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Abstract

Spercheios River discharge rates of nutrients, suspended particulate matter (SPM) and particulate organic carbon (POC) and seawater concentrations of these parameters as well as chlorophyll a (chl a) were measured in the Maliakos Gulf, Greece, on a monthly basis between 1992-1993. From all the nutrients measured, silicate showed the highest discharge rates followed by nitrate, phosphate and nitrite. The river introduced significant amounts of SPM (8.5 – 35.5 Kg d^{-1}) with very low POC content (<3%). Most of the variables measured showed no gradient from the river to the outer gulf, which could be attributed to fast mixing of the incoming water. However, chl a had higher concentrations in the inner (0.3 – 4.9 $\mu g\ l^{-1}$) and lower in the outer gulf (0.05 – 2.5 $\mu g\ l^{-1}$). It is suggested that the nutrients introduced by the river are consumed faster in the inner gulf and that a number of temporal streams and non-point sources at the periphery of the gulf prevent the formation of a gradient.

Keywords: Nutrients, chlorophyll, Particulate matter, Organic carbon, Coastal, Spercheios River, Maliakos Gulf, Eastern Mediterranean.

Introduction

Rivers are the main arteries of nutrient transport from land regions to freshwater lakes and the sea. Apart from nutrients, rivers carry dissolved chemical compounds and suspended solids, however, their concentrations and discharge rate is variable depending on the topography of catchment area, land use and latitude (LUDWIG & PROBST, 1996). These materials may also be transformed near river mouths by physical, chemical and biological forces and they usually meet diverse fates (SKRESLET, 1986; NITTROUER, 1993; ARTEMYEV, 1996). Estuaries function as significant sinks and transformers of nutrients (NIXON *et al.*, 1996), thus altering the quantity and quality of nutrients, which are transported from the land to the sea and become available for phytoplankton growth (JORDAN *et al.*, 1991a). Organic matter is also trapped in estuaries, resulting in non-uniform distribution of sedimenting organic material (PEARSON & ROSENBERG, 1987), that impacts the structure of benthic communities. Thus, a common feature of estuaries and coastal waters that receive the input of rivers is a decreasing gradient of salinity, the concentration of river transported materials and biotic factors of planktonic and benthic communities from the river mouth seawards, often resulting in more eutrophic conditions in the areas close to freshwater source (e.g. TAYLOR 1993; TEXIER *et al.*, 1993; YSEBAERT *et al.*, 1993; LOPES, 1994; BOYNTON *et al.*, 1996; YIN *et al.*, 1997, KRSTULOVIĆ *et al.*, 1998; YIANNAKOPOULOU, 1998).

Although the key role of such investigations for the coastal processes has been recognised, little information is available regarding the quality and load of discharged material by Greek rivers (POULOS, 1997). The Aegean Sea is generally considered as one of the most oligotrophic areas of the world (STERGIOU *et al.*, 1997) but it is known that its enclosed and semi-enclosed bays and its northern part are more eutrophic compared to the offshore waters and its southern part. This is attributed either to agricultural and municipal waste and/or the river runoff. Five major rivers, the Evros, the Nestos, the Strimonas, the Aliakmonas and the Axios, flow into the northern Aegean Sea (STERGIOU *et al.*, 1997), which receives 93.7% of the total river discharge of the Aegean (THERIANOS, 1974). In Greece, most studies of coastal research are conducted in bays, gulfs and lagoons that are influenced by human activities or are situated close to river mouths (STERGIOU *et al.*, 1997 and references therein, FRILIGOS *et al.*, 1997; PSYLLIDOU-GIOURANOVITS *et al.*, 1997; PSYLLIDOU-GIOURANOVITS *et al.*, 1998; YIANNAKOPOULOU, 1998). However, no direct quantification of riverine input and its impact to these systems has ever been made.

The study area, Maliakos Gulf, is a semi-enclosed embayment influenced by the river Spercheios, which flows in its inner part, as well as by anthropogenic activities including fishing and farming of fish and shellfish. The gulf, along with Spercheios River and its valley are a specially protected area under the NATURA 2000 project, initiated by the European Union (DAFIS *et al.*, 1996). While this study was undertaken, there was an intense debate by the authorities whether to construct in the gulf either an immersed (undersea) tunnel or a bridge in order to shorten the current highway, that goes around the gulf, the biggest highway route in the country (PSOMAS, 1996). This will have an impact on the system's current functioning, especially through a dramatic increase in suspended matter during the construction of the tunnel.

