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A synoptic study on the phosphate and phytoplankton relationship in the hypereutrophicated Izmir bay (Aegean Sea)

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Abstract

Eutrophication has become an important environmental problem in coastal waters and its effects have increased due to the inflow of organic compounds and nutrients as well as the alterations in nutrient ratios. Besides the impact of streams, Izmir Bay, particularly the inner part of the bay, receives mainly continuous domestic and industrial inputs of phosphate. Occasionally, these inputs can reach extreme levels. Consequently, continuous phosphorus enrichment has been occurring. Nevertheless, the fate of phosphate, its effect on the phytoplankton biomass and the species dominancy in this biomass are poorly known. The seasonal patterns of phosphate, chlorophyll-a and abundance distributions of phytoplankton were determined in Izmir Bay between 1993 and 1994 in order to document the relationship between phosphate and phytoplankton.

In spring, the increase in phytoplankton abundance associated with the phosphate decline suggested that the phosphorus uptake by phytoplankton was a major process responsible for the phosphate removal. It seemed that the bulk of inorganic phosphate in summer, i.e., June 94, results from the resuspended anthropogenic sediment load in the water column in the inner part of the bay, which is a semi-enclosed coastal basin. Owing to inadequate light conditions caused by high turbidity in this basin, it was assumed that the high amount of phosphate could not be recycled, but rather transported to the middle part of the bay where it enhanced the formation of phytoplankton bloom.

Key Words: phosphate, phytoplankton, eutrophication, Izmir Bay, PCA (Principal Component Analysis).

Aşırı Ötrofikasyona Maruz Kalan İzmir Körfezi'nde Fosfat ve Fitoplankton İlişkisi Üzerine Sinoptik İnceleme

Özet

Ötrofikasyon kıyı sularında önemli bir çevresel problem oluşturmaktadır. Organik madde ve besin tuzu girdilerindeki artış, besin tuzu oranlarındaki değişimler, ötrofikasyonun etkilerini arttırmaktadır. İzmir Körfezi'ne, özellikle iç kesimine, nehirlerin etkilerinin yanısıra fosfatça zengin arıtılmamış evsel ve endüstriyel atık sular da taşınmaktadır. Bu girdiler bazen aşırı seviyelere ulaşabilmektedir. Sonuç olarak, İzmir Körfezi'nde aşırı fosfat zenginleşmesi oluşmaktadır. Bununla birlikte, fosfat döngüsünün gidişat özellikleri ve bunun fitoplankton biyokütlesi üzerindeki etkileri ve bu biyokütledeki baskın türler üzerine elde edilen bilgiler sınırlı kalmıştır. 1993-1994 yılları arasında yapılmış olan bu çalışmada, fosfat, Chl-a ve fitoplankton bolluk dağılımı mevsimsel olarak izlenerek ve fosfat ve fitoplankton ilişkisinin görüntülenmesi amaçlanmıştır.

Bahar mevsiminde, fosfatın azalışına karşılık fitoplankton miktarındaki artış, fosfat'ın fitoplankton tarafından kullanımının önemini göstermektedir. Haziran 1994 örneklemesinde, yarı-kapalı kıyısal basen olan körfezin iç kesimindeki aşırı fosfatın, antropojenik sedimanın tekrar su kolonunda asılı hale gelmesi ile suya nüfus ettiği düşünülmektedir. Körfezin iç kesiminde yoğun bulanıklıktan kaynaklanan yetersiz ışık şartları nedeniyle, yüksek miktarda fosfatın biyolojik döngüye tekrar tamamen katılamayarak, önemli bir kısmının körfezin orta kesimine taşınması sonucunda, bu kesimde görülen fitoplankton patlamasına pozitif etki sağladığı düşünülmektedir.

Anahtar Sözcükler: fosfat, fitoplankton, ötrofikasyon, İzmir Körfezi, temel bileşen analizi

Introduction

In the marine research and management communities, there is a need for a clear operational definition of the term eutrophication. Nixon (1995) proposed the following: Eutrophication, as a process, is an increase in the rate of supply of organic matter to an ecosystem. Although various factors and/or mechanisms may increase the rate of organic matter supply to coastal systems, the most common is clearly nutrient enrichment.

