Global NEST Journal, Vol 13, No 2, pp 119-129, 2011

MODELLING THE DISPERSION OF HARMFUL ALGAL BLOOM (HAB) IN THE THERMAIKOS GULF (NW AEGEAN SEA)

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Received: 15/12/09
Accepted: 15/03/11

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ABSTRACT
Coastal hydrodynamics are directly related to important environmental and ecological issues. This paper focuses on the study of harmful phytoplankton cells' dispersion, after an episode of an algal bloom, based on mathematical modeling. The case of Thermaikos Gulf was used for the simulation. The necessary hydrodynamic information was obtained by the application of a 2D hydrodynamic model directly coupled with a transport model for the simulation of the harmful cells' dispersion. The model describes hydrodynamic and biological processes such as advection, dispersion and cell growth and losses. The mechanical processes are described with the mass and momentum conservation equations while the movement of the particles is described with the Random Walk simulation. The biological processes of cell growth rate were described as a function of temperature light and nutrients, and embodied to the simulation as input data for the model runs while the biological losses are simulated by the removal of particles randomly selected from the field. The reliability of the model was tested using data of a real algal bloom episode. Finally the study is completed with the detection of the distribution of the harmful phytoplankton cells in Thermaikos for different wind conditions and different sources of algal bloom.

KEYWORDS: phytoplankton bloom, dinophysis, hydrodynamics, biological processes, algal growth, matter transport, numerical modeling.

1. INTRODUCTION

Coastal hydrodynamics are directly related to important environmental and ecological issues, like matter transport, pollutant's transport, erosion and deposition, as well as biological and physicochemical interactions. Thermaikos Gulf is a semi-enclosed area located in the northwest Aegean Sea, east Mediterranean Sea (Figure 1). One of the biggest commercial harbours in Greece is located in the inner part of the gulf, where the Thessaloniki city lies. The most important shellfish cultivating area of Greece, with an annual production of 40000 tons of Mytilus galloprovincialis (Koukaras and Nikolaidis, 2004) is lying along the western part of Thermaikos Gulf. Three rivers, Axios, Aliakmon and Loudias, discharge into the west coasts of the gulf. During the last decades, the river discharges were decreased dramatically due to the operation of hydroelectric plants and irrigation projects (Huthnance*,*1997). As far as the bathymetry of the gulf is concerned, the waters are very shallow along the coastlines, while, offshore the coast, the depths reach to 40 meters.

Concerning the hydrodynamics of the Thermaikos Gulf and the greater area of the Aegean Sea, a lot of work has been done up to now. More specifically, Koutitas (1987), Poulos *et al.* (1997, 2000), Dodou *et al.* (2002), Hyder *et al.* (2002) and Savvidis *et al.* (2005), have presented relevant works concerning the hydrodynamic circulation in the Thermaikos gulf as well as in the greater area of the North Aegean Sea. Furthermore, Mpimpas *et al.* (2001) studied the water pollution while Savvidis *et al.* (2001), Kourafalou *et al.* (2004) and Krestenitis *et al.* (2007) have studied the hydrodynamics and

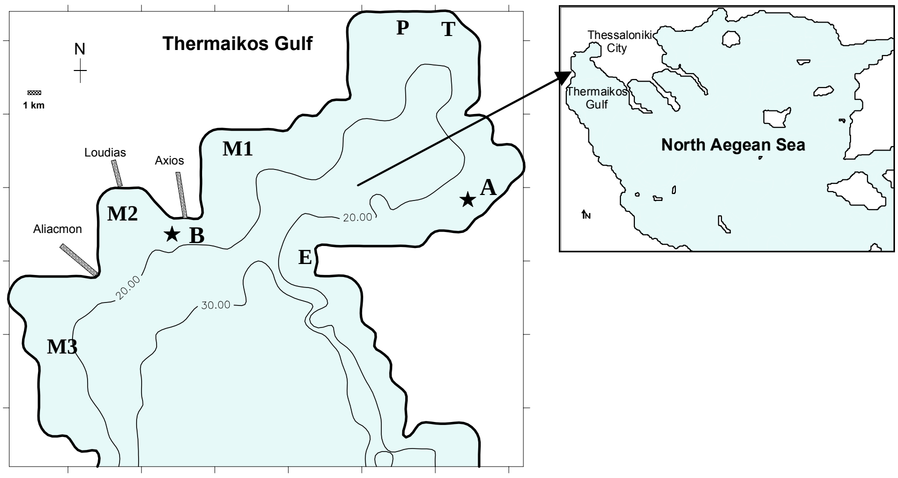

Figure 1. The study area of Thermaikos Gulf and the greater area of NW Aegean Sea (A & B are control positions for the initial application of the model, T the city of Thessaloniki, P the Thessaloniki Port, E the area "Megalo Emvolo", M1, M2 and M3 mussel culture areas)

