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Temporal Variations of Nutrients, Chlorophyll *a* and Particulate Matter in Three Coastal Lagoons of Amvrakikos Gulf (Ionian Sea, Greece)

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With 4 figures and 1 table

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Abstract. The temporal variations of nutrients, chlorophyll *a* (chl *a*), suspended particulate matter (SPM) and particulate organic carbon (POC) were measured over 12 months in three shallow coastal brackish water lagoons of the Amvrakikos Gulf, Ionian Sea. Two of the lagoons, Tsoukalio and Rodia, are interconnected but separated from Logarou by a narrow strip of land. Logarou has a better water exchange with the sea as indicated by the higher salinity and dissolved oxygen concentrations and the smaller variation of the above-mentioned parameters. Nitrate concentrations were largely the same in the three lagoons and higher than in the Amvrakikos Gulf. Phosphate concentrations in Logarou exceeded by far those of Tsoukalio/Rodia; the increased phosphate levels recorded in January caused an extended phytoplankton bloom with chl *a* concentrations higher than in the other two lagoons. Chl *a* in Tsoukalio was positively correlated with nitrate whereas in the most shallow lagoon, Logarou, it showed a positive correlation with light winds (force 4 and lower), probably caused by resuspension from the sediment. Increased phytoplankton biomass in Logarou coupled with the better water exchange may be related to the higher fish production in this lagoon.

Problem

Coastal lagoons, situated between the land and the sea, are influenced by both marine and terrestrial factors. They are often nutrient rich (Mee, 1978; McComb, 1995; Nixon, 1995) both as a result of input of nutrients by rivers and recycling between the sediment

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and water column, facilitated by their shallowness (Murphy & Kremer, 1985; Nowicki & Nixon, 1985).

Furthermore, coastal lagoons are subjected to increased nutrient inputs worldwide due to anthropogenic activities (Lee & Olsen, 1985; Pavoni *et al.,* 1990; Sfriso *et al.,* 1992) such as modification of land use, effluent disposal and aquaculture. Increased eutrophication reduces eelgrasses and favours macroalgae and phytoplankton proliferation (Duarte, 1995). Subsequent death and decomposition of the increased plant biomass leads to dystrophic crises in the whole system (see Caumette *et al.*, 1996). Anoxia, in turn, releases nutrients from the sediment to the water column, thus affecting nutrient cycling (Souchu *et al.*, 1998).

Through water exchange with the sea, coastal lagoons, like most aquatic ecosystems, act as sources or sinks of nutrients (Billen *et al.*, 1991); this role is particularly significant in the Eastern Mediterranean, which is one of the most oligotrophic areas of the world ocean (Azov, 1991; Stergiou *et al.*, 1997). Detailed information about spatial and temporal variability of nutrients in coastal lagoons is an essential first step towards clarifying this role.

The northern coast of Amvrakikos Gulf is one of the most ecologically important lagoonal systems in Hellas and as such it is protected by the convention of Ramsar. Very little is known about the environmental factors governing these and other Hellenic lagoons despite their importance (Yiannakopoulou, 1998; Petihakis *et al.*, 1999). Apart from some technical reports, most of the published papers concern fauna distribution (Bourgoutzani & Zenetos, 1983; Nicolaidou *et al.*, 1988; Nicolaidou & Karakiri, 1989; Bogdanos & Diapoulis, 1984) and population dynamics (Karakiri & Nicolaidou, 1987; Nicolaidou & Kostaki-Apostolopoulou, 1988) of benthic organisms and zooplankton (Siokou-Frangou, 1986). Some aspects of pollution have also been dealt with (Albanis *et al.*, 1995; Dassenakis *et al.*, 1994; Reizopoulou *et al.*, 1996). The ecological study of Guelorget *et al.* (1986) provides useful information on the hydrochemistry, sedimentology and planktonic and benthic populations of the northern lagoons of Amvrakikos; however, it is based on a one-time survey which took place in the summer.

The present paper presents data on environmental parameters of two interconnected lagoons, Tsoukalio and Rodia, of the northern Amvrakikos Gulf and compares them with those of the adjacent lagoon, Logarou. These lagoons are used for the extensive culture of fish and, although they are separated by a narrow strip of land, Logarou has higher fish production: data from the Ministry of Fisheries and Agriculture showed that in the five years prior to sampling, fish production in weight per surface area was 1.5 to almost 2.0 times higher in Logarou than Tsoukalio/Rodia. Monthly changes of nutrients, chlorophyll *a* and suspended matter have been analysed in relation to rainfall and wind in an attempt to detect possible effects of climatic factors on the yearly cycles of the former.

