Field data analysis and application of a complex water column biogeochemical model in different areas of a semi-enclosed basin: towards the development of an ecosystem management tool

G. Petihakis a,c,*,1, G. Triantafyllou a, A. Pollani a, A. Koliou b,2, A. Theodorou c,1

a Institute of Marine Biology of Crete, P.O. Box 2214, Iraklio, 71003 Crete, Greece
b Public Company of Water Resources, Magnisia, Volos, Greece
c Department of Agriculture, University of Thessaly, Animal Production and Marine Environment, Fytoko, Nea Ionia Magnisias 38446, Greece

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Abstract

The Pagasitikos gulf ecosystem is studied through the analysis of experimental field data acquired during several monitoring projects and the application of a complex biogeochemical model. The gulf was separated into three different parts (internal, top central-external, bottom central-external) according to the patterns exhibited by the key ecosystem indicators. Unlike other semi-enclosed gulfs Pagasitikos can be characterised as meso-oligotrophic undergoing periods of P or N limitation. Although the signal of nutrient inputs is not very clear in the field data, their importance is assessed through simulation. Increased phosphate concentrations either due to mixing or due to anthropogenic activities can result in phytoplanktonic blooms.

* Corresponding author. Tel.: +30 281 0337753; fax: +30 281 0337822.
E-mail address: pet@imbc.gr (G. Petihakis).
1 Tel.: +30 421 93052; fax: +30 421 93054.
2 Tel.: +30 421 55555.

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with significant contribution by diatoms. The effect of hydrodynamic patterns on primary production has been demonstrated through ecosystem modeling indicating that due to long stratification periods, all nutrients released through the benthic regeneration are trapped in the deeper layers, developing a microbial food web. However when the thermocline erodes nutrients find their way up in the upper layers of the euphotic zone and the system turns into more classical type with primary producers growing significantly faster.
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1. Introduction

Pagasitikos is a semi-enclosed gulf located in the western Aegean Sea north of Evia Island surrounded by the mountainous areas of Pilio, Halkodonio, Giouras and Othrys. The mean depth of 69 m characterizes the system as a shallow gulf while the deepest area (108 m) is found at the eastern part where more pronounced gradients are observed. The total area is 520 km² and the total volume 36 km³. It is connected with the Aegean Sea and north Evoikos through the narrow (5.5 km) and relatively deep (80 m) Trikeri channel. Although the ribbon development in the coastal areas is not considered significant, at the north part of the gulf is situated the city of Volos with a population of 120,000 and major industrial production. The development started during the 1960’s characterized by population explosion, industrialization and intensive agriculture affecting the littoral and sub-littoral systems, which received considerable quantities of rural, industrial and agricultural effluents. Although a sewage treatment plant for the domestic effluents was planned as early as 1964 it took 23 years for it to become operational. Another important event was the draining of Lake Karla in the early 1960’s via an aqueduct in the north part of Pagasitikos when large quantities of nutrient enriched waters were poured into the system. Although the lake is dried up at present, winter rains wash the soil in the wider area of Karla basin, becoming enriched with fertilizers, pesticides and particulate material a proportion of which finally reaches Pagasitikos. In addition large quantities of fertilizers rich in nitrogen, phosphate and sulphur are used annually in the scattered farmlands along the coastline where intensive agriculture of cereals and cotton is practised. Although there are no major rivers in the wider area, it is believed that a significant proportion of these nutrients enter the system during winter through a network of small torrents (Fig. 1).

The microclimate follows the general characteristics of the Mediterranean basin with two major wind groups: the Etesian blowing from July to September with a north–west direction exhibiting maximum values during afternoon and minimum at night and a second group composed of southerly warm and dry winds. Generally the winds are characterized as particularly weak resulting in the formation of a prolonged thermocline. The mean annual air temperature is 16.5 °C with maximum 31.0 °C in July and minimum 11.0 °C in January.
During 1982 dense mucilage composed of phytoplankton cells, bacteria, zooplankton excretions and detritus covered large areas in the north part of the gulf causing significant problems to the fishing community and to tourism. This phenomenon was greatly reduced both in space and time in the following years, to return however with greater severity in 1987 which was the worst year ever recorded. Although the exact causes are not known it is suggested that the nutrient inputs in conjunction with the shallow depths at the north part of the gulf and the high summer water temperatures are the factors responsible for this phenomenon (Friligos, 1987).