matter transport in Thermaikos Gulf with mathematical simulation. Concerning the dynamics from the biological point of view, only few models, describing zoobenthos dynamics (Patoucheas and Stamou, 1993), phytoplankton growth rate (Patoucheas and Haritonidis, 2002; Patoucheas and Dasiou 2002), Chl-a and nutrients (Ganoulis, 1991, Nikolaidis *et al.* 2006) have been developed and applied for the case of the Thermaikos Gulf. The present work aims at the development and application of a Hydro-Biological model for the study of phytoplankton growth and dispersion after an algal bloom in the Thermaikos Gulf. As it is known, the dispersion of organic or inorganic mass in a coastal basin is strictly related to the circulation of the water. Especially when shallow waters characterize the coastal basin, as the present case study, a two-dimensional, depth-averaged, hydrodynamic model is sufficient for the simulation of the seawater circulation. In more detail, the mechanical part of the matter transport is adequately described in this work, with the help of a hydrodynamic model. The influence of forcing factors such as temperature, nutrients and sunlight to the growth of the phytoplankton particles is also considered in the study highlighting the biochemical point of view to the matter transfer. Finally, the dispersion and fate of the phytoplankton cells over the area of a basin after an episode of an algal bloom as a result of mechanical and biological processes are examined in this paper. As far as the model application is concerned, the dispersion of dinophysis spp. recorded in Thermaikos gulf after an algal bloom and their distribution in the marine environment of the gulf during January 2000 (Koukaras and Nikolaidis, 2004) was examined. Position A in figure 1 corresponds to the place where the algal bloom A was recorded, while position B corresponds to the place where some important phytoplankton concentrations were observed and recorded in the field, 21 days after the bloom.

2. METHODS - MODEL DESCRIPTION

The present study is based on the use of mathematical modeling as a tool for the study of algae dispersion and growth determined by: a) mechanical processes including advection and dispersion and b) biological processes that include algal growth and total losses.

a) Mechanical processes. A 2D-depth averaged hydrodynamic mathematical model coupled with a transport model is applied for the description of the algal dispersion in the Thermaikos basin. The hydrodynamic model (Koutitas, 1988; Savvidis *et al.*, 2005) is based on the following, well known, equations of mass and momentum conservation.

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

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

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

where h is the depth of the water column, U & V are the vertically averaged horizontal current velocities, ζ is the surfase elevation, f is the Coriollis parameter, τ_{sx} & τ_{sy} are wind surface shear stresses and τ_{bx} & τ_{by} the bottom shear stresses, v_h is the dispersion coefficient according to Smagorinski (1963), ρ the seawater density and g the gravity acceleration.

The knowledge of the hydrodynamic circulation (the velocity field), obtained from the hydrodynamic simulation allows the transport simulation to be applied. The transport model applied for this work is based on the Tracer Method (Lagrange-Monte Carlo Simulation) or Random-Walk Method (Koutias, 1988; Ganoulis, 1994). The simulation of the transport processes based on this method has the important advantage of avoiding numerical problems. Advection and diffusion processes are simulated by means of this method. Jeng (1986), Dimou and Adams (1993), Savvidis and Koutitas (2000), Savvidis *et al.* (2001) and Krestenitis *et al.* (2007) have produced relevant published works.

In this specific work, the two parts of the model, concerning the hydrodynamic and transport processes are fully coupled, including at the same time the biological processes. In more detail, the transport part of the model uses the velocity field, which the hydrodynamic model produces at each time step. According to this method, a large number of particles, representing a particular mass, are introduced to the flow domain through a source. The position of the source is determined from the place where an algae bloom episode takes place. The transport and fate of the particles is traced with time. Advection of the particulate matter is controlled by the local fluid velocity. Turbulent diffusion is simulated by the random Brownian motion of the particles (due to turbulence). More specifically the Tracer Method contains the following steps (Koutitas, 1988): (a) the velocity field is determined by a set of values of velocity components at specific grid points (the local velocity is then obtained from these velocity components, using interpolation schemes), (b) the time step is selected, (c) the range of the random velocity $\pm U_r$ is computed from the equation (4):

$$U_r = \sqrt{6D/dt} \quad (4)$$

where *D* is the local diffusion coefficient and dt is the time step, (d) in the case of continuous discharge, for each time step a specific number of particles is released from the source with coordinates (*Xo, Yo*); while in the case of instantaneous discharge a specific amount of particles is released at once from the initial source, (e) integration in time is executed and the new coordinates of each particle are computed. The motion of each particle is analyzed into a deterministic (advective transport) and a stochastic part (diffusion).
The horizontal positions of the particles are computed from the superposition of the deterministic and stochastic displacements:

