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Eutrophication patterns in an eastern Mediterranean coastal lagoon: Vassova, Delta Nestos, Macedonia, Greece

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Abstract

The results of an intensive monitoring study of main eutrophication parameters in relation to fish farming management, climate and hydrography in the Vassova coastal lagoon (Nestos Delta) are presented. The overall aim is to produce basic knowledge in order to contribute to the management of eutrophication of coastal lagoons at local and national levels. Due to extensive spatiotemporal variability of the measured parameters correlation and regression polynomial analysis was used to identify patterns (p<0.05).

Freshwater was the main source of nitrate and phosphate in the lagoon. This finding has justified the reduction of freshwater inflow in the past, which, however, has increased mean salinity to 30 PSU and reduced spatial salinity gradients. Maximum nitrate values in winter coincided with adverse climatic and hydrographic conditions (high precipitation, strong NE to E winds and low tide) and fish farming management that hinder water circulation. Dissolved phosphorus variability indicated the combination of the external (freshwaters) and internal (sediment) P-sources. N/P water values indicated nitrogen being the most important nutrient for primary producers throughout the year, except in winter, when phosphorus was the most important nutrient. Practical measures for improving fish farming practices to decrease "eutrophication risk" during winter are suggested. Existing nutrient data from the Vassova and from other Greek lagoons in comparison were also presented and discussed.

Keywords: Monitoring; Nitrogen; Phosphorus; Climate; Hydrography; Fish management.

Introduction

The Mediterranean coastal lagoons are shallow high productive interface ecosystems between marine and watershed water bodies (KJERFVE, 1994) that, due to climatic and hydrological influence, exhibit an extreme variability of their environmental parameters (PETIHAKIS *et al*., 1999; BASSET *et al*., 2001). Since most of the lagoons are used for aquaculture exploitation, e.g. Thau Lagoon, France (DE CASABIANCA *et al*., 1997), Nestos Delta lagoons, Greece (KOUTRAKIS & TSIKLIRAS, 2003; present study), a narrow outlet is often built to better manage fish stocks and seawater flushing rates. Limited water exchange with the sea coupled with nutrient input by agricultural runoffs, aquaculture and precipitations cause water stratification and high nutrient concentrations in the water and in the sediment. The end result is the formation of macroalgal blooms of opportunistic species, like *Ulva* and *Gracilaria* (SFRISO *et al*., 1992; DE CASABIANCA, 1996; SFRISO & MARCOMINI, 1996; DE CASABIANCA *et al*., 1997). This biomass accumulation further increases the nutrient and oxygen variability in the lagoon by assimilating nutrients and causing hyper-oxygenation during growth, and by realising nutrients and causing anoxia during decay of organic material (SFRISO, 1995; SCHRAMM & NIENHUIS, 1996).

The consequence of nutrient excess in the sensitive coastal lagoons is now widely recognized (TAYLOR *et al*., 1995) and their protection and sustainable management has become a key issue in the European legislation (Habitat Directive 92/43, Water Framework Directive 60/2000). For this purpose, however, a basic knowledge of the key eutrophication parameters is required, which in most cases, especially in areas like the Eastern Mediterranean, is not always available. For example in Greece, where extensive lagoonal systems are located on its Western and Northern coasts (ZALIDIS & MANTZAVELAS, 1994), information regarding nutrient concentrations is known for a very limited number of case studies, e.g. the Gialova lagoon (KOUTSOUBAS *et al*., 2000; PETIHAKIS *et al*., 1999), the Amvrakikos lagoons (NCMR, 2001; KORMAS *et al*., 2001).

This paper aims to present basic knowledge regarding spatial and seasonal patterns of the main eutrophication parameters in relation to fish farming management, the climate and hydrography of the Vassova coastal lagoon, Nestos Delta, in order to contribute to the management of eutrophication at local and national levels. Existing nutrient data from Vassova (THEOCHARIS *et al*., 2000; SYLAIOS & THEOCHARIS, 2002; SYLAIOS *et al*., 2003) were compared and discussed with those from other Greek lagoons (NCMR, 2000, 2001; KORMAS *et al*., 2001; KOUTSOUBAS *et al*., 2000). Vassova is a typical eutrophicated lagoon dominated by opportunistic macroalgae (ORFANIDIS *et al*., 2000), which is used for extensive fish cultivation. To our knowledge information regarding possible interactions between eutrophication and fish cultivation practices in the Greek coastal lagoons is very limited or does not exist.