Material and Methods

The lagoonal complex of the northern Amvrakikos Gulf is formed in the common delta of the rivers Arachthos and Louros. Two main systems can be distinguished (Fig. 1), separated by a narrow piece of land: the complex Rodia (2600 ha), Tsoukalio (2900 ha) and Logarou (4900 ha). Rodia is connected to Tsoukalio through a very narrow opening approximately 10 m wide. Tsoukalio and Logarou are separated from Amvrakikos itself by a narrow barrier with openings allowing limited water exchange with the sea. Drainage canals collect water

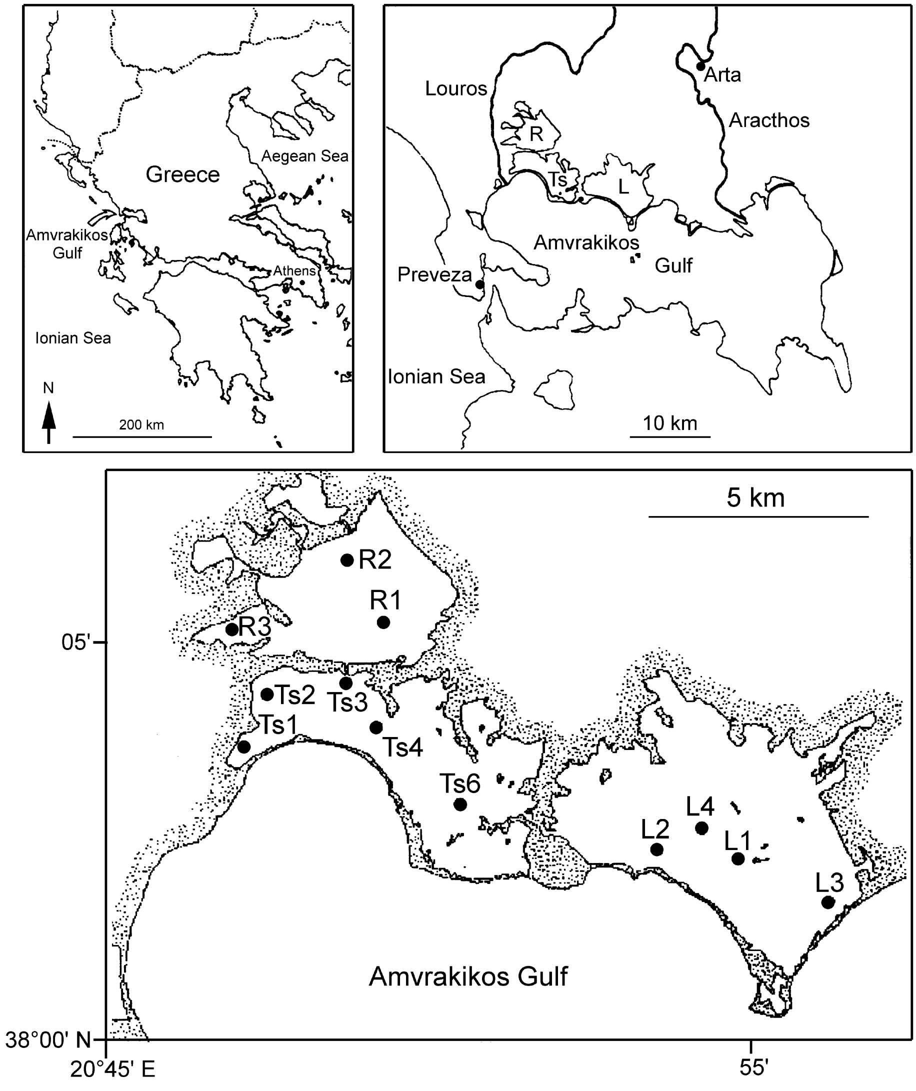

Fig. 1. Tsoukalio, Rodia and Logarou lagoons with sampling stations.

from the fields surrounding Logarou and discharge it into Amvrakikos at the west of the lagoon. The depth in Tsoukalio ranges from 0.6–1.8 m, in Rodia from 1.0–3.5 m and in Logarou from 0.85–1.5 m. The substratum is muddy in all lagoons. At the time of the investigation, macroalgae fringed the N-NW periphery of Rodia whereas they were absent from Tsoukalio. Most of the bottom of Logarou was covered by macroalgae, mostly Charophyta.

After a preliminary survey in July 1993, five stations were established in Tsoukalio and three in Rodia, which were sampled monthly from January to December 1994. In Logarou four stations were established; due to access difficulties, however, sampling was possible only on seven occasions throughout the year, *i. e.* from January to April, and in July, September and October of the same year.