Semi-enclosed coastal systems, such as estuaries, bays and fjords, have generally been regarded as one of the most productive aquatic systems in which nutrient supply is an important factor in sustaining the higher rates of primary production. Thus, there are important scientific and economic reasons to quantify nutrient supply and its recycling in these productive aquatic systems. These processes support directly the primary producers, i.e., the rate of nutrient supply determines the maximum phytoplankton biomass, its growth rate, and hence the primary productivity, and also determines indirectly the yield of secondary producers, i.e., herbivorous zooplankton, in these systems. Nevertheless, excessive nutrient loading into these systems, which results in eutrophication, is a major environmental problem with highly significant and serious negative economic impacts, particularly in terms of losses in exploitable resources.

In this study, the seasonal fluctuations of dissolved inorganic phosphate (DIP), chlorophyll-a (Chl-a) and phytoplankton abundance with respect to eutrophication in Izmir Bay were investigated. A description of the interrelated dynamics of phytoplankton biomass and DIP during spring bloom was obtained. Finally, the bloom period, the peaking period of pollutant loads and ceasing period in winter when relatively stagnant conditions prevail were compared on the basis of the dynamics described.

It is hoped that the results obtained may produce some useful outcomes which will also encourage the managerial decision makers in their efforts to control phosphorus loads discharged into the bay.

Description of Izmir Bay

Izmir Bay is one of the largest embayments along the eastern coast of the Aegean Sea. It can be divided into three parts according to oceanographic characteristics, which are referred to hereafter as: inner, middle and outer parts of Izmir Bay (Figure 1). In addition to the untreated domestic wastes originating from the increasing population (currently exceeding 3 million), the substantial industrial growth, the heavy maritime traffic and the intensive agricultural activities in the surrounding areas have exerted considerable pollution loads on the inner and middle parts of the bay, particularly the inner part. Thus, the inner part of the bay, which has a depth less than 15 m, is heavily polluted. The inner part and the moderately polluted middle part are together about 24 km long and about 6 km wide. The relatively unpolluted outer part of the bay is about 45 km long. At the junction to the Aegean Sea, the water depth exceeds 72 m (Aksu et al., 1998).

The wastes to which the bay is exposed are composed of 105,000 m^3/day of industrial discharges, and 308,000 m^3/day of sewage. These wastes are dumped directly into the inner part via 128 canals and 10 streams, without any treatment (UNEP, 1994). The Gediz River, which flows through agricultural areas by collecting irrigation and precipitation drainages and reaches the bay at the northeastern coast, is the major freshwater input. Apart from the Gediz River, there are many small tributaries that flow directly into the bay. However, the amounts of pollutants discharged by the Gediz River are significantly higher than the total amounts discharged by these tributaries (O.D.T.U., 1994).

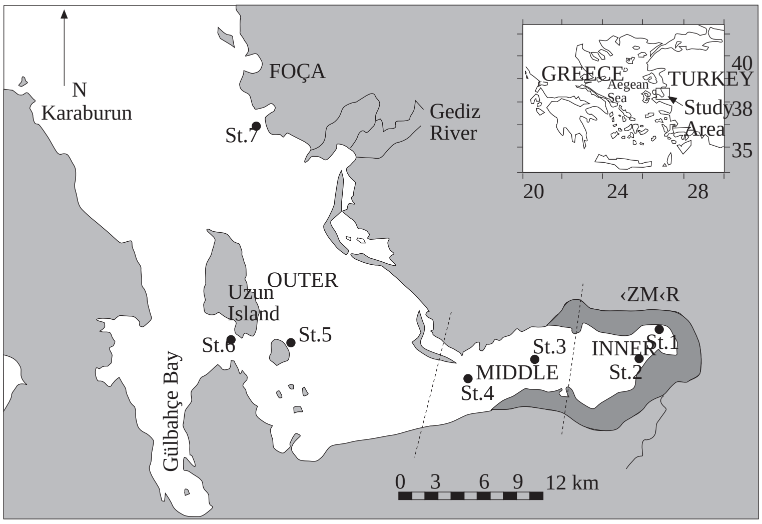

Figure 1. Locations of sampling stations in Izmir Bay.