In spite of the system's importance, very little information about the role of the Spercheios River on the Maliakos Gulf exists and most of that is based largely on seasonal data of the gulf (CHRISTOU *et al.*, 1995; PSYLLIDOU-GIOURANOVITS *et al.*, 1997; KORMAS *et al.*, 1997, KORMAS *et al.*, 1998). Thus, it was believed that a study of the environmental parameters both in the river and the gulf simultaneously and at shorter time intervals, would contribute towards a better understanding of the ecosystem functioning and a more effective management (conservation strategy, river management, aquaculture development) of this ecologically important area. The information obtained could be used, together with a model of water circulation, to predict possible impact of the construction of the tunnel/bridge and would form a baseline against which future comparisons could be made.

Materials and Methods

Study location

The Spercheios River has a length of 82.5 Km. It ranks tenth in Greece in terms of mean annual flow and seventh in annual sediment discharge (POULOS, 1997). Its valley covers 15,000 ha and its watershed comes up to ca. 115,800 ha. The river's delta covers 10,000 ha.

Maliakos Gulf covers an area of ca. 11,000 ha and it is divided by two headlands in two parts (Fig. 1). At the eastern end, the gulf is connected to the Aegean Sea through the Orei Channel and to the Evoikos Gulf through the Knimida Channel. This part has an average depth of 36 m. The western part, where the Spercheios River meets the sea, forms a basin with a maximum depth of 27 m, while closer to the river mouth the depth does not exceed 10 m. This river is the major source of terrigenous material in the gulf, however, temporal streams, which do not belong to the catchment of the Spercheios and discharge directly into the gulf, are important occasionally. The mean tidal range is 30 cm.

Sampling and analyses

The sampling site in the river was located 7.5 Km upstream from its mouth. Measurements were conducted monthly from October 1992 to September 1993. The flow rate (m^3 s^{-1}) was calculated by multiplying the water velocity (m s^{-1}) by the total surface area (m^2) of the river's transect in the sampling site. Four to five litres of water from the middle of the flow were collected for nutrient and suspended matter analyses. In particular, water samples for nutrient analyses were frozen in polyethylene bottles and processed within two days from collection. Nutrient (phosphate, nitrate, nitrite and silicate) concentrations were determined spectrophotometrically as described in PARSONS *et al.* (1984) after filtration of the sample through a 200 μm mesh to retain large particles and zooplankton; measurement of ammonia concentrations was not feasible at that time. Suspended particulate matter (SPM) was determined by the difference of weight before and after filtration of seawater on precombusted (500 °C, 4 h) and preweighed Whatman GF/C filters (SRICKLAND & PARSONS, 1972). Particulate organic carbon (POC) was determined by wet ashing after filtering seawater on precombusted (5000C, 4 h) Whatman GF/C filters (PARSONS *et al.*, 1984). The discharge rate of nutrients and suspended solids were calculated by multiplying their concentrations by the river flow. Although the results of the analyses are given for the whole period of study the possible impact of the river is focused on the period from October to May since for the rest of the year the entire water supply is being used for agricultural irrigation. Rainfall data were obtained from the National Meteorological Service.

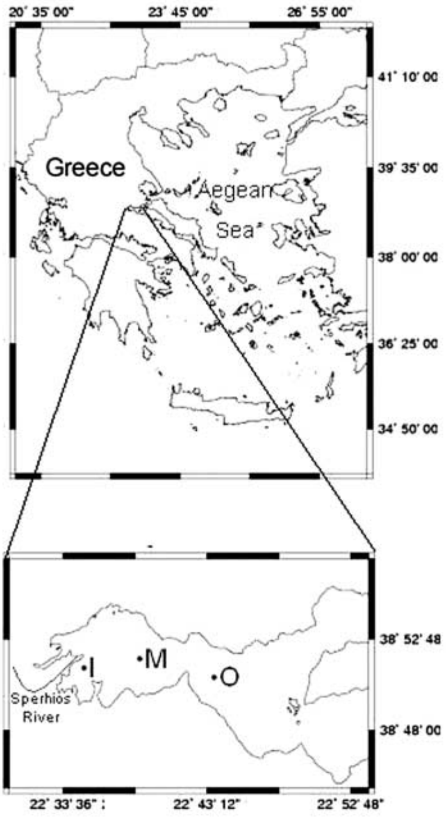

Fig. 1: Map of the study area with sampling stations. (I: Inner, M: Middle, O: Outer station).