The wind and precipitation data were provided by the National Meteorological Service. Temperature, salinity and dissolved oxygen (DO) were measured at the water surface and just above the bottom using temperature/salinity and oxygen probes (Yellow Springs Inc.). Samples for nutrients (phosphate, nitrate and silicate) were collected just below the surface in polyethylene bottles and kept frozen until laboratory analyses (< 2 days). The nutrient concentrations were determined by chemical methods (Parsons *et al.*, 1984) after filtration of the sample through a 200 µm mesh net to retain large particles and zooplankton, as practiced in other lagoons (*e.g.,* Souchu *et al.*, 1998). Precision at the median concentration of the detection ranges and accurracy (± SD) for the determination of nitrate, nitrite, phosphate and silicate were 20 ± 0.038, 1 ± 0.002, 3 ± 0.002 and 10 ± 0.019 µM, respectively. Phytoplankton pigments were determined spectrophotometrically using the acetone extraction method (Parsons *et al.*, 1984) on Whatman GF/C filters (approximately 1.2 µm retain capacity). Suspended particulate matter (SPM) was determined by the weight difference before and after filtration of known volumes of seawater on precombusted (500 °C) and preweighed Whatman GF/C filters (Strickland & Parsons, 1972). Particulate organic carbon (POC) was determined according to Parsons *et al.* (1984) after filtering seawater on precombusted (500 °C) Whatman GF/C filters.

Since the distribution of most water quality parameters tends to be non-normal (Sanders *et al.*, 1987) and often follows a log-normal distribution, statistical procedures used in this paper were non-parametric tests based on ranks of data rather than absolute values. The Kruskal-Wallis test showed no significant differences between surface and bottom values for temperature, salinity and DO and between stations in each lagoon for nearly all the parameters. Thus, for every lagoon the average values calculated on data collected from different stations and depth layers are taken into account.

Results

Temperature (Fig. 2) showed the expected seasonal pattern with maxima ranging from 24.4 °C to 28.3 °C during the summer months and minima ranging from 11.2 °C to 13.0 °C during the winter. Tsoukalio and Rodia showed higher seasonal variations than Logarou. Salinity (Fig. 2) in the three lagoons was at its maximum in summer, while the lowest values were recorded in the winter months. For most of the year, salinity in Tsoukalio (13.0–28.9) was higher than in Rodia (11.6–25.0), but in Logarou it ranged from 15.7 to 26.6. Dissolved oxygen (Fig. 2) never reached limiting concentrations in any lagoon (minimum: 6.0–9.2 mg·l^{-1}) and increased markedly in autumn and early winter in Tsoukalio (10.7 mg·l^{-1}) and Rodia (10.4 mg·l^{-1}). Data were not available for Logarou from August to December; however, from the comparable data, Logarou always had higher DO concentrations (9.2–12.1 mg·l^{-1}).

Phosphate (Fig. 3) ranged from below the detection limit to 0.08 µmol·l^{-1} in Tsoukalio and 0.14 µmol·l^{-1} in Rodia, with highest concentrations in June and March, respectively. In contrast, phosphate in Logarou never dropped below the detection limit (0.12 µmol·l^{-1}) while its highest concentration (1.08 µmol·l^{-1}) occurred in January. Nitrate (Fig. 3) showed a similar pattern in Tsoukalio and Rodia, with maxima in March (8.60 µmol·l^{-1}) and February (9.35 µmol·l^{-1}), respectively. During spring and summer it remained close to analytical zero and in autumn and early winter it never exceeded 1.2 µmol·l^{-1}. In Logarou, nitrate showed a similar seasonal pattern and ranged between 0.00–8.78 µmol·l^{-1}. Silicate (Fig. 3) in Tsoukalio and Rodia showed two periods of high concentrations, early winter and early summer, followed by two periods of low concentrations, early spring and early autumn. The maxima occurred in summer (Tsoukalio 84.81 µmol·l^{-1}; Rodia 51.92 µmol·l^{-1}). In Logarou, silicate concentrations were higher in winter compared to Tsoukalio and Rodia. The maximum was observed in January (72.74 µmol·l^{-1}), the minimum in October (18.07 µmol·l^{-1}).