$$x_i^{n+1} = x_i^n + \Delta x_i^n + \Delta x_i^{n\,\prime} \quad (5)$$

$$y_i^{n+1} = y_i^n + \Delta y_i^n + \Delta y_i^{n\,\prime} \quad (6)$$

where $\Delta x_i^n = u_i^n\ (x_i^n,\ t^n)\ dt$ and $\Delta y_i^n = v_i^n\ (y_i^n,\ t^n)\ dt\ \Delta y_i^n$ (deterministic displacements) and $\Delta x_i^{n\,\prime} = u_i^{n\,\prime}\ dt\ \ rnd[-1,1]$ *and* $\Delta y_i^{n\,\prime} = v_i^{n\,\prime} dt\ rnd[-1,1]$ (stochastic displacements) with $u_i^n (x_i^n,\ t^n)$ the deterministic velocity at time t^n at the location x_i^n of the i particle and $v_i^n\ (y_i^n,\ t^n)$ the deterministic velocity at time t^n at the location y_i^n of the i particle, $u_i^{n\,\prime}$ & $v_i^{n\,\prime}$ are the random (stochastic) horizontal velocities at time t^n at the location x_i and y_i respectively, $u_i^{n\,\prime} = v_i^{n\,\prime} = \sqrt{6D_h/dt}$, D_h is the horizontal sediment diffusion coefficient & *rnd* is a random variable distributed uniformly between -1 and +1. The spatial particle distribution resulted from the above process can then lead to the computation of the particle concentrations, relative to the number of particles, contained in each grid box.

***b)* Biological processes.** In populations following exponential growth (like phytoplankton) the factors that regulate their density in space and time include the starting population (N_0), the growth rate (μ) and the total losses (TL), according to the following equation (7):

$$N=N_0\, e^{(\mu-TL)} \tag{7}$$

Predation, competition, sinking, water movement and stratification are the most common processes that usually influence TL, while μ is influenced by abiotic factors such as temperature, light and nutrients, as they act directly on the individuals' biochemistry (Patoucheas, 1995; Patoucheas and Dasiou, 2002). In the biological part of the model (table 1), the phytoplankton maximum growth rate μ (T) is computed as a function of temperature, using Eppley's equation (1972) as it was modified by Bissinger *et al.* (2008). Then a limitation factor is computed as a function of light and nutrients concentrations. Light limitation (Llim) is computed using Steele's equation (1962), while field data (Anonymous 2001) were used for the estimation of the photosynthetic active radiation (par) and sun shine duration (Putt *et al.*, 1988). Nutrient limitation (Nlim) is computed according to Michaelis–Menten enzyme kinetics. As phytoplankton cells are transported from the coast to the middle of the gulf, temperature and nutrients concentrations are considered to change randomly following normal distribution with means and standard deviations according to field observations (Koukaras and Nikolaidis 2004).

Table 1. Internal processes and constants used in the biological compartment of the model

Function	**Definition**	**Formula**	**References**
μ	Phytoplankton growth rate (day-1)	μ(T) . Llim . Nlim . Plim	Andersen and Nival, 1989; Patoucheas, 1995
μ(T)	Temperature depended growth rate (°C)	$0.81\, e^{0.0631\, T}$	Eppley, 1972; Bissinger *et al.,*2008
Llim	Light limitation	$\frac{I}{I_{opt}} \cdot e^{1-\frac{I}{I_{opt}}}$	Steele, 1962
Nlim	Nitrogen limitation	$\frac{N_t}{K_N + N_t}$ (Nt: μmole N)	Michaelis–Menten enzyme Kinetics
Plim	Phosphorus limitation	$\frac{P_t}{K_P + P_t}$ (P_t: μmole P)	Michaelis–Menten enzyme kinetics
Constants	**Definition**	**In model**	**In literature**
TL	Total losses (grazing + sinking + natural death)	~ 0.33 (day^{-1}) estimated from numerical tests and bibliographical references	0.07-0.67 (season depending) Landry and Hassett 1982; Landy *et al.,* 1995; Peperzak *et al.,* 2000; Garcés *et al.,* 2005
I_{opt}	Optimum light irradiance	110 W m^{-2}	100-170 W . m^{-2} Patoucheas, 1995; McCreary *et al.,* 1996; Huret *et al.,* 2007
K_N	half-saturation for nitrogen uptake	3 μM	0.4 – 10 μM Eppley *et al.,* 1969; Pasciak and Gavis, 1974; Andersen and Nival, 1989; Huret *et al.*, 2007
K_P	half-saturation for phosphorus uptake	0.2 μM	0.09 – 3.4 μM Taft *et al.,* 1975; Yamamoto and Tarutani, 1999; Yamamoto *et al.,* 2004