When the overall nutrient data are considered, it should be emphasized that highly significant nutrient enrichments, i.e., particularly phosphate and ammonium, have been observed especially in the inner part of the bay during the last two decades (Bizsel and Uslu, 2000). The human activities mentioned above, over the past 50 years have greatly affected the nutrient transport and recycling mechanisms in the bay. The DIP reached about 50 μM in this study, whereas it was measured in the ranges of 0.00-0.02 μM during 1974-1975 (Geldiay et al., 1975), 0.05-1.9 μM during 1977-1979 (Kocatas et al., 1980), 0.76-1.96 μM during 1983-1985 (Büyükışık, 1986) and 0.21-2.51 μM during 1990-1992 (Balcı et al., 1995), as also shown in Table 1. In the same table, it is striking to see how the turbidity, in terms of decreasing secchi-disc depth and its range, has also gradually increased since 1977.

Table 1. The range of some variables measured since 1974 in the inner bay.

	SAMPLING PERIOD			
	1974-75	1977-79	1983-1985	1993-1994
Phosphate (μM)	0.0-0.02	0.05-1.9	0.76-1.96	0.36-49
DO (ml/l)	3.61-5.73	0.49-6.23	2.24-5.95	0.00-11.42
TSS (mg/l)	NM	4-100	5-50	4-348
Secchi-disc depth (cm)	NM	54-265	121-357	30-190
*NM: No measurement.				

To able to comprehend the general patterns in the dynamics of water masses better, 2-D and 3-D mathematical models have been developed for the bay (Karahan, 1988; Uslu, 1990; Saner, 1994). Their results have shown that the bay has significantly higher water exchange potential than the previous estimations. Furthermore, these results have produced reasonable explanations of how the extremely heavy pollutant loads received by the inner part of bay have been diluted by being transferred towards the Aegean Sea through the path over the middle part and the outer part. However, the dilution ability of the water mass circulation in the bay has steadily been weakened by the continuously increasing loads and shallowing effects of high sedimentation caused by the increased concentration of suspended particle matter.

Materials and methods

The water samples were collected seasonally during 1993-1994 from the surface (about 0.3m depth) and bottom (about 1m above the bottom) at 7 stations throughout the inner (Stations 1 and 2), middle (Stations 3 and 4) and outer (Stations 5, 6 and 7) parts of Izmir Bay (Figure 1). The location of each sampling station was selected by considering the general hydrodynamic characteristics of the bay. The water samples were kept in polyethylene bottles that had been soaked in 4M HCl and rinsed 6 times with distilled water prior to sampling. The sample bottles were filled after they were rinsed with the sample water collected from the corresponded sampling depth.

In situ of temperature and salinity were measured by using YSI model 33 S-C-T meter, and pH with a Hanna Instrument (HI8314). Discrete water samples were obtained by a research boat, Fırtına, which is an 8 m wooden skiff. Dissolved Oxygen (DO) was determined using the Winkler method.

After filtering the relevant water samples through a GF/C filter (Whatman, about 1μm), the spectrophotometric analysis for measuring the concentration of dissolved inorganic phosphorus (DIP) was based on the methods of Murphy and Riley (1962). The water samples for Chl-a and POC, again after being filtered through a GF/C filter (Whatman, about 1 μm), were preserved and analysed according to the method given by Strickland and Parsons (1972). The analysis of ammonia was based on the method of Reusch et al. (1977), while silicate was by Koroleff (1983 a) and the reactive and total iron were by Koroleff (1983 b). Phytoplankton were preserved in 4% buffered and filtered formalin solution. The phytoplankton cell numbers were then estimated on the basis of microscopic counts replicated 5 times, obtained from a representative volume of subsamples.