Materials and Methods

Study area

Vassova is an almost rectangular shaped lagoon with a narrow outlet (30 m wide, 1.5 m depth) covering an area of 0.785 Km^2 (Fig. 1). It consists of four different basins: the shallow, not deeper than 0.5 m, main basin (62% of the total area), the South East basin of 13, up to 2 m deep, artificially constructed channels (29%), and the North West up to 4 m depth over-wintering (6.5%) and stocking (2.4%) basins.

Traditional fish aquaculture, which prevents fish-immigrants from returning to the sea by a system of metallic mesh frames (MFa-d, Fig. 1) is influencing the nutrients in the lagoon as follows: (1) Freshwater sources (small canals) are cleaned in mid February to partly improve the freshwater inflow (almost constant throughout the year) and therefore, the fry ascent (stocking) facilitation. (2) During stocking, from mid February till May, MF-a remains open whereas MF-b, -c and -d

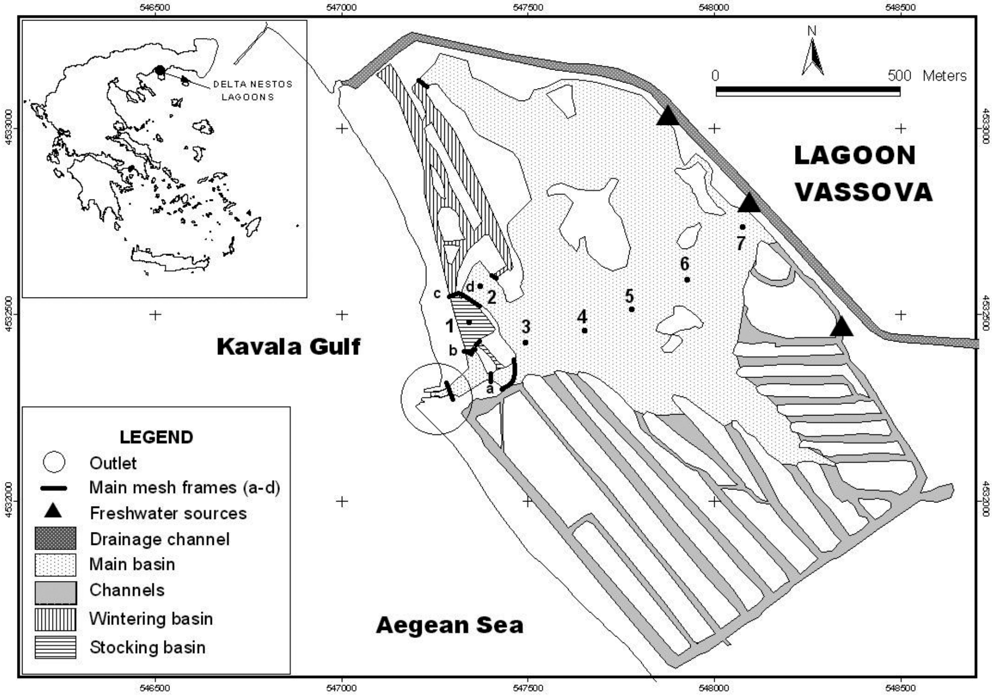

Fig. 1: A GIS-based map of the study area. Numbers show sampling sites.

are closed. During this period of time supplementary food is added to the wintering and stocking basins. When fry stocking is considered satisfactory MF-a is closed and MF-c and -d are opened to allow stocked and overwintered fishes to invade the main basin. The lagoon seawater exchanges are facilitated through MF-b. The system of mesh frames, together with depth modifications, operates as barriers for water exchanges. (3) From August, fishing commences either with gill and seine nets or at the fish barrier (MF b). In autumn, the species tend to leave the lagoon under the effect of their reproduction, age or thermal impulses and gather in the stocking basin. (4) From May to October young fry from local hatcheries are acclimated to lagoon conditions in a unit (max. capacity 50.000 or 1.5 ton fishes) located close to site 1. The main species fished in the lagoon are *Mugil cephalus*, *Dicentrarchus labrax*, *Sparus aurata* and *Anguilla anguilla*.

The catchment of the Western Delta Nestos River Lagoons is mainly an intensively cultivated agricultural area (ca. 284 Km^2), where corn, cotton, cereals and beans are the main cultivated crops. Freshwater sources of Vassova are limited agricultural runoffs mainly coming in from a neighbouring drainage channel (freshwater sources shown in Fig. 1) and precipitation. The freshwater sources inflows were considerably reduced in the past in order to reduce algal bloom formations and to improve water quality (Agricultural Fisheries Cooperative of Kavala Lagoons, personal communication). The lagoon is protected by the Ramsar convention and was recommended to be included in the European Natura 2000 network (code GR1150010).