In more detail, the information with the growth rate coefficients was introduced to the model as a time series of mean daily growth rates. The modeling approach, concerning the increase of the particles due to division and the decrease due to particle losses, was organized as follows:

After a day's period a new amount of particles equal to $\mu \cdot N_0$ is generated, where μ is the growth rate coefficient and N_0 is the number of particles before the division (total particles of the previous day). The total number of particles N, after the growth process, is then computed as $N=N_0+\mu \cdot N_0$. The position of the new particles is determined from the positions of other particles randomly selected. Additionally, a decay coefficient (TL) was adopted for the population decrease and particle disappearance of the water column. At the end of a day's period a new amount of particles equal to $TL \cdot N$ is drawn out, where TL is the aforementioned decay coefficient and N is the number of particles before the particle losses (total particles of the previous day plus the particles added due to the growth process of the present day). These particles are no longer taken into account in the numerical computations. Consequently, the total number of particles N_t, after the growth process and total losses, is then computed as $N_t = N - (TL \cdot N)$ or $N_t = [N_0+\mu \cdot N_0] - [TL \cdot (N_0+\mu \cdot N_0)]$

According to the simulation practice, the number of particles, as the next day starts, is $N_0 = N_t$ (the new values are stored as old ones). It was considered that a value less than the mean TL=0.37 (resulted from the range 0.07 to 0.67 reported and published in the international literature i.e. Landry and Hassett, 1982; Landy *et al.*, 1995; Peperzak *et al.,* 2000; Garcés *et al.,* 2005) was appropriate for the model runs corresponding to the period of January (with low temperatures) where field data were available for the model calibration and evaluation. Finally values of TL 0.31-0.33 seemed to be the most appropriate ones, leading to computed concentrations of harmful algal cells close to the ones recorded in the field.

As far as the boundary conditions are concerned, the realistic simulation of the phenomenon requires that particles reaching the coast, return to their previous position. The particles, reaching the open sea boundary, are trapped there and no further computation is made for them. These particles are then excluded from the computational loops. The position of the source (and the particle concentration) is determined from the place where an episode of an algal bloom, combined with the toxic dinophysis (HAB) burst, was observed and recorded, such as the one at 10^{th} of January of 2000 (Koukaras and Nikolaidis, 2004). Population density (the particle concentrations) is then computed from the number of particles, which are found at each grid box. Finally the horizontal distribution of the concentrations over the Thermaikos and especially along the coastal zone is obtained from the model runs.

3. MODEL APPLICATION - DISCUSSION

Application for a real episode

The application of the simulation concerned an episode that took place in Thermaikos Gulf on 10th January of 2000. The equations of the hydrodynamic model, described in the previous section, were numerically solved by the finite difference method. The field was discretised with a grid 32×36 grid cells (Fig. 2). The spatial-discretisation step was dx=1000 m. The pattern of the mean water circulation, during the study period of the 20 days, is given in the following figure (Fig. 3).

The knowledge of the hydrodynamic circulation in a costal basin, such as the above computed one, can contribute to the preliminary tracing of potential place of harmful algal blooms. According to Xie *et al.* (2007) the development of eddies in a coastal area appear to be directly related with the Dinophysis (HAB) coastal events and they may be a potential effective prediction tool. As a step next to this tracing a hydrodynamic model fully coupled with a transport and a biological model is applied in this paper. So, concerning the present application to the real coastal geomorphology of Thermaikos Basin, the most intense phenomena of HAB, with values of Dinophysis abundances 10^4 - 10^5 cells/litre were recorded in northeastern and northwestern Thermaikos Gulf during January 2000. It is noted that 1000 particles have been used initially in this application. 619000 particles are finally recorded at the end of a 21 days' period. More specifically, a simulation for the sudden appearance of dinophysis (HAB) in the northeastern Thermaikos Gulf and the recorded populations at the northwestern part of the gulf is studied, with control points A and B, depicted in figure 2. These concentrations constitute a very small percentage, hardly 3-4% of the total concentration of phytoplanktonic cells observed at each place.