Based on the characteristics of the gulf mentioned above and after a preliminary survey (KORMAS *et al.*, 1997), three sampling sites were chosen representing three ecologically different compartments of the gulf (Fig. 1): the shallow south-west area near Spercheios River (Inner compartment, 7 m), the outer gulf connected to the Aegean Sea (Outer compartment, 23 m) and the intermediate basin (Middle compartment, 23 m). At these stations, monthly water samples were collected from the surface, 1, 5, 10 and 20 m using a LIMNOS water sampler. Salinity, temperature, dissolved oxygen (DO) and chlorophyll *a* (Chl *a*) were measured from June 1992 to September 1993, nutrients (nitrate, nitrite, phosphate, silicate) from September 1992 to October 1993 and SPM and POC from October 1992 to September 1992, all on a monthly basis. A HYDROBIOS thermometer attached to the water sampler was used for measuring temperature. Salinity was measured with an AUTOSAL 3000 salinometer and DO was determined by the Winkler method as modified by CARRIT & CARPENTER (1966). Chl *a* was determined spectrophotometrically using the acetone extraction method (PARSONS *et al.*, 1984) on Whatman GF/C filters (ca. 1.2 μm retain capacity). Nutrients, SPM and POC were determined as described above for Spercheios River.

Since none of the parameters in the gulf showed any statistical differences with depth (non-parametric test of Kruskal-Wallis, Zar, 1998), depth integrated values are presented here. All statistical analyses were performed using the software package STATISTICA (Statsoft Inc.).

Results

Spercheios River

The flow rate of the river (Fig. 2) increased gradually from November until March when it reached a maximum of 12.98 $m^3 s^{-1}$ following the rainfall pattern. The discharge rates of nutrients and suspended matter are shown in Fig. 3 and 4 respectively. Phosphate discharge was at its maximum (17.7 Kg d^{-1}) in May. Nitrate discharge fluctuated considerably with its maximum occurring in March (111.5 Kg d-1) while nitrite discharge was highest in January (23.4 Kg d^{-1}). The silicate discharge was rather constant from October until April with a maximum rate in May (832.2 Kg d^{-1}). SPM discharge rate was maximum in April (35.5 Kg d^{-1}) while the rate of POC discharge increased throughout autumn and winter, reaching a maximum (0.23 Kg d^{-1}) in March and then decreasing once again.

Maliakos Gulf

Depth integrated temperature (Fig. 5) followed the expected seasonal pattern with lowest values in the winter (9.5 °C) and highest

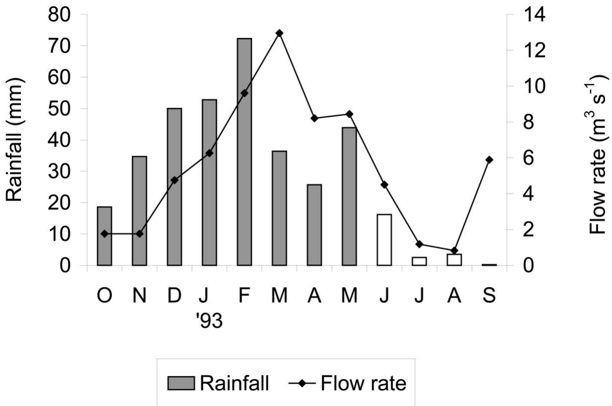

Fig. 2: Rainfall data and the Spercheios River flow rate. (White bars indicate the period when the river water does not reach the gulf).