In this study, one of the multivariate statistical methods, principal component analysis (PCA), was also used (Rohlf, 1992; Manly, 1994) in order to explain which parameter(s) is/are the main source(s) of the variations among the defined parts of the bay.

Results and Discussion

Before starting the discussion in detail on the spatio-temporal variations in the DIP, phytoplankton and Chl-a during the sampling period of 1993-1994, it is necessary to give the annual ranges and means of selected oceanographic parameters at 7 selected stations during the study period in Izmir Bay (Table 2).

The average salinity of surface layer in the bay varies seasonally between 37.02 ‰ (in January) and 39.16‰ (in October). It may decrease to 18-20‰ in winter because of increasing precipitation and decreasing evaporation. The freshwater input decreases drastically during the summer and early autumn due to the typical Mediterranean climate while the evaporation through the sea surface reaches its maximum. The average temperature of the surface reaches its minimum, 11.2°C, in December and its maximum, 28.3°C, in July. The vertical distribution of temperature is homogeneous during winter and early spring, whereas a thermocline is formed in summer as the surface layers warm up. Later in autumn, the thermocline begins to disappear as the surface layers cool down and a homogeneous vertical temperature profile is thus re-formed (Uslu, 1994).

It has been claimed by various researchers that when the N:P ratio decreases below 4.5:1, N appears to be the limiting factor for algal growth in the lagoon of Venice (Sfriso et al., 1988) and in different Italian coastal waters (Chiaudani et al., 1983). Low N:P ratios for the bay, i.e., 0.3:1 for the inner part and 4:1 for the outer part, were found. These observations together with anoxia indicated that N, as an apparent limiting factor for algal growth and DIP concentration in the water column, is an indicator of eutrophication in Izmir Bay (Bizsel & Uslu, 2000). Due to anoxic conditions in the deep water and thus in bottom sediments, and the dredging activities for deepening and high anthropogenic pollutant loads, the DIP concentrations in the inner part of the bay are quite high, and this also affects the middle part of the bay (Table 3). When the DIP maxima measured in some similar systems such as urbanized estuaries, bays and harbours are compared, it is clearly seen that the DIP maxima measured in all three parts of the bay should be considered fairly high (Table 3).

Relative to a healthy bay ecosystem, which is unexposed to significant pollutant loads, hypoxia has been observed throughout the bay while anoxia is not very occasional in the inner part of the bay (Büyükışık, 1986; Bizsel, 1996). The resuspension of anoxic sediments in the inner part of the bay is an important positive feedback source of DIP in the water column. During the study, oxygen concentrations less than 0.70 ml/l were recorded in the inner part (Table 2). One of the important reasons for this event is likely to be the co-occurence of stagnant physical conditions and a drastic increase in the level of eutrophication in the area during warmer periods of the year. The DO concentrations in the bottom waters of the inner part (6m depth) were below 0.48 ml/l in April 1993, which corresponds to approximately less than 4% of the oxygen saturation level and they were below the detection limits, i.e., 0.01-0.02 ml/l, in November 93 and June 94. In contrast, the extremely dense bloom of a diatom species, *Skeletonema costatum*, Greville, caused an extraordinarily pronounced supersaturation of the DO concentration in the surface layer of Station 1, by producing the saturation level of 215% or 11.42 ml/l at 18.5 °C and 35.3 ‰ salinity, in April 94 (Figure 2). Because the exchange rate between atmosphere and sea considerably declines, the enhancing role of the simultaneous occurrences of stagnant physical conditions is also a critical factor in the existence of this extraordinary supersaturation of DO. *Skeletonema costatum*'s peak cell densities of more than 56×10^6 cells/l is clear evidence of how eutrophication affects the species composition of the phytoplankton. At heavily polluted Station 1, the diatom population was monotonously composed of this species, and together with some other species, the dominancy of diatoms was observed throughout the bay, excluding Station 6, during April 94 (Figure 2). In January 94, another diatom species, Thallassiosira sp. with less abundance was dominant monotonously throughout the bay, again excluding Station 6 (Figure 2). The dominancy of dinoflagellates was only observed with the species belonging to the class Euglenophycea during the peak periods of pollutant loads (Figure 3), i.e., November 93, at Station 1 and June 94 throughout the bay.