The system of Pagasitikos has been studied since 1975 (Friligos, 1987; Friligos & Gotsis-Skretas, 1989; Friligos et al., 1990; Koliou-Mitsou, 2000) on a number of physicochemical and biological indicators. From the results of these projects it has been found that the water mass is homogeneous during winter in contrast with the rest of the year when two layers of different salinity and density are formed. This is caused mainly by the inflowing and warmer waters from the Aegean Sea. During August another layer is observed, separating thus the water column into three layers. The surface mixed layer (0–20 m) is characterised by high temperatures and low salinities, followed by an intermediate layer (20–50 m) of sharp increase in salinity and corresponding drop in temperature. Below the depth of 50 m there is a third layer with more or less constant characteristics. In winter, under certain environmental
conditions, a strong vertical mixing takes place resulting in the homogenisation of the water column, although the date of onset varies significantly (September–November). The water renewal takes place along the Trikeri channel. The gulf can be separated into three sub-areas with different functioning modes, the internal gulf characterised by shallow depths (0–60 m), strong coupling between water column and benthos and minimum influence by Aegean Sea, and the two sub-areas of the outer gulf. At the central-external area the deeper water column in conjunction with the intense thermocline and the low light conditions close to the bottom, results in the development of two significantly different parts: the upper layer occupying the top 50 m and the lower water column layer (50–70 m) characterised by relatively low temperature and light conditions.

In this work the characteristic behaviour of Pagasitikos is described using the data from the latest research project (Theodorou & Petihakis, 2000) while all available historic field data are reviewed both through time series and objective analysis. Additionally in an attempt to reveal the governing dynamics in the gulf subsystems and the mechanism behind algal blooms, a complex ecosystem model is used. Initially this water column model was customised and validated in the whole gulf area (Petihakis, Triantafyllou, & Theodorou, 2000b) while later, in another study, it was applied along a north–south transect to assess the effect of nutrient inputs from Lake Karla (Triantafyllou, Petihakis, Dounas, & Theodorou, 2001). This modelling effort is a fundamental step towards the development of an integrated ecosystem management tool, capable of describing the ecosystem processes and predicting the temporal and spatial evolution of the system.

2. Materials and methods

2.1. Study area – field data

A number of research projects took place in Pagasitikos from 1975 to 1992 with measurements of physical (water temperature, salinity, transparency), chemical (oxygen, nutrients, heavy metals) and biological ecosystem components (chl-a, phytoplankton, zooplankton) (Friligos, 1987; Friligos & Gotsis-Skretas, 1989; Friligos et al., 1990). Unfortunately the sampling intervals were very irregular with the sampling stations being concentrated at the north part of the gulf.

During 1998–1999 in the framework of a research project (Theodorou & Petihakis, 2000) monthly samplings were carried out in a dense and well-spaced grid (Fig. 2). The measurements included water temperature, salinity and oxygen profiles using a CTD and water currents with an ADCP in 59 stations covering the whole area of the gulf as well as the connection channels with Aegean Sea and north Evoikos. For the estimation of nutrient concentrations 11 stations were used representing the different parts of the system covering the area in front of the city of Volos, the area of the sewage outfall, the central gulf, the Trikeri channel and the outer area influenced by the Aegean and Evoikos waters (Koliou-Mitsou, 2000). Nine of those stations were chosen for the study of the biota both in pelagic and benthic systems.
**2.2. Objective analysis**

According to this method data fields are calculated from individual observations on a grid of sampling stations. The scheme used in this study is similar to that described by Levitus (1982) which is an interactive difference-correction scheme (Cressman, 1959) with a weight function developed by Barnes (1964). First the area is divided into equally spaced boxes (grid), which in this case was 926 m and the first guess \( F \) is determined by setting the initial value of the analysis grid to the arithmetic average of the observations in the area. Then the difference between the raw observed data \( R \) and the first guess \( F \) is computed

\[
Q_{ij} = R_{ij} - F_{ij}
\]  

(1)

at grid point \( i, j \).

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(Pancucci-Papadopoulou & Christaki, 2000). Finally the water quality of the seasonal small rivers and torrents was estimated although measurements of water quantities entering the system were not performed (Mitsios & Gatsios, 2000).

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Fig. 2. Sampling station grid (● physical measurements, ◆ water nutrients, ◊ biotic measurements).
Following the smoothed analysis increments are calculated

\[ C_{ij} = \frac{\sum_{s=1}^{n} W_s Q_s}{\sum_{s=1}^{n} W_s}, \]  

where \( W_s \) the Barnes weight function: \( W_s = \exp\left(-\frac{4r^2 R^-2}{C_0^2}ight) \) for \( r \leq R \) where \( r \) is the distance between the \( s \)th data point and the grid point \((i, j)\) and \( R \) the radius influence.

Once the smoothed analysis increments have been computed they are used to update the first guess

\[ F_{ij} = F_{ij} + C_{ij}. \]  

Finally a 5-point linear filter (Shapiro, 1970) was used according to which the smoothed value at a grid point is

\[ S_{ij} = G_{ij} + \frac{a}{4} (G_{i-1,j} + G_{i+1,j} + G_{i,j-1} + G_{i,j+1} - G_{i,j}), \]  

where \( a \) is a smoothing parameter. Two passes with the filter are suggested with \( a = 0.5 \) for the first pass and \( a = -0.5 \) for the second pass. Since the amplitude of the large scales may be dumped in the first pass it is restored with the second pass. The filter is not applied to grid points located on the land as well as if any of four adjacent grid points is located over land.