Sampling

Sampling in the Vassova lagoon was performed seasonally (sites 1, 3-5, 7 in July 1998, November 1998, January 1999, February 1999, April 1999) along a transect from the outlet to the freshwater sources of the lagoon (Fig. 1). Sampling at sites 2 and 6 was performed monthly from March `98 to March `99. Depth of the sites ranged from 1.8 m at site 1 to 0.4-0.5 m at sites 3-6, and to 0.75 m at sites 2, 7. Fishing practices (stocking) and extreme low water level did not allow sampling at sites 1 and 7 in February `99 and April `99 respectively. In order to reduce tidal variation, all samples were taken from a small rowing boat during low tide, between 10.00 to 13.00 h. Sites 1, 2 and 7 were dredged two years ago in order to improve water circulation and fish movements in the lagoon, whereas the rest of the sites were natural. Two replicates of fresh and seawater were sampled close to freshwater sources and the adjacent sea of the lagoon in July1998 and January 1999.

The following water parameters were measured at each site in the middle of the water column: temperature (T °C), salinity (PSU), dissolved oxygen (% air saturation measured in BOD bottle; magnetic mixing of water) and pH were measured *in situ* using portable meters (WTW instruments). Additional measurements close to the surface and the maximum depth were performed in order to identify periods of water stratification. Water samples collected from the middle of the water column employing a water sampler or plastic bottles (vol. 1 L) were transferred within one hour, cool preserved, to the laboratory. Immediately on return to the laboratory the water samples were divided into two sub-samples, one filtered through cellulose nitrate membrane filters (0.45 μm, MILLIPORE) for the nutrient analysis and the other through GF 52 Schleicher & Schull glass fibre filters for the chlorophyll-α analysis. The filtrates for the nutrient analysis were divided into 4 sub-samples and preserved deep-frozen (–20°C) for later analysis of nutrients (N-NO_3, N-NO_2, N-NH_4 and P-PO_4) following GRASSHOFF *et al*. (1983) modified by SCHRAMM *et al*. (1988) within two weeks. Three replicate analyses of each of the samples did not differ by more than 5 % of the mean. Chlorophyll-α (Chl-α) was determined photometrically in 90%-acetone extracts of the filter residue (STERMAN, 1988). The suspended solid (SS) of the sample was determined as weight of filter residue heated to constant weight at 110°C (A.P.H.A., 1989).

Light extinction coefficient (k) was determined only seasonally by measuring photosynthetic active radiation (PAR; μE m^{-2} s^{-1}; Li-Cor instruments) at 0.05, 0.25 and/or 0.75 m depths using the formula (JERLOV, 1970):

$$k = (\ln Io – \ln Iz)/z$$

[(Io = PAR at 0.05 m depth; Iz = PAR at z m depth; k = extinction coefficient (m^{-1})]

During the sampling (years 1998-99), the water temperature and the tidal fluctuation (cm) were recorded close to site 1, two or three times a week. A maximum-minimum mercury thermometer was used to measure temperature extremes and a tide gauge was used to measure water level. The tide was estimated as relative tide, i.e. the difference between high water level at time *t* to the lowest water level ever recorded in this study. Air temperature, wind and precipitation data were obtained from the meteorological station of Chrisoupolis, Kavala airport, which is located ca. 5 km away from the study area.

Data analysis

Non-transformed data of the water parameters measured were best fitted by 1st or 2nd order regression polynomial to reduce variability and to identify seasonal and spatial trends. A pattern was only accepted when $p<0.05$. In order to find out significant relations between different parameters, correlation coefficient and one way-ANOVA tests were applied. Since extreme data values are explainable and consistent with the overall picture they were not excluded from the analysis as outliers. The analysis was performed using the STATISTICA v. 7.1 (STATSOFT) software package.

Results

Eutrophication conditions

Table 1 shows the seasonal and annual means of the eutrophication parameters of fresh, lagoon and seawater. High confidence intervals of the annual means ranging from 0.7 to 124% (mean value 32%) of the mean value indicate considerable variability in the measured parameters.