Table 2. Annual ranges and means of selected oceanographic parameters at seven stations in Izmir Bay, between May 1993 and July 1994. Values are the mean of 24 of 40 discrete samples taken at each station's water column (Bizsel, 1996). Mean values are indicated in bold. Data are shown for the locations in the inner bay (Stations 1 and 2), the middle bay (Stations 3 and 4) and the outer bay (Stations 5, 6, and 7). (BDL-Below detection limit).

Parameters	Station 1	Station 2	Station 3	Station 4	Station 5	Station 6	Station 7
Temperature(°C)	13.3-28.3	13.0-27.6	11.5-25.7	12.5-25.5	14.2-25.8	14.4-25.7	14.2-24.0
	19.9	19.2	18.2	20	19.5	19	18.3
Salinity	34.7-38.0	33.0-38.1	34.2-38.5	37.3-39.6	38.0-39.8	38.0-39.3	36.0-38.8
	36.34	36.02	36.94	38.19	38.62	38.56	37.99
pH	7.66-8.95	7.70-8.35	7.73-8.45	7.74-8.39	8.06-8.39	7.98-8.43	8.15-8.45
	8.05	8.11	8.2	8.11	8.25	8.23	8.3
TSS (mg/l)	5.75-348	4.00-64	3.2-56	1.70-24	0.20-17	0.17-24	0.49-15
	33.62	21.65	15.4	9.34	4.93	5.44	6.41
Secchi depth (cm)	30-100	100-190	110-300	100-300	650-1150	650-1600	650-800
	57	133	179	193	833	983	725
DO (μM)	BDL-1020	60-650	130-790	170-840	170-660	200-750	90-730
	144	302	364	412	398	429	346
PO_4^{-3} (μM)	0.94-49	0.36-5.43	0.18-3.79	0.06-1.72	BDL-1.08	BDL-0.87	BDL-6.42
	6.94	2.53	1.19	0.56	0.29	0.28	0.45
Chl-a** (μg/l)	BDL-189	1.13-58	0.50-62	0.80-13	BDL-2.95	BDL-1.48	BDL-1.79
	24.61	17.51	11.01	4.46	0.71	0.66	0.64
Phytoplankton **(cell/l)	25100-56.800.000	2400-1.350.000	1275-2.900.000	225-150.000	498-45.000	102-430.000	1574-320.000
	3.230.000	310.000	552.000	12.630	8850	260.300	84.000

*BDL: Below detection limit. Mean values are indicated in bold. ** Data from Metin, 1995.

Chl-a concentrations showed considerable variations throughout the bay (Table 4). During the spring bloom, the total biomass composed of diatoms and dinoflagellates (about 57×10^6 cells/l) and Chl-a (140μg/l) increased while the DIP concentrations decreased to 0.36-0.94 μM in the inner part of the bay (Table 2). During the study period, the maxima of Chl-a in the inner and middle parts of the bay reflect the eutrophic character of the system (Table 4), when compared with the values obtained during the peak production period of an oligotrophic coastal ecosystem which has a maximum around 3

μg/l (Gilabert et al., 1990). Another observation that supports the above-mentioned argument on the eutrophic character of the system is the occurrences of non-exhausted DIP pool in the inner part of the bay and of the limiting concentrations of DIP in the outer part (Table 2).

Table 3. The maximum values of DIP measured in Izmir Bay and in some other pristine and urban estuaries, bay and harbour in tropical and temperate climates. The average values are written in parentheses.

