels cultured (Carrington, 2002) with an implicit increase of the danger for the mussels to be detached more easily by an external force (waves and/or human activities in culture) (personal observation).

For the application of the model, the blockage of the water circulation was simulated with the change of the dispersion coefficient values (shear due to increased turbulence and the consequent internal friction), caused by the presence of the mussel cultures. The detailed determination of these parameters with their approach as spatial function (units' spacing, distances of the long lines) and temporal function (increase of the mussel volume) needs further study. Also, a more detailed study including the tidal influence, the wind forcing, as well as other forcing factors for the generation of the hydrodynamic circulation in the basin, will follow this work. The aforementioned research reveals the significance of the mathematical simulation in issues of operational planning of mussel cultures. The present study was focused on the analysis of an incident which occurred in the past. The use of mathematical modelling allows a better study and determination (with high accuracy) of the interaction between the aquaculture and the hydrodynamic conditions of the study area. These models can ultimately constitute a useful tool for the suitability of a region as a host for aquaculture settlements.

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