Chl *a* (Fig. 4) variation was similar in Tsoukalio and Rodia, with the highest concentrations (3.4 and 6.5 µg·l^{-1}, respectively) in March. Thereafter it remained at lower concentrations (< 1.8 and < 4.0 µg·l^{-1} in Tsoukalio and Rodia, respectively). In Logarou,

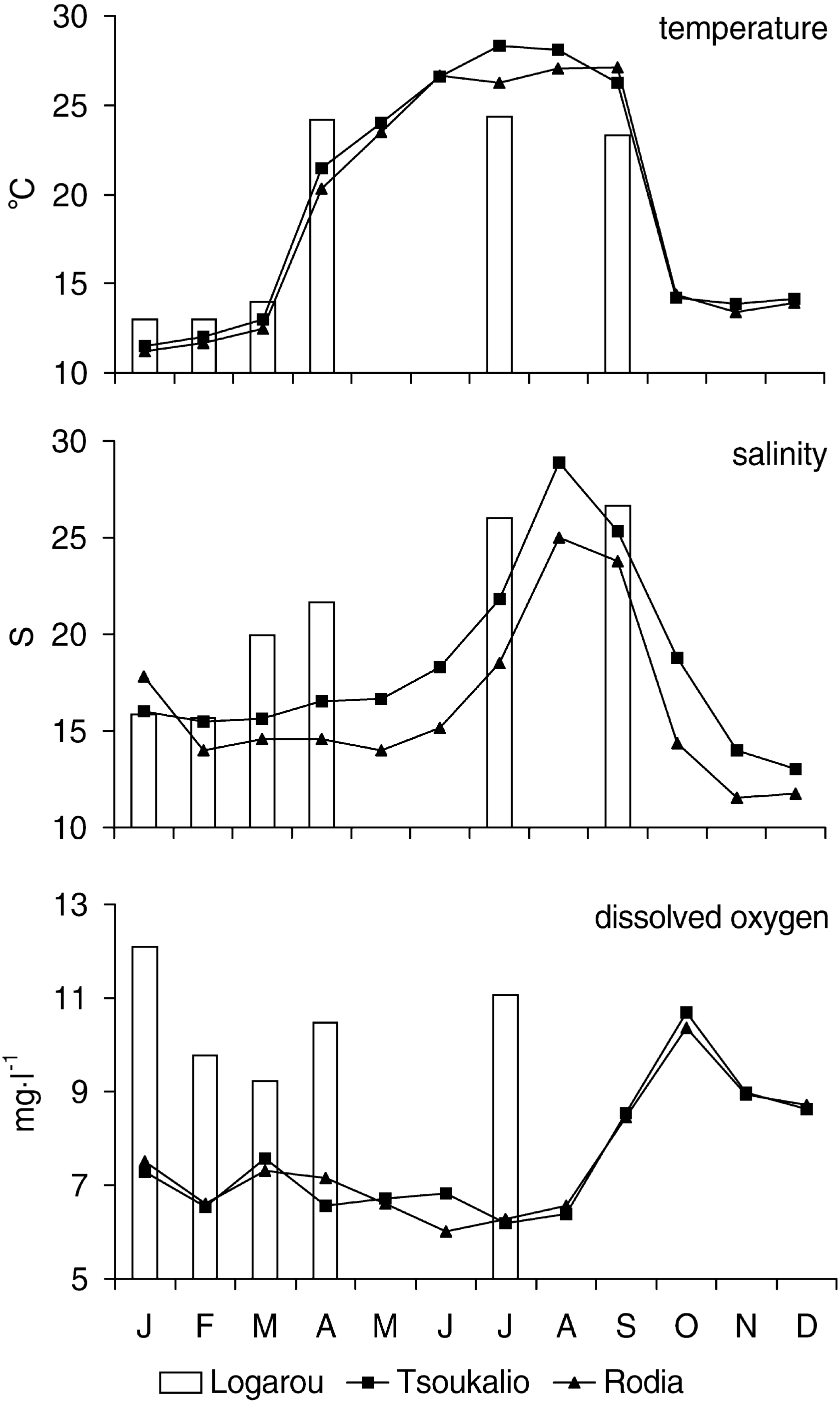

Fig. 2. Average values of temperature, salinity and dissolved oxygen in Tsoukalio, Rodia and Logarou lagoons.