The above sequence was repeated with a different radius of influence \( R \) that decreased with each pass. The reason for this is that large \( R \) makes small corrections in the large gaps between stations while with smaller values more spatial resolution is retained in regions with densely spaced stations. Six passes were performed in total with radii of influence of 9260, 5556, 3708, 2778, 1852 and 926 m, respectively.

2.3. Ecosystem model

For the ecosystem modelling a complex generic model was used in the vertical dimension. The ecosystem model is based on the 1D European Regional Seas Ecosystem Model (Baretta, Ebenhoh, & Ruardij, 1995, 219), and has been successfully applied by the authors in a variety of systems from lagoons (Petihakis, Triantafyllou, Koutsoubas, Allen, & Dounas, 2000a) to coastal and enclosed areas (Petihakis, Triantafyllou, Allen, Hoteit, & Dounas, 2002; Petihakis, Triantafyllou, & Koutitas, 2001; Petihakis et al., 2000b; Triantafyllou et al., 2000; Triantafyllou et al., 2001) and to offshore deep systems (Petihakis et al., 2002).

The model has been applied tuned and validated in Pagasitikos with two different experimental setups in the past. The first application (Petihakis et al., 2000b)
involved the simulation of the whole area of the gulf and resulted in the configuration of a robust simulation tool. Later the tuned and validated model was used in a cross-section from north to south (Triantafyllou et al., 2001) in an attempt to assess the changes in the ecosystem functioning caused by nutrient inputs from Lake Karla.

In this study two separate model runs were performed one representing the internal shallow coastal areas (0–60 m) and the second the outer and deeper parts of the gulf. The vertical resolution was set to 10 boxes at both configurations irrespective of depth. Thus in the inner gulf the total depth was set to a mean value of 30 m, with each model box equal to 3 m, while in the central-external part each box was set to 7 m (70 m total depth). Each model was initialised with January in situ data (average values of the available station data at each particular area).

The physical forcing was provided by a one-dimensional version of the Princeton Ocean Model (Blumberg & Mellor, 1978) which was relaxed to the monthly mean surface temperature and salinity and forced with daily wind speed, humidity, cloud cover and air temperature data, obtained from Anhialos airport for the year 1999. Incident sea surface radiation was calculated from the latitude and modified by the cloud cover data using the methods of Patsch (1994). The physical sub-model in addition to transport describes irradiances, temperature, and sea surface boundary conditions.

Ecosystem processes are described by a separate pelagic–benthic sub-model coupled to the physics. The structure of the ecosystem model is complex including four functional groups of phytoplankton (diatoms, pico, nano & flagellates), bacteria, heterotrophic flagellates, microzooplankton, mesozooplankton and detritus (Baretta, et al., 1995). The separation was based on the trophic level, subdivided according to size classes or feeding method. Biological functional growth dynamics are described by both physiological (ingestion, respiration, excretion, egestion, etc.) and population processes (growth, migration and mortality). Phytoplankton growth is controlled by light, temperature and nutrient availability while bacteria depend on nutrient and dissolved organic carbon (DOC) concentrations (Allen, Somerfield, & Siddorn, 2002). The benthic–pelagic coupling is achieved through the settling of organic detritus into the benthos and diffusional nutrient fluxes into and out of the sediment after mineralization and diagenesis. The benthic system is composed of seven functional groups including aerobic and anaerobic bacteria, suspension and deposit feeders, meiobenthos, epibenthic and infaunal predators. All functional groups contain internal nutrient pools and have dynamically varying C:N:P ratios while the biologically driven carbon dynamics are coupled to the chemical dynamics of nitrogen, phosphate, silicate and oxygen. In original ERSEM chl-α is calculated from a constant C:Chl ratio, producing thus the maximum chlorophyll concentration at the same depth with the maximum phytoplankton biomass. Because this is not realistic the chl-α calculation has been modified and chl-α content increases with depth according to a predefined function. The complete food web with the carbon pathways is depicted in Fig. 3.
3. Results and discussion

3.1. Data analysis

The results from the analysis of the field measurements in Pagasitikos during 1998–1999 (Theodorou & Petihakis, 2000), are given as spatial distributions at
particular depths and as cross-sections for the whole water column. In addition con-
sidering that the gulf ecosystem can be separated into three distinct parts with differ-
ent characteristics and functioning, time series plots were produced for each part.
Thus all the available data for the internal, central-external (0–50 m) and central-ex-
ternal (50–100 m) were averaged and mean values were plotted. Finally in an attempt
to reveal any long term patterns and/or signals from the major anthropogenic distur-
bances (Lake Karla drainage) all the available historic data were grouped and plotted
for each part of the gulf.

3.2. Hydrodynamics

Fig. 4(a) shows the vertical distribution of temperature at latitude 39.22° and the
characteristic 3 layer formation in August 1999. There is a temperature
homogenisation during winter months and a subsequent thermocline formation
(also halocline and picnocline) in the depths 20–40 m for the rest of the year.
The minimum water temperature (12.5 °C) was recorded during February–March
1999, increasing in the following months until July 1999 when maximum values
were measured (27.4 °C).