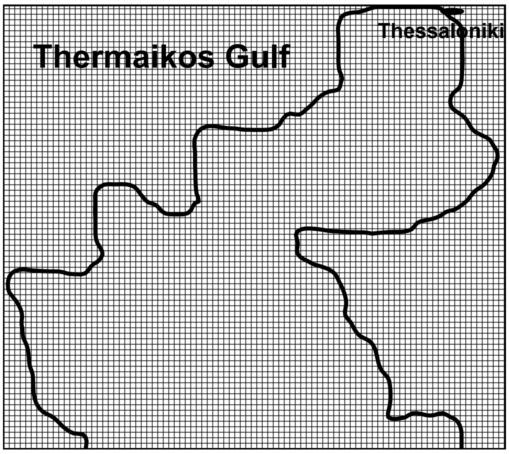

Figure 2. The domain of Thermaikos Gulf and the grid used for the model application

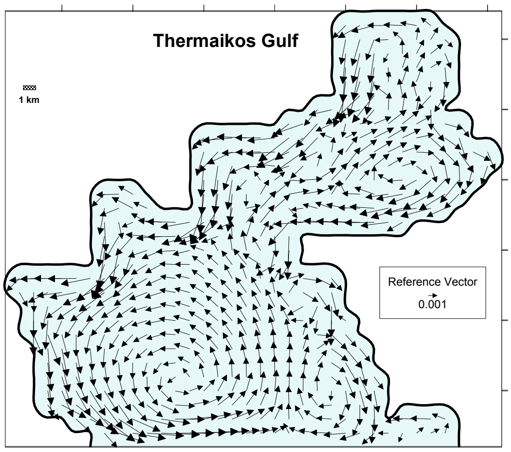

Figure 3. Current velocity field (mean currents during the period 10 to 30 January of 2000)

The numerical experiments were performed for the period between 10th and 31st January 2000, and for the wind conditions of this period (predominance of winds with main northern components), which is quite a characteristic condition in the Thermaikos. As far as the initial conditions are concerned, the model runs were always starting from scratch, e.g. zero current velocities at the start of the simulation time. The effect of tide in the general pattern of dispersion is negligible, since the tidal signal is small (~0.25 m) and the residual currents due to the tide are negligible. Besides, it is well known that the influence of the tides to the hydrodynamic circulation of the Mediterranean waters is small; It is innportant to mention here a recent work by Barale and Gade (2007) who studied the coupling between algal blooms observed in two regions of the Mediterranean Sea with the wind patterns prevailing over these areas; this study was based on remote sensing methods and the corelation concerned the algal dispersion in relation to the wind conditions only. Finally, the present numerical simulation was performed for the wind generated circulation, under the winds blowing over the area during the above mentioned 21days period. The time series of wind data was recorded from a meteorological station of the Institute of Forestry Research at the area of Sani, Chalkidiki. The transport model was applied, considering the position A as the local source of pollution and instantaneous (burst of algae) bloom where large concentrations of dinophysis (HAB) were observed. The daily estimated growth rate used in the biological model (fig 4), has a range between 0.176-0.489 divisions per day.

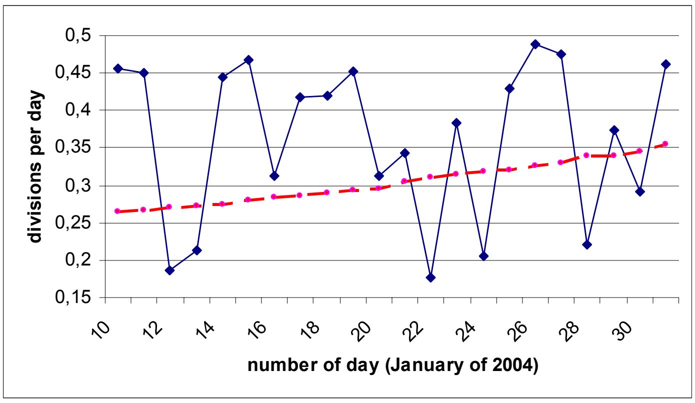

Figure 4. The daily estimated growth rate. a) the solid line corresponds to the biological model and b) the dashed line, corresponds to a long term deterministic model (Patoucheas, 1995; Patoucheas and Dasiou, 2002)

These values are comparable with those that had been estimated using long term (one year) deterministic model for dinoflagellates in the same area (Patoucheas, 1995; Patoucheas and Dasiou, 2002). In literature the values of dinoflagellates growth rates vary within a range of 0.04-0.7

depending on time and local conditions (Graneli *et al.,* 1997; Gisselson *et al,.* 2002; Garces *et al.,* 2005; Xie *et al.,* 2007). The model results, concerning the distribution of the harmful phytoplankton cells in the end of January, e.g. three weeks (21 days) after the most intense bloom (January 10^{th}) are given in the figure 5.