The seasonal and spatial trends of the lagoon data, by means of polynomial fitting, are shown in Figures 2 and 3, respectively. Temperature decreased from summer to winter and then increased towards spring (Fig. 2). The maximum and minimum values recorded close to MF-b were 31°C (August) and 2°C (January), respectively. Salinity decreased from winter to summer (Fig. 2) being lowest at site 2 (19 PSU) in winter under water stratification conditions. Dissolved oxygen slightly decreased from spring-summer towards autumn-winter and from the inner parts to the outlet (Figs 2, 3). However, the maximum dissolved oxygen value (275 % of air saturation) was recorded at site 6 in February under sunny and calm conditions, whereas the lower value (64%) was recorded at site 2 in August. pH decreased from spring-summer towards autumn-winter and from the inner parts to the outlet (Figs 2, 3). The maximum pH value (9.01) was recorded at site 6 in March 1998, whereas the lower value (8.03) was recorded at site 2 in August. Suspended solids (SS) decreased from summer-autumn towards winter-spring and from the inner parts to the outlet (Figs 2, 3). The maximum SS value (129.09 mg/l) was recorded at site 6 in August, whereas the lower value (11.2 mg/l) was recorded at site

Table 1
Seasonal and annual means of the eutrophication parameters in the Vassova lagoon.

Water type	*Season*	*Temp.* (°C)	*Sal.* (PSU)	*Oxygen* (% air satur.)	*pH*	*k* (m^{-1})	*N-NO$_2$* ($\mu mol l^{-1}$)	*N-NO$_3$* ($\mu mol l^{-1}$)	*N-NH$_4$* ($\mu mol l^{-1}$)	*TDIN* ($\mu mol l^{-1}$)	*P-PO$_4$* ($\mu mol l^{-1}$)	*Chl-a* ($\mu g l^{-1}$)	*SS* ($mg l^{-1}$)	*N/P*
Lagoon	*Summer*	27.69	27.67	139.09	8.38	1.81	0.24	2.04	1.11	3.39	1.01	0.16	39.05	6.92
	Autumn	16.83	28.96	103.65	8.30	2.19	0.25	1.83	1.79	3.86	1.08	0.50	70.16	4.08
	Winter	10.34	31.42	115.85	8.38	0.89	0.62	7.29	3.18	11.09	1.04	3.08	26.93	234.6
	Spring	16.20	31.62	151.94	8.64	0.67	0.21	1.66	1.52	3.38	0.54	0.13	17.89	12.15
	Total Mean	17.15	30.04	126.65	8.42	1.37	0.35	3.55	2.00	5.90	0.93	1.14	38.34	78.6
	±95% C.I.	±1.98	±0.98	±13.16	±0.06	±0.34	±0.13	±1.05	±0.79	±1.40	±0.18	±0.83	±9.70	±97.4
Freshwater	*Summer*	25.5	1.6	63.3	7.47	-	1.06	21.24	3.82	26.12	3.56	-	-	7.34
	Winter	9.6	2.5	86	8.74	-	2.5	82.1	3.15	87.75	8.49	-	-	10.34
Seawater	*Summer*	28.7	32.7	130.4	8.3	-	0.09	0.72	0.6	1.41	0.04	-	-	35.2
	Winter	10.2	34.1	125	7.9	-	0.1	0.9	0.75	1.75	0.15	-	-	11.7