		The maximum DIP value (μM)	
Delaware Estuary (Lebo, 1991)		5	
Itchen Estuary (Ormaza-Gonzales, 1991)		55	
Beaulieu Estuary (Ormaza-Gonzales, 1991)		(0.10)	
Thames Estuary (Ormaza-Gonzales, 1991)		44	
Humber Estuary (Ormaza-Gonzales, 1991)		0.90	
San Francisco Bay (Conomos, 1979)		40	
Charlotte Harbour (Froelich, 1985)		90 (phosphate strip mining and processing plants)	
IZMIR BAY (Present study)	INNER	49	(4.84)
	MIDDLE	19	(1.19)
	OUTER	6	(0.34)

In the middle part of the bay, November 93 and June 94 were observed to be the blooming periods of diatoms and Euglenaphyceae, respectively. During the dominancy of the species of Euglenophyceae in June 94, relatively higher DIP concentrations were observed throughout the bay. The simultaneous increase in DIP and phytoplankton biomass can be explained by both the mixotrophic feature of Euglenophyceae and the occurrence of dredging activitiy in the inner part of the bay. Furthermore, the increase in Chl-a concentration in July 94, in spite of the simultaneous decrease in phytoplankton population, supports the occurrence of grazing activities, i.e., by taking into consideration the Chl-a content of the phytoplankton ingested by zooplankton (Bizsel, 1996). Due probably to this mixotrophic character of Euglenophyceae or due to other grazing activities, the DIP may be kept at higher levels in the water column in June and July 94.

When assuming the inner part of the bay, particularly at Station 1, is a pollutant source for Izmir Bay due to the higher water exchange rate estimated by Uslu (1994), particularly in autumn and in summer, i.e., November 93 and June 94, respectively, the extremely high concentrations of DIP, ammonium, total and reactive iron (Figure 4) should be transferred to the middle part of the bay where the POC (16.19 mg/l) and silicate (33.63 μM) also reached extremely high values in June 94 (Figure 4). In the same figure, it is clearly seen that the inputs of DIP to the inner part of the bay increased by factors of approximately 7 and 10 in November 93 and June 94, respectively (Bizsel, 1996). The extreme increases in the parameters mentioned above have been attributed to the dredging activities carried out by the harbour authority in the vicinity of Station 1 in the inner part of the bay.

Table 4. The maximum values of chl-a (μg/l) in the three sections of the bay.

	INNER	MIDDLE	OUTER
WINTER	11.59 (Surface)	13.11 (Surface)	1.61 (2 m)
SPRING	140.26 (2 m)	10.42 (2 m)	2.95 (Deep)
SUMMER	59.80 (5 m)	41.74 (2 m)	1.55 (Surface)
AUTUMN	7.21 (2 m)	18.83 (Surface)	1.00 (Surface)