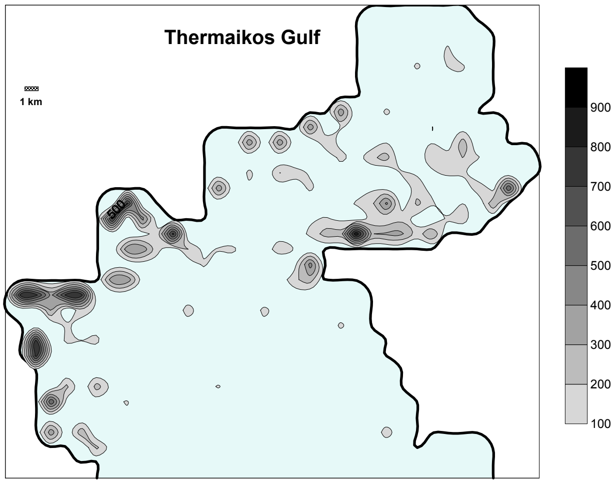

Figure 5. The dinophysis concentrations (cells/lt) 3 weeks after the bloom in position A

The simulation shows that twenty days after the bloom at the northeastern of the inner Thermaikos gulf with initial concentration of 57000 cells/liter at the position A (that is 57000·1000·Vol particles, where Vol is the water volume, in m^3, of the mesh corresponding to position A, with Vol $=dx \cdot dx \cdot h_A$ where h_A the depth in meters of the water column in position A) and under the influence of winds of northern and norteastern direction, the main mass was dispersed to the central and east coasts of the inner Thermaikos, as well as to the western coasts of the gulf; Concentrations of more than 200 cells per lt are found to the region northeast of Aliacmon river mouth and south of Axios river mouth (position B in figure 2). These concentrations, resulting form the model run, are very close to the ones reported by Koukaras and Nikolaidis (2004), according to which, the concentration of the Dinophysis cells (the Dinophysis abundance) at that particular position is larger than 200 cells per lt. Concerning the northwestern coasts of the gulf e.g. the region of mussel cultures northeast of Axios delta (north of position B, area M1) the application of the model for the particular episode leads to values up to 400 cells/lt. These episodes were also reported by Karageorgis *et al.* (2005). Furthermore, concerning the west and southwestern coasts of the gulf i.e. the areas of mussel cultures south of Loudias river mouth (mussel culture area M2, fig.1) and west and south of Aliakmon river mouth (mussel culture area M3, fig. 2) the application of the model for the particular episode leads to values up to 900 cells/lt. The dinophysis concentrations seem to reach similar values at the northern area of “Megalo Emvolo” (position E, fig. 1). Along the coasts of Thessaloniki city (position T, fig. 2) important dinophysis masses are not found. The following figures 5,6,7,8 depict the model results concerning the spatial distribution of the harmful phytoplankton cells i.e dinophysis cells, 5, 10, 15 and 20 days respectively after the intense bloom of January 10^{th}.

According to the patterns of the dinophysis’ dispersion depicted in figures 5,6,7,8, it seems that 5 days after the bloom at position A (figure 6), dinophysis (HAB) masses transported and concentrated in the area of Megalo Emvolo (position E, in figure 1) west of the position A; 10 days after the initial bloom (figure 7), concentrations of dinophysis reached to some areas of the west coasts of Thermaikos while 5 and 10 more days later, e.g. 15 days and 20 after the bloom (figures 8 and 9), concentrations of dinophysis seem to have been dispersed to a relatively great area of the outer Thermaikos Gulf and mainly along the west coasts of the gulf.

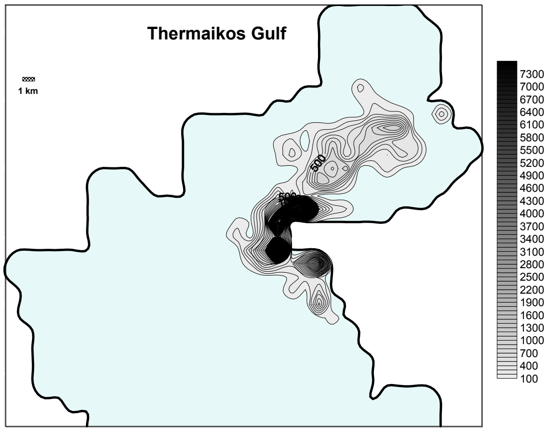

Figure 6. The dinophysis concentrations 5 days after the bloom in position A (cells/lt)