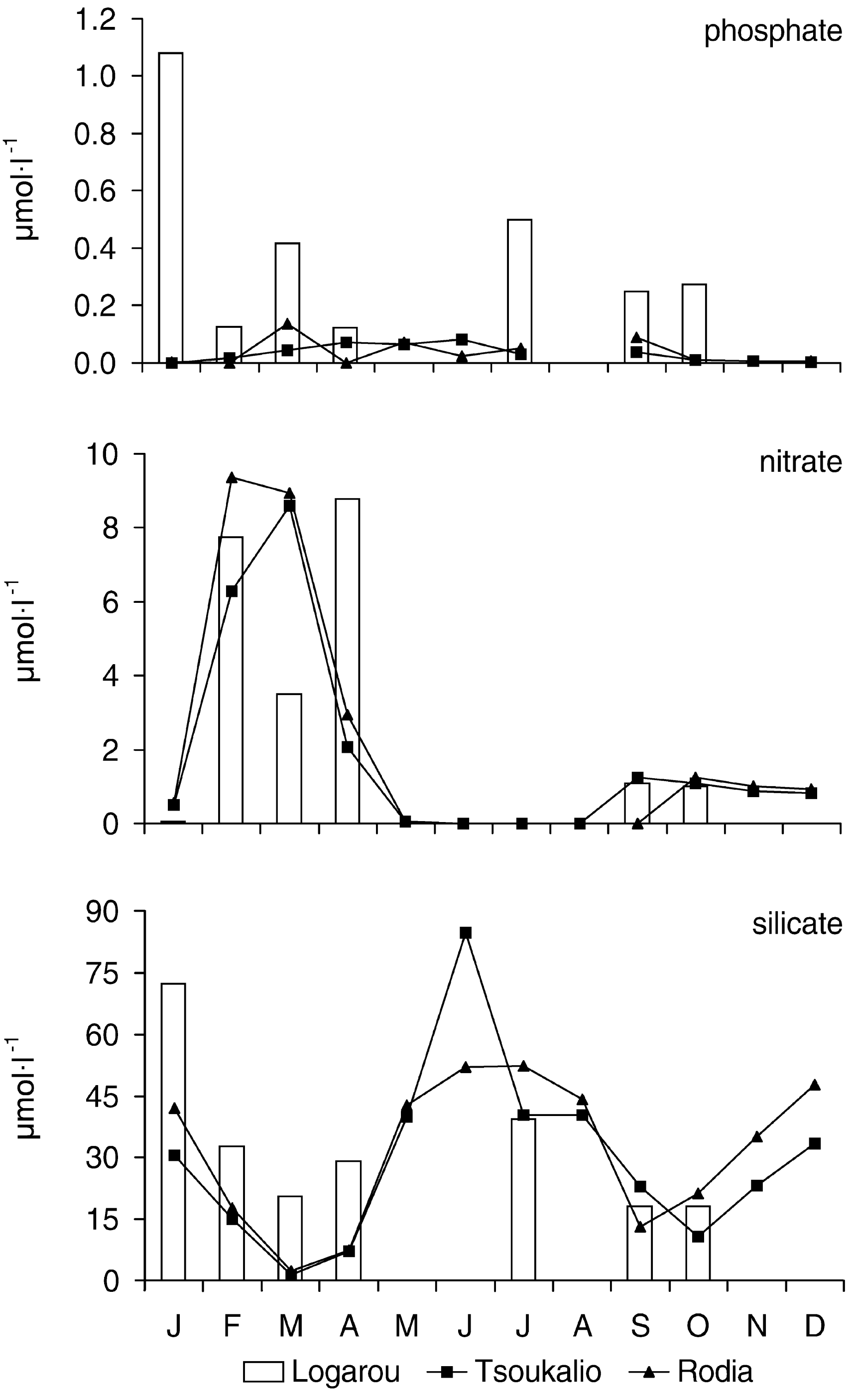

Fig. 3. Average values of phosphate, nitrate and silicate in Tsoukalio, Rodia and Logarou lagoons.