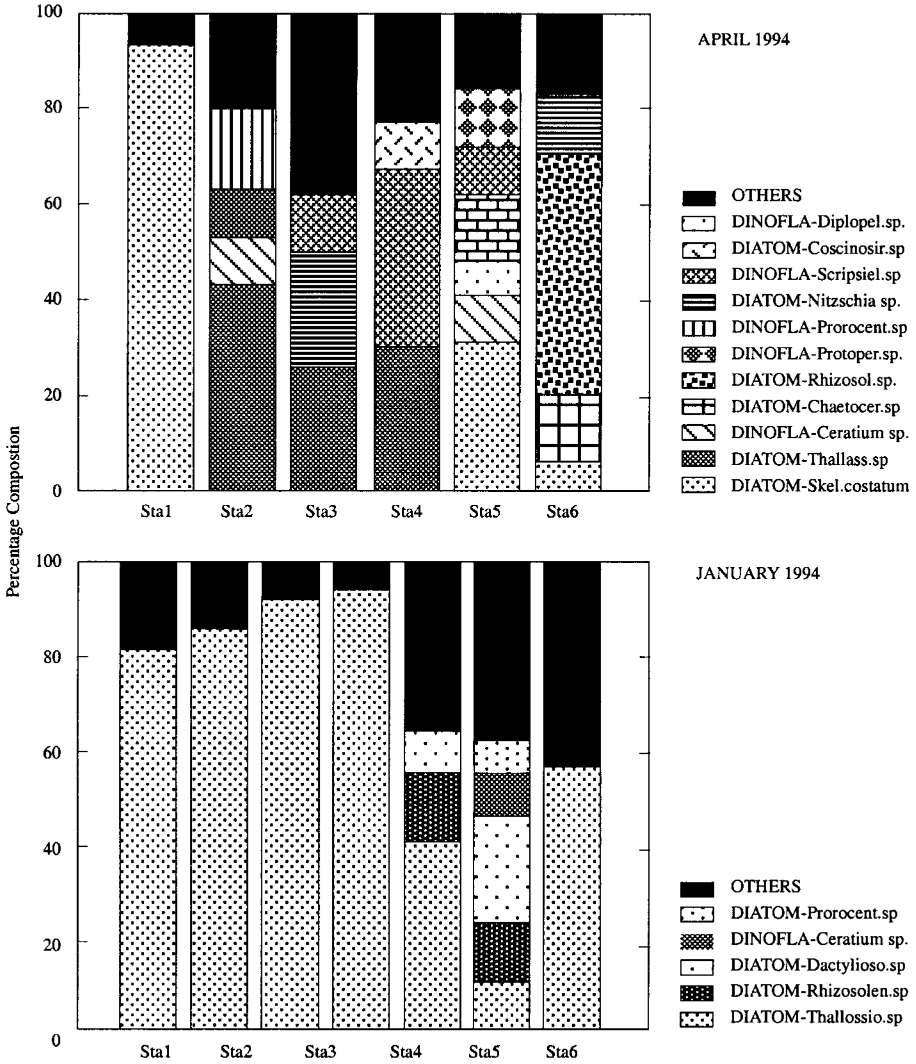

Figure 2. The distribution of phytoplankton species in April 1994 and January 1994 in Izmir Bay.

PCA showed that about 35% of the variation in the data was related to reactive iron; phosphorus forms excluding DOP, i.e., DIP, TDP and TP; and ammonium, as expressed in the components of the first axis (Z1) while about 14% is related to Chl-a, phytoplankton cell numbers, DOP, DO and pH, as the components of the second axis (Z2). The variables considered the components of the first and second axes are shown below:

$$\begin{aligned} Z1 = & - 0.12(\text{Chl-a}) - 0.09(\text{Cell}) - \mathbf{0.37(Ammonium)} - 0.17(\text{Nitrite}) \\ & + 0.03(\text{Nitrate}) - \mathbf{0.38(DIP)} - 0.22\ (\text{Si}) - \mathbf{0.30(Fe)} - 0.27(\text{TPP}) \\ & - 0.10(\text{DOP}) - \mathbf{0.40(TDP)} - \mathbf{0.41(TP)} + 0.19(\text{DO}) - 0.24(\text{TSS}) \\ & - 0.05(\text{Temp}) - 0.09(\text{pH}) \\ Z2 = & \ \mathbf{0.39(Chl\text{-}a)} + \mathbf{0.43(Cell)} - 0.16(\text{Ammonium}) + 0.12(\text{Nitrite}) \\ & - 0.15(\text{Nitrate}) - 0.11(\text{DIP}) + 0.09(\text{Si}) - 0.06(\text{Fe}) - 0.18(\text{TPP}) \\ & + \mathbf{0.41(DOP)} + 0.01(\text{TDP}) + 0.03(\text{TP}) + \mathbf{0.34(DO)} + 0.05(\text{TSS}) \\ & + 0.20(\text{Temp}) + \mathbf{0.46\ (pH)} \end{aligned}$$