Salinity concentrations along a cross-section at latitude 39.22° during February
1999 are shown in Fig. 4(b). There are evident inflows of fresh water in the areas
of Almyros and Mount Pilio. Modelling experiments and field observations (Petiha-
kis, 2004) show that Pagasitikos has negative heat flux budget and exhibits low sur-
face salinity concentrations. These phenomena are attributed to the intrusion of
relatively warmer and fresher water from the Aegean Sea, which due to the existence
of the thermocline does not mix with the underlying masses.

The surface waters were well oxygenated with maximum concentrations recorded
in April 1999 (10.5 mg/l) and minimum in February of the same year (4.5 mg/l). These low concentrations were recorded in the area of Volos with minimum values
at the surface increasing with depth. Since none of the biological characteristics measured at the time can justify this phenomenon, a possible explanation is inputs of polluted waters through the Karla aqueduct. A noticeable feature in all samplings is the observed gradient with higher concentrations in the outer area of Volos decreasing towards the central area (Fig. 5(a)). At mid-depths although the oxygen concentrations were lower compared to the surface, the difference was rather insignificant indicating a well-oxygenated system. At the bottom layer the oxygen concentrations were very high (10 mg/l) which might be caused by the exchange of waters with the Aegean Sea.

The water velocity fields were rather small (<40 cm/s) as expected from the weak winds blowing in the area, considering that in semi-enclosed areas like Pagasitikos the wind is the main driving force. The circulation pattern at the surface–subsurface layers of the outer gulf is rather complex affected by wind action, water mass exchange with the Aegean Sea and the tidal movement of north Evoikos. On the other hand the dynamic behaviour of the internal gulf is dependent largely on the wind. The above are in agreement with Balopoulos, Papageorgiou, Charalabakis, and Papadopoulos (1977) who found that the modulation of the velocity fields in Pagasitikos is achieved with the contribution of energy from high period variability (>3 days) attributed to wind and barometric pressure. The contribution of tidal movements was suggested to be particular small. The circulation pattern at the communication channel (Trikeri) exhibits a rectilinear motion almost parallel to the coast line. At the bottom layer water masses enter Pagasitikos from the east coast and outflow from the west coast, while the opposite pattern is observed at the surface layer.

Although the circulation patterns are usually transient, in this case there is an almost stable dipole, an anticyclone in the east Pagasitikos and a cyclone in the cen-

![Fig. 5. In situ (a) surface oxygen concentrations during June 1999 and (b) mean velocity and vorticity fields during July 1999.](image-url)
tral-west Pagasitikos, accompanied by smaller jets and eddies (Fig. 5(b)). The presence of the dominant anticyclonic circulation is rather significant in the ecosystem functioning, since it acts as a transportation mechanism of organic material to the benthos and at the same time inhibiting the upward movement of nutrients and dissolved organic carbon. On the contrary, the cyclonic movement uplifts water masses transporting water nutrients to the top layers of the water column.

3.3. Water nutrients

In May 1998 during the sampling period maximum ammonium concentrations (11 μg at/l) were found at the area of the sewage outfall (Fig. 6(a)) while minimum values were below limits of detection in November 1998 at the inner & western parts of the gulf. It is interesting that significant gradients were observed in the area in front of the sewage outfall, with concentrations decreasing with increasing distance, which was attributed to technical problems associated with the functioning of the sewage treatment plant (Koliou-Mitsou, 2000). Deeper at 30 m (not shown) maximum concentrations were observed in the area of Volos (6 μg at/l) in May 1998. There were also gradients in the sewage outfall area but with a reversed pattern compared to the surface layer. At the bottom layers the concentrations were lower with maximum values (1.7 μg at/l) measured at the north part of the gulf.

Ammonium concentrations in the internal gulf exhibited greater variability compared to the central and external parts (Fig. 7(a)). The internal part of the gulf being more productive exhibited higher concentrations followed by the deep layer (50–100 m) of the central-external area. The difference between the upper and lower layers of the central-external gulf is an effect caused by the prolonged presence of the thermocline and the preference of zooplankton to stay below this layer. The extreme ammonium concentration measured in the internal gulf in May 1998 was also due to the problems of the sewage plant (Koliou-Mitsou, 2000). Interestingly, this effect also the other two parts of the gulf, where high values were recorded. A noticeable feature on the ammonium field data was the absence of annual periodicity indicating the variable character of the system.

Although the mean measured concentrations of nitrite and nitrate in the gulf were not particularly high, there was a peak in the data during May 1998 in the internal gulf (Fig. 7(b) and (c)), caused by malfunction of the sewage plant (Koliou-Mitsou, 2000). Also maximum concentrations were recorded in all three parts during December 1998–May 1999 most possibly due to rain inputs. The influence of fluxes into the system was shown by the increased nitrate values in front of the area of Almyros and Volos during May 1998 (Fig. 6(b)). Although the mean nitrate concentrations exhibited significant variations in all three parts of the gulf, the lower values were recorded in the upper layer of the central-external gulf (Fig. 7(c)). It is worth noting that the internal gulf and the lower layer of the central-external had similar nitrite and nitrate concentrations.