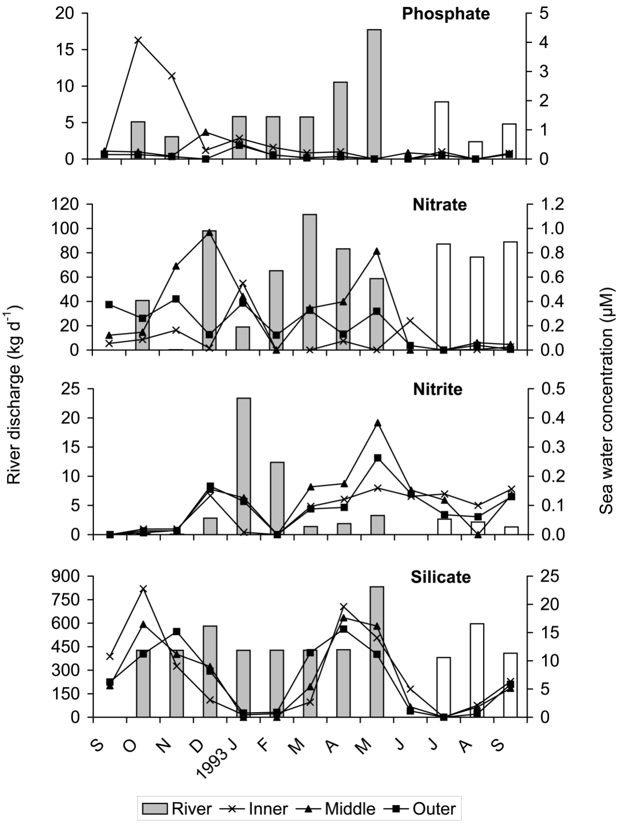

Fig. 3: Nutrient discharge rates from the Spercheios River and depth integrated nutrient concentrations of the Maliakos Gulf. (White bars indicate the period when the river water does not reach the gulf).

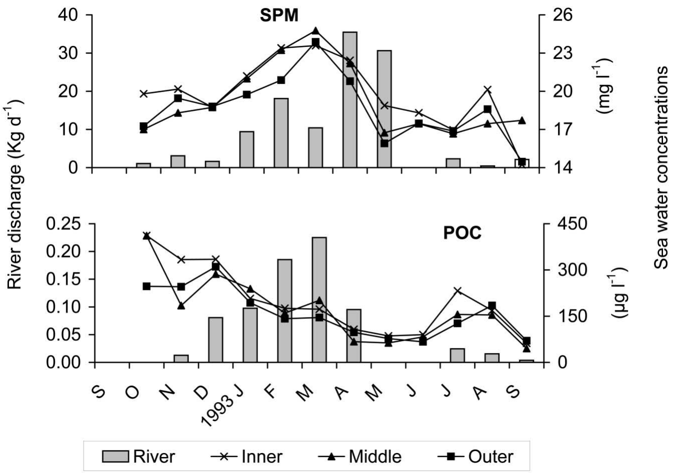

Fig. 4: Suspended particulate matter (SPM) and particulate organic carbon (POC) discharge rates from the Spercheios River and depth-integrated SPM and POC concentrations of the Maliakos Gulf (White bars indicate the period when the river water does not reach the gulf).

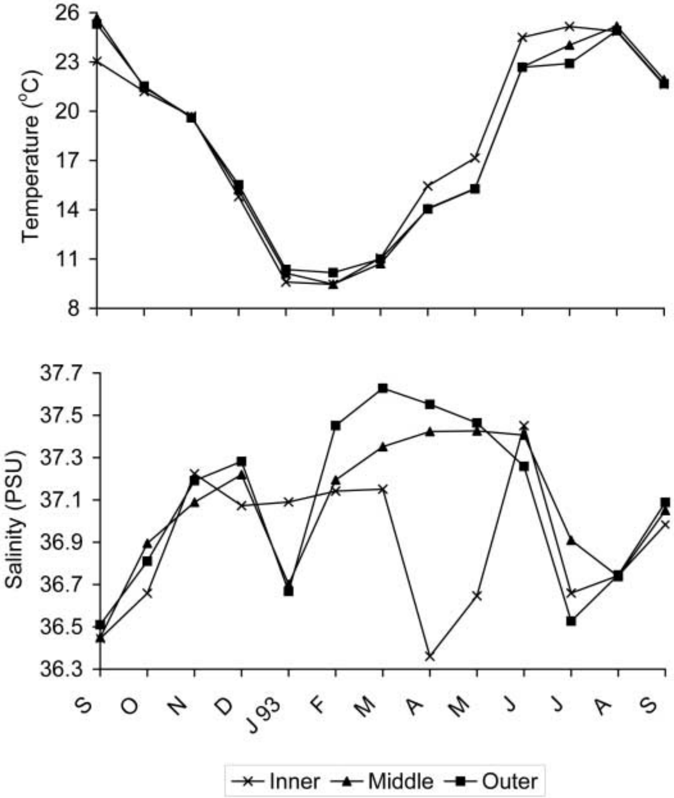

Fig. 5: Depth integrated temperature and salinity in the Maliakos Gulf.

in the summer months (25.7 °C). There was no obvious thermocline at any time and in any part of the gulf. Depth integrated salinity (Fig. 5) varied between 36.7 and 37.6 psu, the lowest values obviously occurring at the surface, following the increased flow rate of Spercheios River; this trend was more apparent in the inner compartment of the gulf. Dissolved oxygen concentrations fluctuated seasonally (3.97 – 9.5 ml l^{-1}) but never dropped to limiting levels. The highest value (9.5 ml l^{-1}) was observed at the surface layer in the winter.