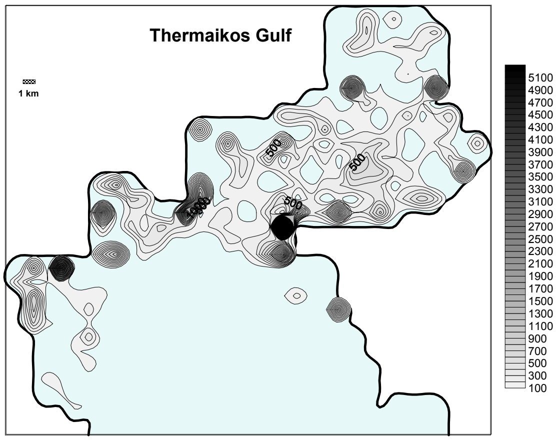

Figure 7. The dinophysis concentrations 10 days after the bloom in position A (cells/lt)

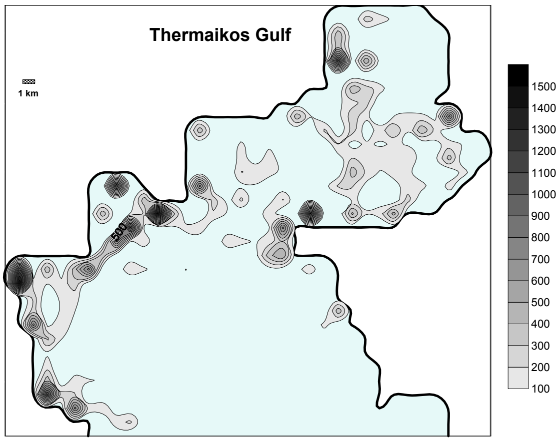

Figure 8. The dinophysis concentrations 15 days after the bloom in position A (cells/lt)

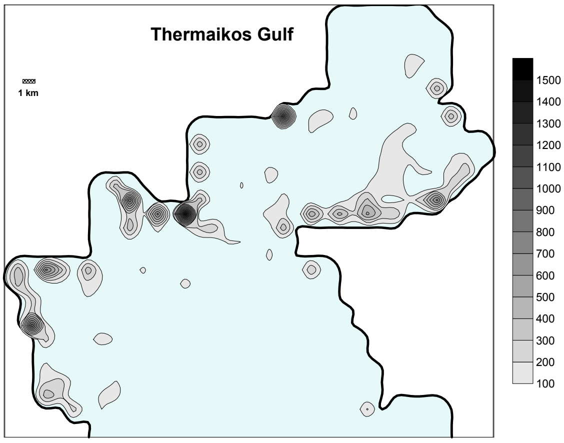

Figure 9. The dinophysis concentrations 20 days after the bloom in position A (cells/lt)

Application for the case of SE blowing winds and the same position of the bloom

Accordingly to the above described process, the scenario of the secondly most frequent blowing winds (SE winds), especially in summer period, is examined here. The source of the algal bloom is considered to be the same as the previous case examined, i.e. at the east coasts of the Gulf, near the area Megalo Emvolo (position E, in figure 1).The model results are depicted in the following figures (fig. 10 and fig 11)

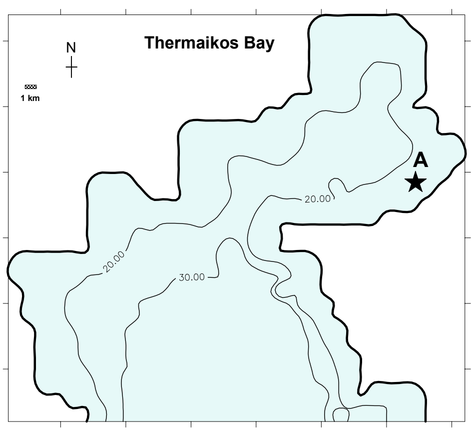

Figure 10. The bloom in the position A

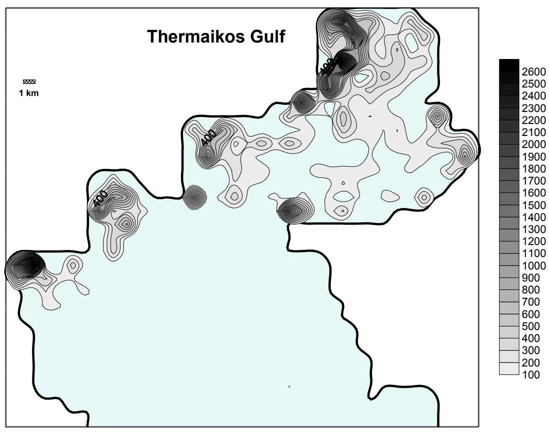

Figure 11. The concentrations 3 weeks after the bloom (cells/lt)

It is obvious to note that under the influence of southeastern winds over the Gulf and an episode of algal bloom occuring at the east coasts of the gulf, and north of the Megalo Emvolo, the final disperion of the harmful cells leads to important amounts of concentrations along the Thessaloniki city waterfront (seafront), and especially along the west coasts of the inner Thessaloniki Gulf. Important concentrations of harmful cells are also computed in the mussel culture areas in the northwestern and western coasts of Thermaikos Gulf.