Measured phosphate concentrations in the 0–30 m layer were generally low with maximum value (0.5 μg at/l) recorded at the surface in front of Volos in April 1998 (Fig. 6(c)) while at 60 m, high concentrations were found both in Volos and in the
area of Almyros. The deeper layers exhibited smaller variability in time with the sediment-overlying layer significantly richer (not shown) possibly due to benthic release from the activity of benthic fauna. Once more in front of the sewage outfall significant gradients were measured.

Mean phosphate concentrations in the internal gulf had slightly higher values compared to the other two parts (Fig. 7(d)). The upper layer of the central-external area was characterised by constant concentrations in contrast with the other two parts where fluctuations with a similar trend were observed.

Phosphorus is thought to be the limiting nutrient for phytoplankton and bacterial growth in a large part of the Mediterranean with decreasing concentrations from west
to east. The N/P ratio increases in the same direction, i.e., Alboran Sea 22.5, Cretan Sea 24.3–26.8, Eastern Levantine basin 27–29, (Berland, Bonin, & Maestrini, 1980; Krom, Kress, & Brenner, 1991). Also closed and semi-closed systems are characterised by phosphate limitation because the amount of biologically available
phosphorus is small in relation to the quantity required for algal growth (Mason, 1983). Thus, although one would expect Pagasitikos to follow the above trend with nitrogen ions being in excess, looking at the Redfield ratio (16) in the measured data, the system of the gulf undergoes alternating periods of nitrogen / phosphorus limitation (Fig. 7(e)). The top layer of the central-external gulf exhibits longer periods of phosphate limitation in contrast to the deeper layer which is mostly nitrogen limited. The internal gulf is also mostly nitrogen limited although there is a significant period (May 1998–September 1998) during which the N/P ratio is equal to the Redfield ratio.

The above observed patterns in the internal gulf around the sewage outfall are very interesting since they illustrate how the inflows can affect the nutrient concentrations and subsequently the ecosystem functioning. Sewage discharges are rich in phosphate and ammonia and low in nitrate (sewage outfall), in contrast with the agricultural run-off in which nitrate dominates (Almyros–Volos).

3.4. Chlorophyll-a

The absence of periodicity in the system of Pagasitikos is illustrated in the mean chl-\(a\) concentration data (Fig. 7(f)), where maximum concentrations are observed during April 1998 and January 1999 at the inner gulf. The mean concentrations in this part of the gulf were higher due to shallow depth and nutrient inputs from the city of Volos and the area of Almyros. Chl-\(a\) concentrations (not shown) were highest at the surface layer (3.5 \(\mu g/l\)) and were observed in the city of Volos area with a reducing gradient towards the central-external gulf. This pattern was also found at 30 m, while following the nutrient distribution significant gradients and variability was found in the area of the sewage outfall. Deeper at 60 m the concentrations dropped and there were no significant gradients in that area. The maximum concentration measured was 0.5 \(\mu g/l\) in July 1999 and minimum at 0.06 \(\mu g/l\) in September 1998. At the bottom layer the concentrations were similar to the 60 m depth.

Ammonia concentrations are coupled to the chl-\(a\) concentrations with a faster response (short time lag) in the oligotrophic central-external parts of the gulf compared to the mesotrophic internal area (Figs. 7(a) and (f)).

During the first measured bloom (April 1998), nitrate concentrations decrease in contrast to the phosphate concentrations, which remain high but decreasing later. This possibly is due to a strong mixing event enriching the water column with nutrients and since the phosphate is required in smaller amounts, there is an increase in the background levels. Soon after both nutrients increase due to the degeneration of phytoplankton through the recycling mechanism. Later the formation of the thermocline results in rather constant chl-\(a\) levels with most of the primary production being regenerated.

The second phytoplankton bloom (January 1999) as depicted by the increased chl-\(a\) concentrations was associated with a drop in the silicate concentration (not shown) indicating the significant participation of diatoms especially in the inner part of the gulf. A modeling experiment in this part (Triantafyllou et al., 2001) showed that under nutrient enrichment diatoms contribute \(\approx 2/3\) of the total phytoplankton biomass followed by picoplankton and flagellates. This is in accordance with observations in
the semi-enclosed gulf of Thermaikos where diatoms formed most of the reported algal blooms (Mihalatou & Moustaka-Gouni, 2002).

It is interesting to note that although as mentioned before the system undergoes periods of nitrate and phosphate limitation, during both phytoplanktonic blooms it is the shortage of phosphate that stops primary production (Fig. 7(e)).