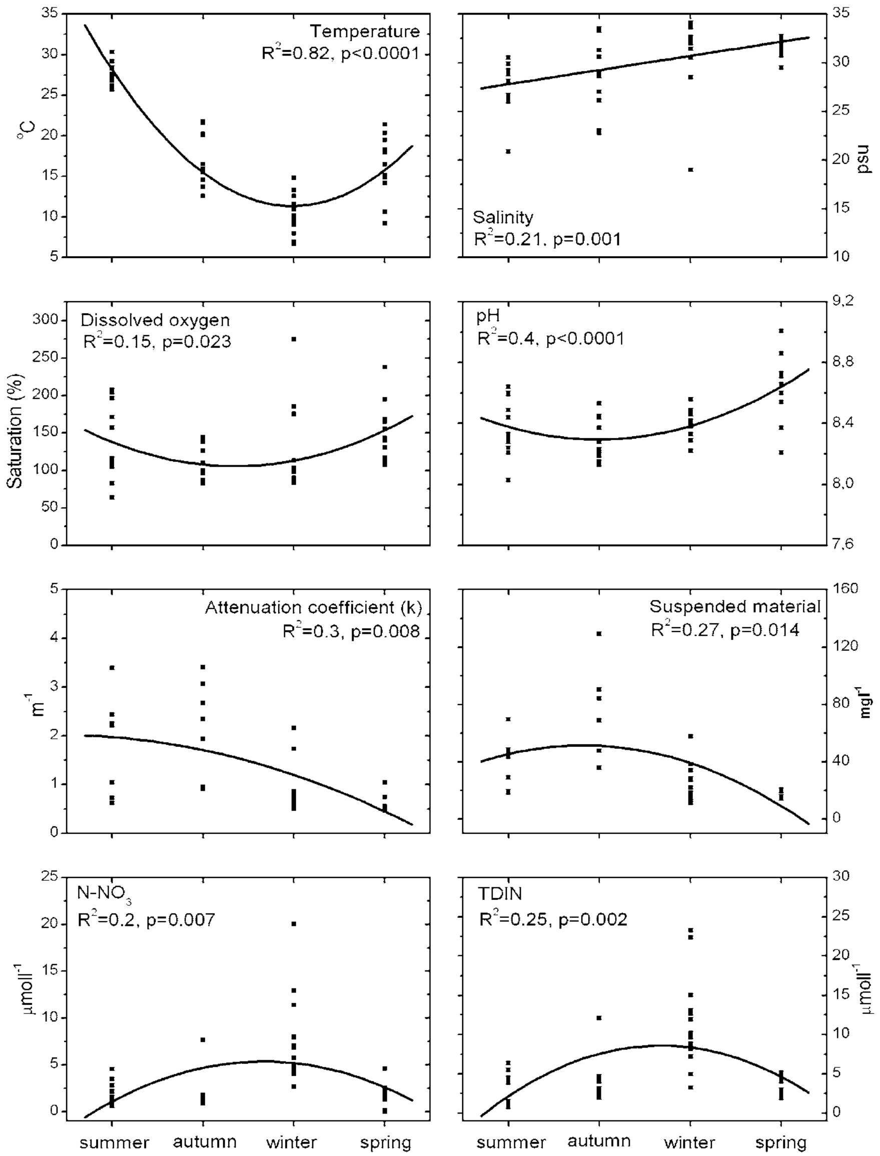

Fig. 2: Polynomial fitting curves of eutrophication parameters indicating seasonal patterns.

2 in January. Light attenuation coefficient (k) decreased from summer-autumn towards winter-spring and from the inner parts to the outlet (Figs 2, 3). The maximum k value (3.07 m^{-1}) was recorded at site 4 in August, whereas the lower value (0.47 m^{-1}) was recorded at site 2 in March 1999.

Chl-α increased from the outlet to the inner parts (Fig. 3) being maximal (19.58 μgl^{-1}) at site 7 in January. Total dissolved inorganic nitrogen (TDIN) and nitrate-N (60% of TDIN) increased from summer to winter and then decreased towards spring (Fig. 2). The maximum TDIN value (23.32 μ$moll^{-1}$) was