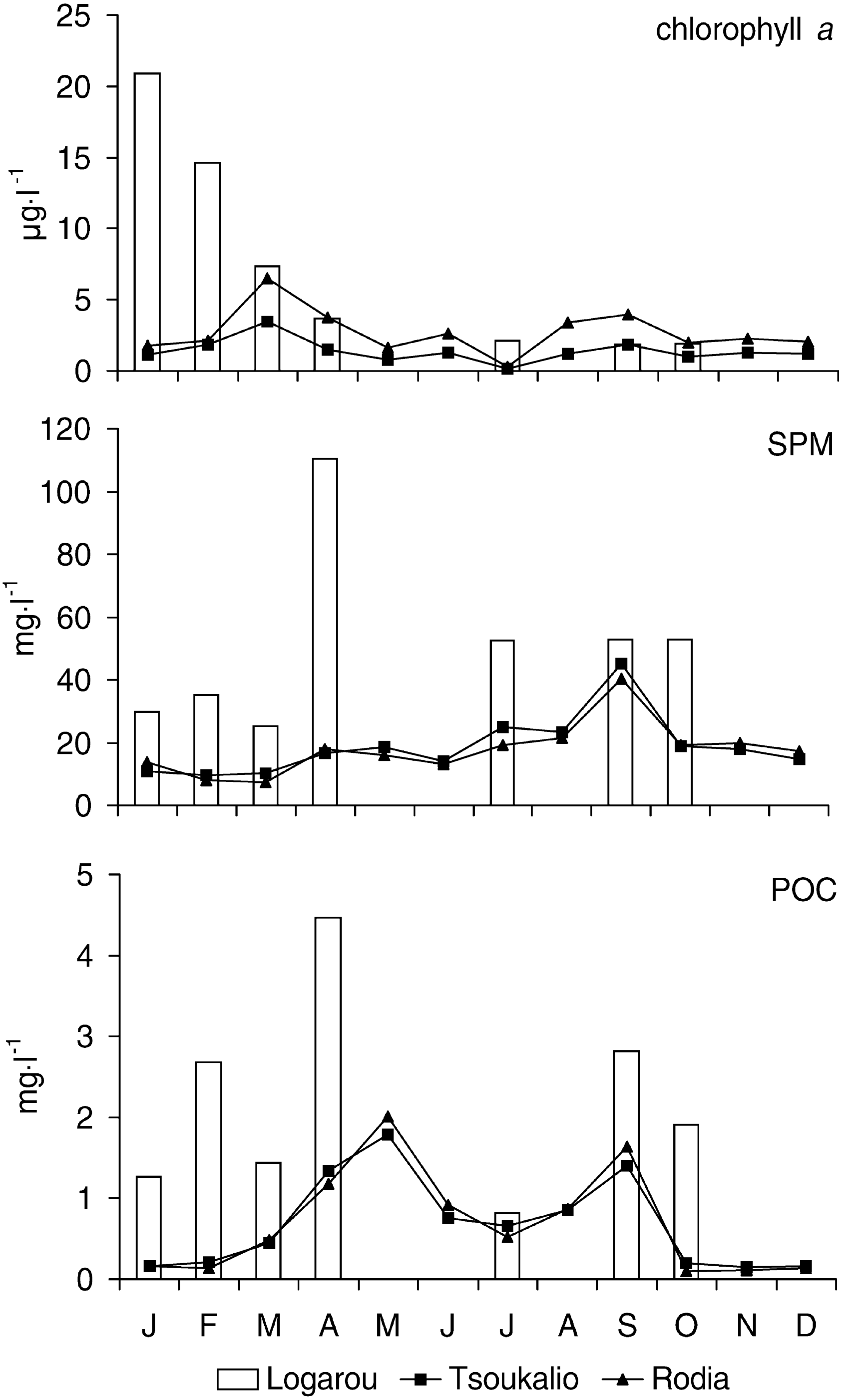

Fig. 4. Average values of chlorophyll *a*, suspended particulate matter (SPM) and particulate organic carbon (POC) in Tsoukalio, Rodia and Logarou lagoons.

chl *a* concentration peaked in January (20.9 $\mu g \cdot l^{-1}$) followed by a constant decrease down to 1.8 $\mu g \cdot l^{-1}$. SPM concentrations (Fig. 4) were very similar in Tsoukalio and Rodia (9.7–45.3 $mg \cdot l^{-1}$ and 7.5–40.4 $mg \cdot l^{-1}$, respectively), with maxima in September. Logarou always had higher SPM concentrations (25.2–110.4 $mg \cdot l^{-1}$) than the other two lagoons. POC concentrations (Fig. 4) were similar in Tsoukalio (0.14–1.78 $mg \cdot l^{-1}$) and Rodia (0.10–2.01 $mg \cdot l^{-1}$), with maxima in May; high POC concentrations were also observed in September. In Logarou, POC was always higher (0.82–4.47 $mg \cdot l^{-1}$, maximum in April) than in the other two lagoons.

Correlation analyses were carried out between all the parameters measured. Only the significant correlations are shown in Table 1. Salinity was positively correlated with temperature and negatively with rainfall in all the lagoons. Rainfall was negatively correlated with phosphate and positively with nitrate in Tsoukalio and Rodia. Chl *a* showed negative correlation with temperature in all three lagoons and with salinity in Tsoukalio and Logarou. There was also a positive correlation of chl *a* with silicate in Logarou. SPM was positively correlated with POC only in Tsoukalio.

Table 1. Spearman rank correlation coefficients between rainfall, salinity, temperature, phosphate, nitrate, silicate, chlorophyll *a* (chl *a*), suspended particulate matter (SPM) and particulate organic matter (POC) in Tsoukalio (Ts), Rodia (R) and Logarou (L) lagoons. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$. Only significant correlations are included.

		rainfall	temperature	salinity	silicate	SPM
salinity	Ts	–0.739***	0.736***			
	R	–0.847***	0.687***			
	L	–0.710***	0.655**			
phosphate	Ts	–0.260*	0.405**			
	R	–0.587**	0.506**			
nitrate	Ts	0.279*	–0.623**		0.521**	
	R	0.330*	–0.631**			
chl *a*	Ts		–0.331**	–0.343**		
	R		–0.386**			
	L	0.390*	–0.763***	–0.806**	0.603**	
SPM	Ts	–0.312*	0.406**			
POC	Ts	–0.486**	0.686***			0.424**
	R	–0.490**	0.750***			