3.5. Nutrient inputs and inter-annual variability

Mitsios and Gatsios (2000) found that nitrate ions pose a significant pollution problem since all concentrations in the rivers and torrents examined, were at levels able to cause eutrophic conditions in the gulf. This was more evident in the area of Almyros where intensive agriculture using nitrogen-based fertilizers is practiced. Phosphate concentrations were also high in most of the systems examined, with highest levels also in the area of Almyros. However, since measurements of the volume of water entering Pagasitikos were not made, it is not possible to estimate the percentage contribution to the gulf nutrient background levels.

Although nitrate concentrations do not exhibit an inter-annual pattern there is a mean maximum concentration around 2 μM/l, with the exception of the extreme values (5.1 μM/l) recorded on the July 1987 soon after the appearance of a dense mucilage algal bloom (Fig. 8(a)). The above extreme concentration is not so pronounced in the phosphate time series (Fig. 8(b)), were concentrations exhibit similar variability in the period 1975–1999. Although the available data are scarce, the regression line (not shown) indicates that both nitrate and phosphate concentrations exhibit a small reduction since 1975 at both layers of the central-external gulf. This could be attributed to the water mass movement in the area, which seems to drain the gulf at the bottom layers transporting organic matter and nutrients to the Aegean Sea. This is in agreement with the results of a modeling study (Petihakis et al., 2000b; Triantafyllou et al., 2001) where significant export of organic material at the deeper layers was estimated.

In contrast, the internal gulf exhibits an increase in both nutrients, which is somewhat unexpected since the operation of the sewage treatment plant in 1987 should have resulted in a decrease of their concentrations. However since 1975 a number of industries have been established around the gulf, which might significantly influence the aquatic ecosystem through the discharge of effluents.

3.6. Model results

Tuning, calibration and validation of the model for the whole gulf area was performed by Petihakis et al. (2000b). Some of the major results of the afore mentioned study are briefly discussed here. The analysis of model dynamics indicated two modes of operation, the winter one when the water column is homogenised, and nutrients reaching the photic zone are taken up by large phytoplankton developing a classical food web, with significant proportion of energy passing to big zooplankton, and the summer mode characterised by low nutrients at the photic layer, driving the system into microbial food web, with dominance of small cells among
phytoplankton groups. During the latter period there is a strong competition for nutrients between bacteria and phytoplankton. Additionally the heterotrophic biomass is larger compared to the autotrophic and most of the energy is recycled within this limited web. Although in the above study the application area was the whole gulf area and the model was forced with simplistic atmospheric forcing, valuable information was gained on the functioning of the system providing the substrate for the next step which was the simulation of the gulf ecosystem along a transect from North to South (inner–outer gulf) focusing on the possible effect of nutrient inputs from Lake Karla (Triantafyllou et al., 2001).

The addition of nutrients resulted in a less variable system with small monthly variations, since the sufficient nutrient concentrations in conjunction with the
adequate light conditions support primary production throughout the year. A significant outcome of the modelling study was that small nutrient inputs can cause rapid growth of diatoms and flagellates even though the magnitude of the phenomenon is rather localised in the inner gulf area.

Exploring fully the capabilities of the existing tuned and validated 1D ecosystem model and the information provided from the phenomenology in Pagasitikos gulf, two experimental runs were performed in this study. One run was made in the internal gulf area, simulating the shallow and more eutrophic system, while the second run included the deeper and oligotrophic central-external part of the gulf. Since the two model runs represent different sub systems (internal, central-external 0–50, central-external 50–100), with different functioning characteristics, validation plots for each area were considered necessary and are presented in Figs. 9–11. Thus model results are compared with mean in situ concentrations at each area for the period January 1998–December 1999. In the internal gulf (Fig. 9) the model tends to slightly overestimate phosphate and nitrate concentrations throughout the year in contrast with the ammonia and chlorophyll concentrations where it follows rather closely the field measurements. At the top layer of the central-external gulf (Fig. 10) the model produces lower concentrations of phosphate and nitrate during the period winter–spring. Modelled ammonia and chlorophyll are following very well the

![Graphs showing model validation for internal gulf](image-url)

**Fig. 9.** Validation of model results for (a) phosphate, (b) nitrate, (c) ammonium, and (d) chlorophyll in the internal part of Pagasitikos gulf during 1998.
observed field concentrations. Finally at the 50–100 m layer of the central-external gulf simulated concentrations of nitrate and phosphate (Fig. 11) exhibit small variability, following minimum field values. As in the other two areas simulations of ammonia and chlorophyll are considered as very good.

Due to its 1-D nature, the model does not include important processes of the particular area, such as horizontal advection and vertical mixing arising from circulation patterns and can significantly affect nutrient concentrations. Nevertheless, it provides a successful numerical base for the description and understanding of the ecosystem processes and parameter refinement, for further development towards a 3-D forecasting ecosystem model and the implementation of assimilation techniques.

Further in this paper important information on the functioning of the systems in relation to the observed patterns in the phenomenology is given.