Application for the case of NW blowing winds and the position of the bloom near the port of Thessoloniki. A characteristic situation, commonly seen, is examined with the help of the above described model. An algal bloom is considered to take place in the area close to the port of Thessaloniki. NW winds which are the most frequent blowing winds are taken into account as the external force for the generation of the hydrodynamic circulation. The model results are depicted in the following figures (Fig. 12 and Fig 13)

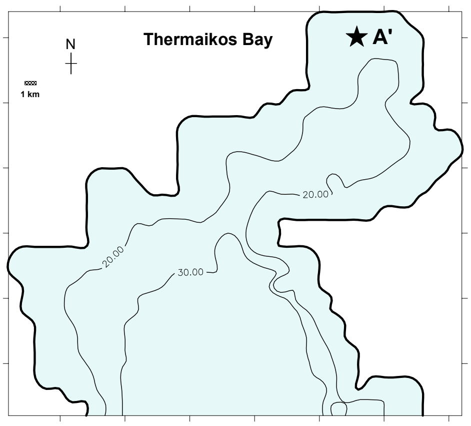

Figure 12. The bloom in the position A´

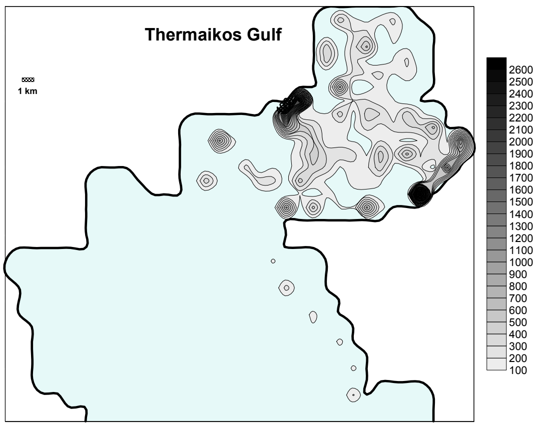

Figure 13. The concentrations 3 weeks after the bloom (cells/lt)

According to the application of the simulation of this last scenario, taking account the influence of northwestern winds over the gulf and an episode of algal bloom occurring at the north coasts of the gulf, near the port of Thessaloniki (position P, in figure 1), it is easy to see that the final dispersion of the harmful cells leads to large amounts of concentrations south the city of Thessaloniki and northeast of the Megalo Emvolo area, as well as along the northwestern coast line of the gulf, to the northeast of the mussel culture area M1 (see figure1).

5. CONCLUSIONS

The model results were very close to recorded field measurements (Koukaras *et al.* 2005) and confirm the value of the presented methodological approach. It is also important to note that this work, based on mathematical modeling, is in line with Koukaras and Nikolaidis (2004) who report that (a) the pattern of bloom development appears to be related to the spatial origin of the Dinophysis population in relation to the water mass circulation in the study area and (b) the fact that all blooms were first recorded in the inner part of the gulf indicates that the Dinophysis population originated from this area. The application of the above presented model comes to complete and confirm the considerations and findings by Koukaras and Nikolaidis (2004). With the appearance of such episodes in Thermaikos and the wind conditions prevailing in each period, each case that concerns the spread of phytoplankton cells in the large area of gulf can be investigated, so that the essential measures of prevention can be applied. In more detail, the present work shows that mathematic modelling can be used as an administrative and operational tool for the prognosis and the investigation of various scenarios that concern the spread of harmful phytoplankton cells in the aquatic environment of a coastal basin. Concerning the application of the real episode, presented in this paper, it seems that after a phytoplankton bloom at the northeast coasts of Thermaikos Gulf (with prevailing northern winds over the coastal basin), concentrations of harmful algal cells, reach to the northwest and west coasts of the gulf where the largest part of the mussel culture of Greece lies (as well as along the bathing coasts of the gulf) within a period of 10 days, while 20 days after the bloom the mass of dinophysis (HAB) seem to be dispersed at quite great areas of the outer Thermaikos Gulf. The above practice can also be appplied in different coastal basins with known hydrographic characteristics, so that prevention measures can be taken as soon as possible.

ACKNOWLEDGEMENTS

Our acknowledgments to the Forestry Research Institute for providing us with the meteorological data.

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