Discussion

The study areas share the environmental characteristics common to lagoons (Barnes, 1980): they are shallow, with well-mixed water oxygenated down to the bottom. Their salinity and temperature show the expected seasonal variation. Salinity was lower during the winter months in accordance with higher precipitation, and was elevated in the summer due to increasing evaporation and low freshwater inputs from the land. The importance of rainfall is indicated by the observed negative correlation of rainfall with salinity. In Rodia some freshwater may stem from groundwater seeping from a karstic network, as suggested by Guelorget *et al.* (1986). Submarine groundwater discharges can be significant nutrient sources in shallow systems and help determine the salinity pattern of lagoons (Johannes, 1980; Johannes & Hearn, 1985; Herrera-Silveira, 1996). Logarou showed the highest salinity of the three lagoons and the smallest variation, suggesting a more effective sea water intrusion. The higher levels of dissolved oxygen in Logarou also indicate better mixing, although the contribution of oxygen by macroalgae may also be significant (Marcomini *et al.*, 1995).

The nutrient concentrations in the lagoons are higher than in Amvrakikos Gulf, except for phosphate (Panayotides *et al.*, 1994), and higher than in other non-polluted coastal areas. In Tsoukalio and Rodia, nitrate levels show a positive correlation with rainfall and negative correlations with temperature and salinity, a relationship also found by Tournier *et al.* (1981) for the lagoon of Thau. This indicates that the terrestrial input of nitrate, mainly as land runoff, was enhanced by the winter rains which, at the same time, lowered the salinity. In addition, nitrate is used immediately by the phytoplankton in the summer, which explains its negative correlation with temperature. As opposed to nitrate, phosphate is negatively correlated with rainfall and positively with temperature and salinity. Tournier *et al.* (1981), who found the same relationships in Thau lagoon, suggest that the most important factor controlling the phosphate content in the water column is temperature, which increases phosphate concentrations through mineralisation and excretion. According to these authors, phosphate is recycled in the water during summer when the activity of aquatic organisms, including microorganisms and fish, is high and prevents this nutrient from returning to the sediment. The latter process takes place in autumn/winter. In Logarou neither of the two nutrients showed any correlation with rainfall, salinity or temperature. Water laden with nutrients drained from the cultivated land behind Logarou is collected in the drainage canal at the west of the lagoon and brought to the sea.

Chl *a* in the lagoons is higher than in non-polluted coastal areas of the Eastern Mediterranean (Friligos & Gotsis-Skretas, 1987; Assimakopoulou & Gotsis-Skretas, 1997; Kormas, 1998) and comparable to those of other Mediterranean lagoons (Vaulot & Frisoni, 1986). This is in disagreement with the remarks of Guelorget *et al.* (1986) who found very low levels of chl *a* in the northern lagoons of Amvrakikos; their data, however, concern only the summer period, when chlorophyll is at its minimum. The chl *a* maxima in Tsoukalio and Rodia occurred in March following the increase of nitrate, which peaked in February/March. In Logarou, peak chl *a* values occurred earlier, initiated by the high phosphate concentration, and remained at relatively high levels supported further by the presence of nitrate. A similar trend of prolonged phytoplankton blooms was observed in a coastal embayment by Kormas (1998) as a reaction to phosphate input by rivers. The seasonal pattern of chl *a* concentrations found here agrees with the cell abundances reported for the same lagoons in an earlier study (Christaki & Gotsis-Skretas, 1990). Ammonia concentrations were not measured in the present study, prohibiting estimation of dissolved inorganic nitrogen (DIN: $NO_3^- + NO_2 + NH_4^+$) and the N:P ratio. The low phosphorus levels in Tsoukalio and Rodia point to P-limitation. A further indication is the ratio A_{480}:A_{664}, where A_{480} is the optical absorbance of the phytoplankton pigments at 480 nm and A_{664} at 664 nm (Heath *et al.*, 1990). Accordingly, nitrogen seems to be the limiting nutrient only in summer, when A_{480}:A_{664} was > 2.1–3.9 for all the lagoons. Hecky & Kilham (1988), in their review of factors limiting phytoplankton development, suggest that P is the limiting element in lacustrine and N in coastal marine environments. This is not true for the Mediterranean Sea, where P is generally the limiting factor (Krom *et al.*, 1991; Stergiou *et al.*, 1997) except where there are excess inputs of phosphate due to human activity. For example, Casellas *et al.* (1990) for the lagoon of Thau and Sfriso *et al.* (1988) for the lagoon of Venice underline that domestic effluents introduce large amounts of phosphate, making nitrate the limiting factor. Furthermore, nutrient limitation can be modified through the preferential utilisation of phosphorus by bacterial activity (Thingstad *et al.*, 1997, 1998). This parameter, however, was not measured in the present study.