3.7. Internal Gulf area

Although the internal part of Pagasitikos is quite shallow the light winds that blow in the area cannot cause significant mixing and thus the water column remains stratified during summer (Fig. 12(a)). The phosphate concentrations (Fig. 12(b)) are
significantly higher compared to the outer area of the gulf (Fig. 13(b)) while the increased values close to the bottom during October–December are due to benthic releases from the decomposition of detrital material which was sedimented earlier as shown in Fig. 12(g). Nitrate concentrations exhibit a similar pattern (Fig. 12(c)), with maximum concentrations being produced towards the end of the year, as a result of detrital decomposition. Although chlorophyll concentrations (Fig. 12(d)) do not exhibit a distinct pattern as far as the evolution of the vertical distribution is concerned, relatively low values are produced in the surface layer (0–10 m) during summer, partly due to the variable C/Chl and partly due to nutrient availability. However, the modelled annual chlorophyll pattern exhibits an early spring bloom as well as a smaller bloom during autumn. Considering the shallow depth and that light is reaching the bottom of the water column without significant attenuation (not shown), it is expected that phytoplankton cells will remain close to the bottom benefiting by benthic nutrient regeneration. Dissolved Organic Carbon (DOC) (Fig. 12(e)) in the model represents only the labile fraction (fresh) of the total DOC present, not taking into account the semi labile and refractory parts. In marine systems dissolved Organic Mater (DOM) production can vary from 1% to 50% of the total phytoplankton production, while its consumption by heterotrophic microorganisms

Fig. 11. Validation of model results for (a) phosphate, (b) nitrate, (c) ammonium, and (d) chlorophyll in the lower central-external part of Pagasitikos gulf (50–100 m) during 1998.
Fig. 12. Model simulations for the internal gulf area: (a) temperature (°C), (b) phosphate (µM), (c) nitrate (µM), (d) chlorophyll (µg/l), (e) dissolved organic carbon (µg C/l), (f) phytoplankton biomass (µg C/l), (g) detritus (µg C/l), (h) bacteria (µg C/l), and (i) heterotrophic flagellates (µg C/l).
Fig. 13. Model simulations for the central-external gulf area: (a) temperature (°C), (b) phosphate (µM), (c) nitrate (µM), (d) chlorophyll (µg/l), (e) dissolved organic carbon (µg C/l), (f) phytoplankton biomass (µg C/l), (g) detritus (µg C/l), (h) bacteria (µg C/l), and (i) heterotrophic flagellates (µg C/l).
is closely connected to its production (Boulion & Hakanson, 2003). Maximum DOC values are produced at the end of spring when nutrients become limited while there is a substantial standing phytoplankton biomass.

The phytoplankton biomass (Fig. 12(f)) exhibits a small temporal variability with higher values in the whole water column during winter–spring period (mixing), but also during summer–autumn at the deeper layers (photo inhibition). The increased biomass of phytoplankton during summer, results in an increase in detritus close to the benthos and its subsequent degradation during autumn and winter (Fig. 12(g)). Bacteria biomass (Fig. 12(h)) follows phytoplankton getting advantage of nutrient shortage and DOC release at the end of spring, while later during summer and autumn when phytoplankton remains at the deeper part of the water column, bacteria remineralise detritus, releasing nutrients which are partly taken up by phytoplankton and partly by bacteria. Heterotrophic flagellates (Fig. 12(i)) although follow the distribution of their prey they cannot fully exploit their resources due to predation by microzooplankton and mesozooplankton.

3.8. Central-external Gulf area

At the central-external area the deeper water column in conjunction with the intense thermocline (Fig. 13(a)) and the low light conditions close to the bottom results in the development of two significantly different parts: the upper layer occupying the first 50 m and the lower water column layer (50–70 m) characterised by relatively low temperature and light conditions. The effect of the formation and erosion of the thermocline in the distribution of nutrients is nicely depicted in the graphs of phosphate (Fig. 13(b)) and nitrate (Fig. 13(c)) where, between December and beginning of April the concentrations are the same in the whole water column. Soon after a distinct layer between 50 and 70 m is formed with significantly higher concentrations, as benthic releases are trapped below the thermocline decoupling the upper part of the water column. Comparing the nutrient concentrations between the two areas, model results indicate that it is the decoupling of the bottom layer during stratification in the deeper areas which largely contributes to the different characteristics and functioning. Chlorophyll concentrations (Fig. 13(d)) follow the nutrients pattern taking advantage of the winter mixing while later when the stratification builds up, chlorophyll deepens below the thermocline. A characteristic pattern produced by the model is the absence of two annual blooms typical of most marine systems, but instead one bloom associated with the increased nutrient concentrations in the upper part of the water column during the mixing period. DOC concentrations (Fig. 13(e)) exhibit a peak towards the end of the mixing period when production is high and nutrients are exhausted. The phytoplankton release of DOC is beneficial for overflow of organic matter production in nutrient limited cells, that are maintaining a high synthetic ability to be able to resume rapid growth when they encounter nutrients (patches). In addition it protects the photosynthetic apparatus under fluctuating (high) light conditions and helps the retaining of nutrients in the water column (avoiding sinking) through the stimulation of bacteria (Fuhrman, 1992). Phytoplankton biomass (Fig. 13(f)) follows the
chlorophyll distribution with biomass and chlorophyll maximum at same depths. Looking at the evolution of phytoplankton and bacteria biomass (Figs. 13(f) and (h)) one can see the different modes of operation of the system. Thus during the mixing period (December–March) phytoplankton uptakes nutrients and starts to grow rather fast as indicated by the maximum biomass values, while later when nutrients are depleted, phytoplankton cells release DOC which is taken up by bacteria. When the water column becomes stratified primary producers are found deeper below the thermocline taking advantage of the nutrient release from the benthic system. Detritus (Fig. 13(g)) and heterotrophic flagellates (Fig. 13(i)) follow phytoplankton and bacteria biomass with the latter being significantly controlled during the mixing period through predation, as it cannot exploit the phytoplankton increase as in the internal gulf area.