Phosphate concentrations (Fig. 3) were high only in the inner station during autumn (4.1 μM) whilst for the rest of the year they remained below 1 μM in all three stations. Nitrate (Fig. 3) fluctuated considerably having higher concentrations (maximum 0.97 μM) in the middle station for most of the year except for the summer months when it dropped close to analytical zero in all stations. Nitrite (Fig. 3) was also highest in the middle station for most of the year with its maximum concentration in May (0.38 μM). Silicate (Fig. 3) showed two periods of high concentrations in the sea (maximum values in the inner station: October, 22.8 μM and April, 19.6 μM) while in the first months of the winter and in the summer months it was close to analytical zero.

Chlorophyll *a* (Fig. 6) peaked in winter. The inner station had the highest values (0.3 – 4.9 μg l^{-1}) and the outer the lowest (0.05 – 2.5 μg l^{-1}).

SPM (Fig. 4) in the gulf showed a similar temporal and spatial pattern in all stations with maximum values (24,800 μg l^{-1}) in March. POC (Fig. 4) varied similarly in all stations with maximum values in October (411.7 μg l^{-1}). The % POC of SPM never exceeded 3% and was

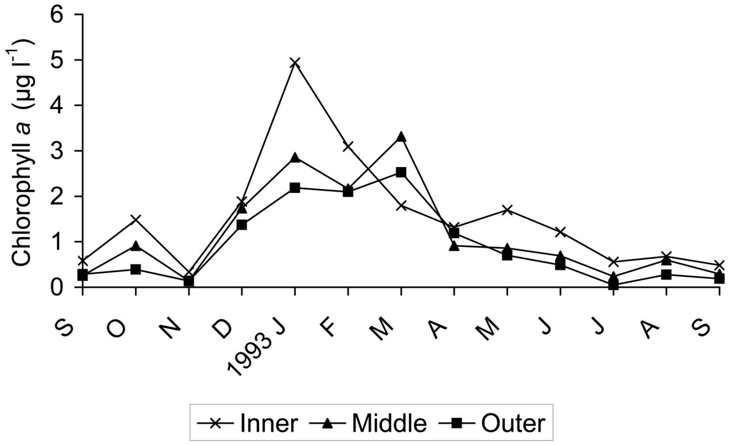

Fig. 6: Depth integrated chlorophyll *a* concentrations in the Maliakos Gulf.

independent of the SPM concentrations (r = -0.021, P = 0.832).

The POC: Chl *a* ratios (Fig. 7) showed the same temporal pattern in the three stations, with two peaks in November and July. The outer station had always the highest ratios (58-2,748) and the inner the lowest (42-994).

Discussion

Nutrient concentrations in Maliakos Gulf are higher than those of the oligotrophic offshore waters of the Aegean Sea (KARYDIS *et al.*, 1987, STERGIOU *et al.*, 1997) but similar with other Eastern Mediterranean coastal embayments (e.g. POLAT, 2002). The mean annual concentration of phosphate and nitrate fall within the limits given by IGNATIADES *et al.*, (1992) for mesotrophic areas. Nutrient concentrations in the Spercheios River are higher than those in the gulf (KORMAS, 1999). It is estimated that the volume of Maliakos gulf is ca. 500 x 10^6 m^3, while annual freshwater inflow from Spercheios is 176.6 x 10^6 m^3 amounting to about 1/3 of the gulf volume. With such contribution, the effect of the river would be expected to be obvious. Many authors (LEVEAU *et al.*, 1990; JORDAN *et al.*, 1991a; HAMA & HADA 1994; MALEJ *et al.*, 1995; SHIAH *et al.*, 1996) have found that even short-term nutrient inputs from rivers to coastal waters can cause the development of phytoplankton bloom.