Chl *a* was negatively correlated with temperature and salinity in Tsoukalio and Logarou, which is predictable because the maxima occurred in winter. The correlations of chl *a* with nutrients are statistically not significant except with nitrate in Tsoukalio and silicate in Logarou. The latter may be due to the larger numbers of diatoms in Logarou in relation to microplankton, as shown by Christaki & Gotsis-Skretas (1990). Chl *a* was negatively correlated with SPM in Tsoukalio and Logarou (no significant correlation in Rodia), suggesting that most of the SPM is not due to the phytoplankton larger than 1.2 µm. In Logarou, in particular, SPM shows a positive correlation with winds stronger than force 5 on the Beaufort scale ($r^2 = 0.664$, $P < 0.010$). Winds of that force probably produce waves able to resuspend the sediment, a fact also noticed in the lagoon complex of Aude in France (Cataliotti-Valdina, 1982). Weaker winds can resuspend microphytobenthos, increasing chl *a* in the water, as shown by the positive correlation of chl *a* with winds of force 4 and lower ($r^2 = 0.523$, $P < 0.010$). In the deeper Tsoukalio and Rodia there was no correlation between chl *a* and wind.

Comparing the two lagoonal systems, Logarou had higher oxygen and salinity, but of narrower range, indicating a better communication with the sea. Nitrate concentrations are largely the same; the phosphate concentrations in Logarou, however, exceed by far those of Tsoukalio and Rodia. The phosphorous enrichment in Logarou leads to increased chlorophyll levels, which are further reflected in higher zooplankton abundance (Pancucci-Papadopoulou & Anagnostaki, 1989) and fish production.

Overall, based on the present study, the observed temporal variations should be attributed to climatic factors including rainfall and wind and to the geomorphological characteristics of the lagoons including depth and communication with the sea.

The investigation of more specific parameters such as primary and bacterial productivity, the biogeochemistry of sediment parameters (*i. e.* nutrients, organic matter) and benthic communities are required before the functioning of the lagoon system is fully understood.

Summary

This paper describes the temporal variations of nutrients, chl *a* and suspended material over an annual cycle in three coastal brackish lagoons of the Amvrakikos Gulf, Ionian Sea. Two of the lagoons, Tsoukalio and Rodia, are interconnected and separated from the third, Logarou, by a narrow strip of land. These lagoons support extensive culture of fish and, despite their proximity, Logarou has a higher fish production per unit area than the other complex.

Logarou has a better water exchange with the sea. This is also indicated by the narrower salinity range (15.7–26.6) and the higher dissolved oxygen concentrations (9.2–12.1 $mg \cdot l^{-1}$) in Logarou compared to Tsoukalio/Rodia (salinity 11.6–28.9, DO 6.0–10.7 $mg \cdot l^{-1}$). The lagoons had higher nutrient concentrations than those of the adjacent Amvrakikos Gulf and other coastal areas. However, they showed lower concentrations compared with other Mediterranean lagoons. Nitrate ranged from 0.00–8.78 $\mu mol \cdot l^{-1}$ in Logarou and between 0.00–9.35 $\mu mol \cdot l^{-1}$ in Tsoukalio/Rodia. Silicate also showed similar ranges, 18.07–72.41 $\mu mol \cdot l^{-1}$ in Logarou and 1.52–84.81 $\mu mol \cdot l^{-1}$ in Tsoukalio/Rodia. Phosphate was always lower in Tsoukalio/Rodia lagoons (0.00–0.14 $\mu mol \cdot l^{-1}$) than in Logarou (0.12–1.08 $\mu mol \cdot l^{-1}$).

Logarou had higher chl *a* concentrations (1.8–20.9 $\mu g \cdot l^{-1}$) than the other two lagoons (0.2–6.5 $\mu g \cdot l^{-1}$). This is probably due to the higher phosphate levels in Logarou. The phytoplankton seasonal pattern was different in the three lagoons. In Logarou, maximum chl *a* content occurred in January, in Tsoukalio and Rodia in March. The positive correlation of chl *a* with light winds (force 4 and lower) in Logarou was probably caused by resuspension due to the shallowness.

Logarou also had higher levels of SPM (25–110 $mg \cdot l^{-1}$) than the other two lagoons (8–45 $mg \cdot l^{-1}$). This was also reflected in the POC composition; in Logarou it ranged from 0.8–4.5 $mg \cdot l^{-1}$ and in Tsoukalio/Rodia 0.1–2.0 $mg \cdot l^{-1}$. POC formed 0.8–12.6 % of SPM.

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