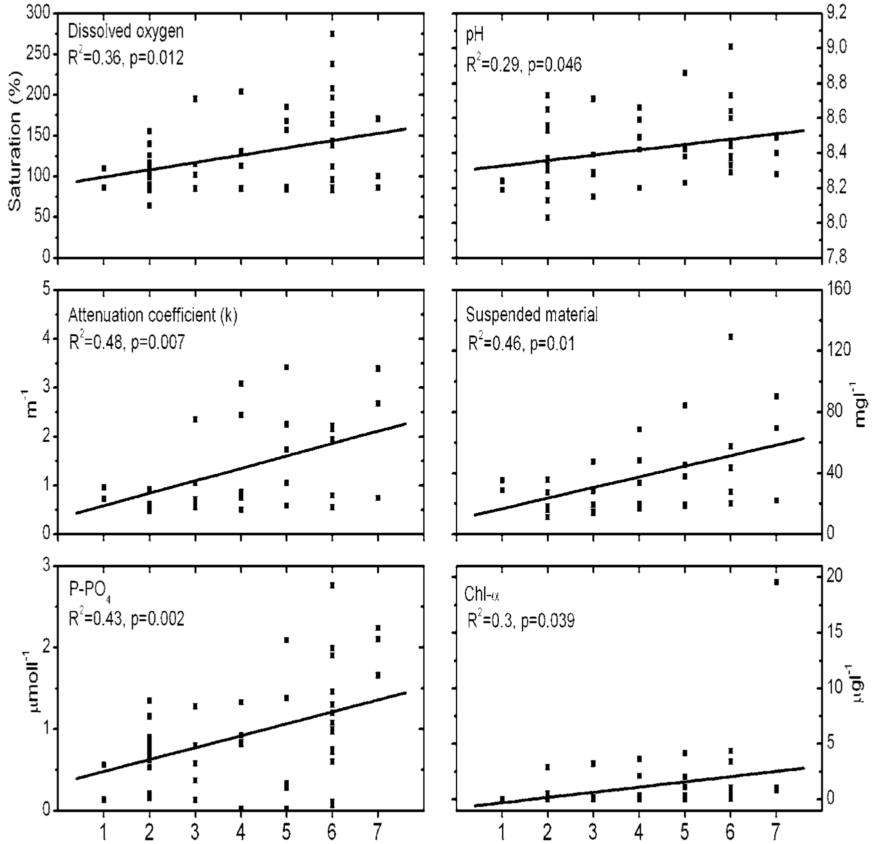

Fig. 3: Polynomial fitting curves of eutrophication parameters indicating spatial patterns from the outlet to the inner part of the lagoon.

recorded at site 2 in January under water stratification conditions. Phosphate-P increased from the outlet to the inner parts (Fig. 3) with the maximum values (2.76 μmoll^{-1}) recorded at site 6 in August. TDIN, nitrate-N and phosphate-P concentrations were significantly correlated with salinity, indicating freshwater being the main source of these nutrients as follows:

(1) TDIN = 35.36 - 0.99 x Sal, R^2=0.41, N=72
(2) N-NO_3 = 30.92 - 0.91 x Sal, R^2=0.41, N=72
(3) P-PO_4 = 4.27 - 0.12 x Sal, R^2=0.48, N=72

Ammonium and nitrite mean values were highest in winter (Table 1) with maximum values measured at sites 4 (N-NH_4=17.64 μmoll^{-1}) and 6 (N-$N0_2$=2.5 μmoll^{-1}) in February and December, respectively. N/P ratio mean values were highest in winter with maximum values (2239) measured at site 4 in February.

Tidal fluctuations varied seasonally with lower values (tide maximum 45 cm) coinciding with strong NE to E winds, which blow in the area during the winter period (Figs 4A, C). Precipitation was higher during autumn-winter, than during the spring-summer period (Figure 4B).

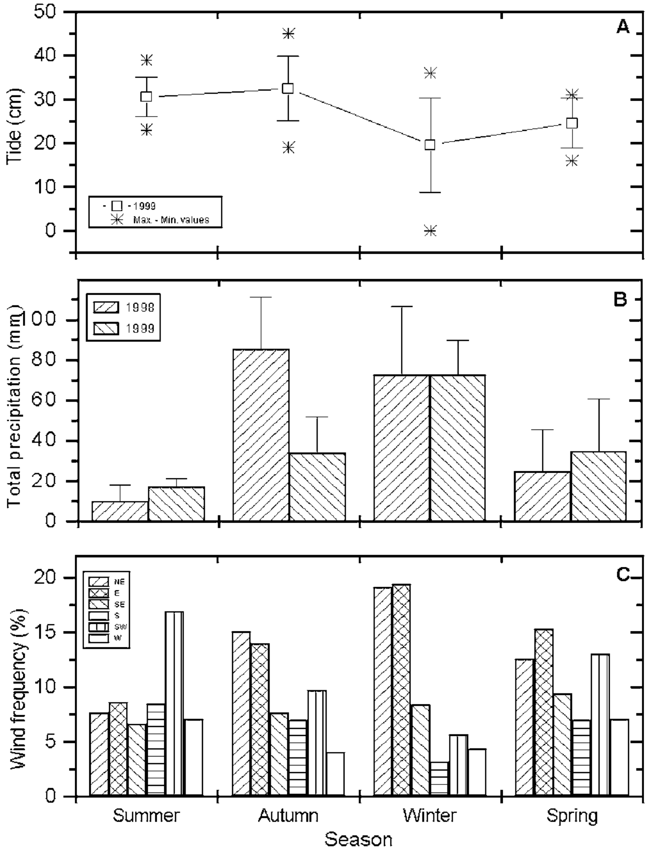

Fig. 4: Seasonal variability of tide (A), precipitation (B) and wind (C) in the Vassova lagoon. Precipitation (years 1998-1999) and wind (years 1984-1997) data from the meteorological station of Chrisoupolis, Kavala airport, which is located ca. 5 km away from the Vassova lagoon. Bars indicate 95% confidence intervals.