The less profound than expected effect of the river could be attributed to several reasons. First of all, there is fast mixing of incoming water as indicated by the constant absence of thermocline and halocline and the weak spatial variations of DO and salinity observed in the gulf. DEL AMO *et al.*, (1997) also attributed the lack of significant DO variations, in a similar Atlantic system, to vertical mixing and water renewal while HOEKSTRA *et al.*, (1989) suggested that weak variation of salinity, which is the case for Maliakos Gulf also, is indicative of fast mixing of the inflowing water. CHRISTOU *et al.*, (1995) suggested that fast dispersion of the freshwater, is probably caused by the anticlockwise circulation in Maliakos Gulf. Fast mixing should be combined with rapid uptake of introduced nutrients by the phytoplankton, as chl a is the only parameter to show a decreasing gradient from the inner to the outer gulf. Furthermore, in the inner gulf, the phytoplankton bloom starts and finishes earlier. EYRE & BALLS (1999) also related the inorganic nutrient uptake by phytoplankton during the bloom period in a coastal area to the non-conservative mixing of the riverine discharge. Nutrient benthic fluxes

(LIBES, 1993) could also contribute to the increased chl a in the shallower inner compartment. In Maliakos, the situation is further complicated by the input of temporal streams and surface run-off at its periphery, especially in the periods of higher precipitation (late autumn/winter and early spring) and snow melting (late spring). Not only their flow but also their contribution of nutrients is erratic, depending on the agricultural practices in the area. It is believed that these non-point sources, contribute smaller amounts of freshwater compared with the river, but higher in nutrients (phosphate and nitrate) washed from the adjacent agricultural areas. Nevertheless, the lack of correlation between discharge rates and seawater nutrient concentrations could be also related to the present sampling scheme, which might not be adequate to monitor immediate changes, especially the responses of the phytoplankton to river input; this could be more intense in sudden and often unpredictable changes in discharge rates. More frequent sampling, on a weekly time scale (JORDAN *et al.*, 1991b), might clarify this issue. The role of such episodic events, which may have been missed on a monthly sampling, is often very important to the annual picture of phytoplankton production (e.g. YIN *et al.*, 1997).

From the data presented in this paper, the river discharge of SPM can be estimated to 33 x 10^5 kg yr^{-1}. Only 0.60 % (0.2 x 10^5 kg yr^{-1}) of this is POC, which is quite low compared to the average value of 4-5 % given for rivers (CADÉE, 1984 and references therein). It is actually at the lower range of POC% (0.5 to 5.0%) given for most world rivers (LUDWIG & PROBST 1996). FERRETTI *et al.* (1989), studying the transport of terrigenous particulate material in the Tyrrhenian Sea, found that during winter the inorganic component predominates making up to 80 - 90 % of the total suspended material in the sea, while in summer it remains below 40% due to the low mineral load of land drainage and to the high primary production in the adjacent coastal waters, which increases the organic fraction of SPM. Owens *et al.* (1997) who also found a relationship of high % POC at low SPM concentrations suggested that, at low SPM loadings, POC contents are high since a greater proportion of the material will be of biogenic origin, especially during summer. In Maliakos Gulf high primary production occurs in the winter-early spring as indicated by the chl a concentrations. Also, KORMAS *et al.* (1997) reported that during summer both phytoplankton and zooplankton show low abundance and biomass. The maximum concentration of SPM, in the gulf in the early spring, could be attributed partly to the inorganic input by the river and partly to the phytoplankton bloom. Thus, the peak of SPM in the gulf does not coincide with the minimum of POC. On the contrary, a small summer increase of POC corresponds to an increase in SPM. At the same time there is an increase in the ratio of POC to chl a indicating that the POC is not of photosynthetic origin.

In conclusion, the Spercheios River provides nutrients to the gulf, which are taken up fast by phytoplankton. It is also a source of SPM although at the time of bloom the contribution of phytoplankton cells to the SPM of the bay is important. Fast mixing and input by temporal streams and non point sources prevent a gradient being formed. It is suggested, however, that in other years the contribution of the river in nutrients and SPM may be more profound than shown by the present investigation. The year of sampling (1992-93) was characterised by low rainfall. According to historical data from the National Meteorological Service, from 1985 till 1991 maximum rainfall in the area ranged from 100 to 200 mm while during this study it did not exceed 72.3 mm.

A better insight into the effect of river on the Maliakos gulf and the functioning of the water column ecosystem would be gained by the study of aspects of physical oceanography such as currents, water residence time in the gulf and exchange with the Aegean Sea and the adjacent N. Evoikos Gulf. The contribution of benthic fluxes to and from the water column needs also to be investigated.

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