4. Conclusions

Semi-enclosed gulfs are shallow protected areas attracting significant development which can lead in the increase of nutrient loads and disruption of the ecosystem functioning. Usually within the gulf there are distinct areas with different hydrodynamic and biological characteristics with a marked transition from shallow nutrient rich waters in the internal part to a deeper marine mixed frontal zone (communication area) where nutrients are lower (Le Pape et al., 1996). An important common characteristic is the prolonged thermocline decoupling the near bottom layer from the upper euphotic zone. Unlike the two other major semi-enclosed gulfs in Greece (Saronikos and Thermaikos), Pagasitikos is considerably less eutrophic with significantly lower nutrient concentrations (Friligos, 1982; Mihalatou & Moustaka-Gouni, 2002). Another significant difference is that although most closed and semi-closed systems are phosphate limited, Pagasitikos exhibits significant periods of nitrogen limitation.

According to the physicochemical characteristics, Pagasitikos can be separated into three parts, the internal gulf characterized by mesotrophic conditions with eutrophic outbursts (formation of mucilaginous algal blooms), the upper central-external depicting an oligotrophic system due to long periods of stratification and the lower central-external where production is sustained below the thermocline. In addition the dominant anticyclonic circulation in the central gulf results in the transport of organic material from the water column to the deep layers from where it is exported to the neighboring Aegean Sea and Oreos channel. Significant production is associated with intense mixing events during which nutrients find their way up into the upper layers promoting growth, while for the rest of the year the presence of stratification pushes the system towards regenerated production.

Although it has been suggested that the dynamics of the gulf ecosystem are significantly influenced by the input of nutrients at the north–west part (Volos, Almyros areas) this is not however clearly shown in the in situ nutrient data. Trying to resolve the dynamics behind the formation of mucilaginous algal blooms it is likely that
excess phosphate can lead into extreme phytoplankton growth since it is the limiting nutrient during blooms.

The effect of hydrodynamic patterns on primary production has been demonstrated through ecosystem modeling indicating that due to long stratification periods, all nutrients released through the benthic regeneration are trapped in the deeper layers, developing a microbial food web. However when the thermocline erodes nutrients find their way up in the upper layers of the euphotic zone. Modelled primary and bacterial production rates (Fig. 14) are very close to the field measured range of 5–23 and 0.2–4.5 μg/l/d, respectively (Pancucci-Papadopoulou & Christaki, 2000) with higher rates during winter to spring for phytoplankton and middle of spring for bacteria at both areas. Highest primary production rates in January were also recorded in Thermaikos (Mihalatou & Moustaka-Gouni, 2002). At the more eutrophic internal station throughout the year the primary producers exhibit much higher rates compared to bacteria without any significant variability with depth. In the outer area the difference in the two rates is small and bacterial rate exceeds that of primary production during nutrient depletion. It is only during the mixing period when the system turns into more classical type and primary producers grow significantly faster. Bacteria respond fast to the increase in DOC as shown by the maximum bacterial production rate, while maximum primary production rates are exhibited soon after mixing starts and are sustained for a substantial period of time until nutrients are depleted.
Considering both the economic value of Pagasitikos to the fishing community and to tourism as well as its aesthetic and recreational characteristics, the necessity of a management system becomes more than evident. Such a system will constitute an essential tool in guiding marine resources management and, additionally, it would form an early warning system of potentially harmful ecological events, helping in the formulation of cost effective preventive and remedial measures.

Predicting the behaviour of the marine environment and understanding its variability is an essential part of the management of marine resources. An important issue for the marine science community is to define the potential time-scales of predictability of the system under study. This work contributes towards improved and innovative, coupled physical–ecological numerical models, capable of underpinning the development of a forecasting system. Additionally, it provides important knowledge towards the development of a monitoring system which in turn will help data assimilation techniques of physical and ecological state variables. Long term monitoring of all those indicators influencing the ecosystem functioning in conjunction with the use of modeling tools can ultimately provide all the necessary information for successful management decisions.

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References