Discussion

The Vassova lagoon is a shallow open dynamic ecosystem following an extensive spatiotemporal variability of key environmental parameters. In order to identify meaningful patterns of the eutrophication parameters we used simple, e.g. averages, and advanced, e.g. regression polynomial, statistical analyses (Table 1, Figs 2, 3). The intensive sampling protocol of this study, which includes data from fresh and marine waters, was suitable for this approach. Since dissolved nutrients are plant residuals the relation between marine, lagoon and freshwater nutrient concentrations with salinity was sufficient to indicate the freshwater origin of nitrate and phosphate (see equations 1-3). This result has justified the reduction of freshwater inflow into the lagoon in the past as a measure to control algal bloom formation and to improve fish farming production. Less freshwater has increased mean salinity to 30 PSU (Table 1) and reduced spatial salinity gradients. Low correlation coefficient (R^2) of equations 1, 2 and 3 indicates that also other internal parameters, e.g. macroalgal biomass, influence nutrient transport from freshwater sources to the outlet (SCHRAMM & NIENHUIS, 1996; VIAROLI *et al*., 2001). Seawater nitrate and phosphate concentrations were much lower in comparison to freshwater (Table 1; see also FRILIGOS & KARYDIS, 1988; NIKOLAIDIS *et al*., 1996). In contrast, the higher ammonium concentrations of autumn and winter could be the result of wind-induced remobilisation of mineralised organic matter accumulated in the sediment (VIDAL & MORGUI, 1995; MENINDEZ & COMIN, 2000). Because the fish yield and mobilization are at a maximum within the lagoon in autumn, additional internal sources of ammonium could be fish excretes and fish induced water turbulence.

Mean annual nutrient concentrations of the Vassova lagoon are in the same order of magnitude with other eutrophicated Greek lagoons, e.g. Papas and Rhodia lagoons (Table 2). Dissolved phosphorus and TDIN annual means are close to those measured in the Urbino and Biguglia lagoons in Corsica and close to one third of those measured in the Venice lagoon, Italy (DE CASABIANCA *et al*., 1997). This is an indication of less human influence in the Greek lagoons in comparison to those of the western Mediterranean, probably due to moderate nutrient inputs. Since nutrients are regarded as supplementary elements for the definition of ecological status (WFD), this statement, however, needs to be confirmed by biotic data (ORFANIDIS *et al*., 2001; REIZOPOULOU & NICOLAIDOU, 2005). Nutrient concentrations reported by THEOCHARIS *et al*. (2000); SYLAIOS & THEOCHARIS (2002); SYLAIOS *et al*. (2003) for selected Northern Greek lagoons, including the Vassova lagoon, fall outside of the reported range (Table 2) and should be regarded with caution.

The seasonal availability of nitrate and TDIN (highest in winter and lowest in summer) could be explained by an inflow of higher nutrient loaded freshwater into the lagoon in winter, than in summer (Fig.2, Table

Table 2

Annual means (±95% C.I) of key eutrophication parameters in different Greek lagoons. Asterisk (*) indicate sum of $N\text{-}NO_3 + N\text{-}NO_2$.

Lagoon	*Temperature* (°C)	*Salinity* (PSU)	$N\text{-}NO_3$ ($\mu moll^{-1}$)	$N\text{-}NO_2$ ($\mu moll^{-1}$)	$N\text{-}NH_4$ ($\mu moll^{-1}$)	$P\text{-}PO_4$ ($\mu moll^{-1}$)	*Notices*	*Literature*
Gialova	*19.24* ± 3.98	41.31 ±*9.07*	2.03 ± 2.58	0.22 ± *0.24*	3.53 ±*4.59*	0.06 ±*0.04*	N=77 All year	KOUTSOUBAS *et al*., 2000
Logarou	20.71 ±6.12	39.47 ±7.81	0.18 ±0.10	0.89 ±0.47	1.32 ±1.10	0.89 ±0.47	N=13 All year	NCMR, 2001 KORMAS *et al*., 2001
Papas	17.8 ±6.3	32.9 ±6.6	4.46 ±4.34*	-	0.53 ±0.30	1.66 ±1.65	N=10 Seasonally	NCMR, 2000
Rodia	20.96 ±6.42	29.22 ±5.77	1.54 ±1.15	1.63 ±0.94	7.79 ±4.05	1.63 ±0.94	N=21 All year	NCMR, 2001 KORMAS *et al*., 2001
Tsoukalio	20.07 ±6.17	27.55 ±7.45	0.14 ±0.07	0.81 ±0.47	1.24 ±0.82	0.81 ±0.47	N=21 All year	NCMR, 2001 KORMAS *et al*., 2001
Vassova	17.15 ±1.98	30.04 ±0.98	3.55 ±1.05	0.35 ±0.13	2.00 ±0.79	0.93 ±0.18	N=72 All year	Present

1). Nitrate denitrification, immobilization in soil organic matter and plant uptake seems to be more efficient in the area during the main agro-ecosystem production in summer than in winter (PAUL & CLARK, 1996). Precipitation, which is maximal in winter (Fig. 4B), may also be a significant source of nitrogen in the Vassova lagoon, because it is located close to the local industrial region (P-industry and crude oil de-sulphurization-industry) and to the national highway via the Egnatia road (PAERL *et al*., 1990).

An additional explanation for nitrate concentrations in winter could be due to the prevailing strong NE and E winds (Fig. 4C) that hinder the seawater inflow during the tidal cycle (Ekman transport; DYER, 1997). The combination of high nutrient (freshwater, precipitation) and reduced flushing seawater increased nutrient concentrations in the lagoon and especially in the seasonally isolated area of site 2. Maximum nitrate concentrations were measured at site 2 at the end of the winter, when the closed MF-d hinders water circulation. In this area of the Vassova lagoon, *Ulva* blooms have been recorded (ORFANIDIS *et al*., 2000; see also SFRISO *et al*., 1992; SCHRAMM & NIENHUIS, 1996 and literature therein) disturbing the local environment (RAFFAELLI *et al.,* 1998).

The phytoplankton concentrations in the lagoon, as indicated by Chl-α estimates, were very low (annual mean of Chl-α=1.14 $\mu g l^{-1}$), with one exception at site 7 (most inner site studied) in January (19.58 $\mu g l^{-1}$). One explanation may be that the phytoplankton cells lack sufficient time to grow due to their short residence time in the lagoon (VALIELA *et al*., 1997), which was estimated during spring tides by SYLAIOS *et al*., (2003) to ca. 5 days. These conditions seems to favour the growth of macroalgae over phytoplankton, which annual mean dry biomass in the inner parts of the lagoon was estimated to ca. 337 gm^{-2} (ORFANIDIS *et al*., 2000). Algal biomass and weather conditions seem to influence the oxygen and pH variability pattern in the lagoon (Figs 2, 3) (SFRISO, 1995; SCHRAMM & NIENHUIS, 1996).

N/P ratio (Table 1) is indicating all year nitrogen importance for primary production (N/P<16:1; REDFIELD, 1958) except in winter, where phosphorus seems to be the most important nutrient for primary production (N/P>>16:1). The pronounced increasing gradient of P concentration from the outlets towards the inner parts of the lagoon (Fig. 3), as well as the relatively small seasonal variation in P concentration (Table 1), suggest an additional internal source of phosphorus in the lagoon, probably as P release from the sediments due to changes in turbulence, pH and redox conditions (GOLTERMAN, 1984; GIORDANI *et al*., 1996; NEDWELL *et al*., 1999). The influence of nutrients import, due to tidal or wind-forced flushing, is obviously of minor importance (Fig. 3) even in summer when low salinity Black Sea water influence stronger than in winter the Macedonian coasts of North Greece (YUCE,1995; ZERVAKIS *et al*., 2005).

Suspended material and light attenuation (PAR) as indicated by k, followed similar seasonal and spatial patterns (Figs 2, 3) showing the importance of wave- (wind) induced particle resuspension to underwater light regime (SCHEFFER, 1998), and thus to growth and survival of marine benthic vegetation in the Vassova lagoon (KIRK, 1994).

Conclusions

This study has indicated the considerable variability of the eutrophicated parameters and the role of adverse climatic and hydrographic conditions (high precipitation, strong NE to E winds, low tide) and fish farming management in the accumulation of nutrients in the Vassova lagoon. This result supports the proposal of the WFD to use abiotic parameters as supplementary elements for the definition of ecological status. The coincidence of the highest "eutrophication risk" in winter with the fry ascent facilitation, prohibits any drastic changes in the fishing practices, except for leaving the MF-d open. This could prevent excessive *Ulva* growth at station 2. The necessity of further improving the water quality requires integrated actions at the catchment, river and lagoon basin scale.

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