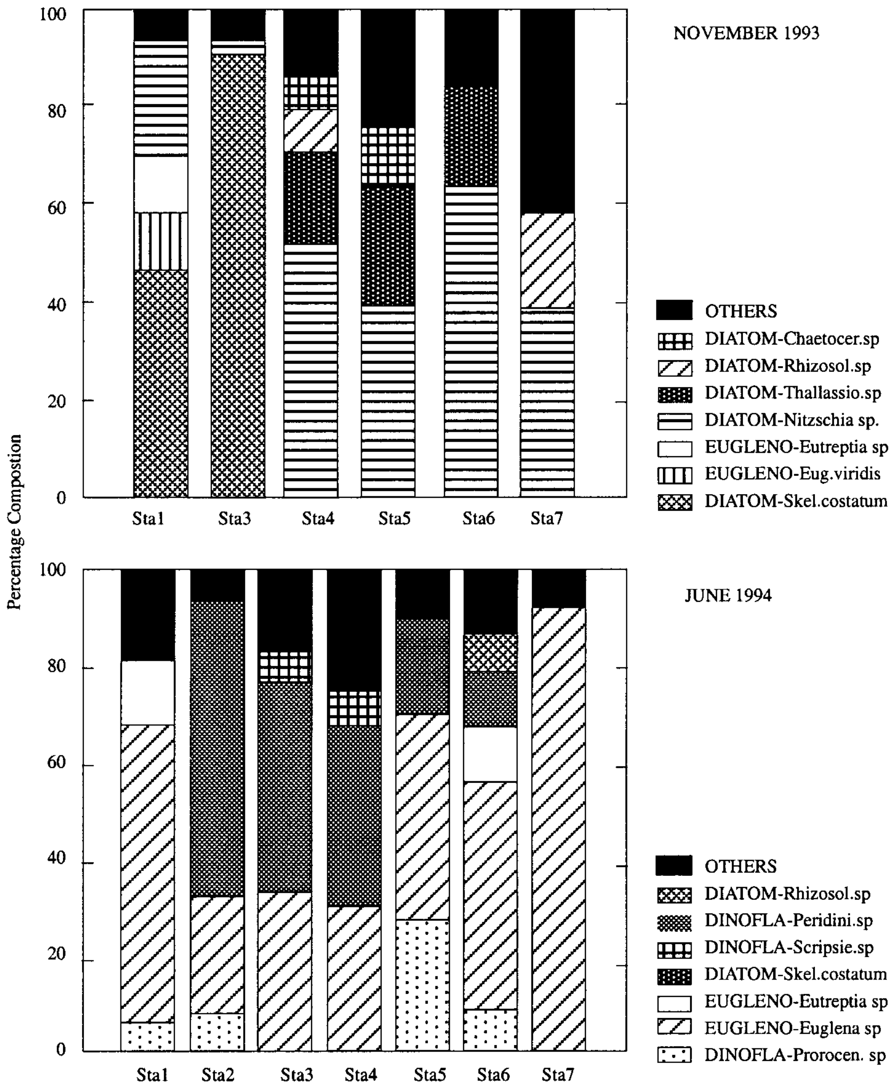

Figure 3. The distribution of phytoplankton species in November 1993 and June 1994 in Izmir Bay.

From these two equations, it is clearly seen that the variations are mainly caused by phytoplankton and the nutrient parameters including iron while the other parameters such as temperature, TSS, pH and DO caused less or no effects at all. By considering the variations of pH and DO, which are interacting parameters, and the limiting levels of nitrogen compounds affected by the levels of phytoplankton production, it may be said that eutrophication in the bay is primarily controlled by phosphorus compounds.

The plots of Z1 versus Z2 values are shown in Figure 5 by tagging each plot so that they represent their location, namely, sections of the bay, inner, middle and outer. The distributions of plots showed the expected situation clearly. The middle bay shows similar characteristics sometimes to the inner and sometimes to the outer bay. So the middle bay can be defined as the transition zone between the heavily polluted and relatively unpolluted sections. The same figure also shows that the condition in the middle bay may sometimes be as critical as that of the inner bay. The other remarkable point is the relative accumulation of the less scattered outer bay's plots in the rightmost part of the figure, which means relatively less variation and more stability, whilst totally opposite conditions were observed for the inner bay.

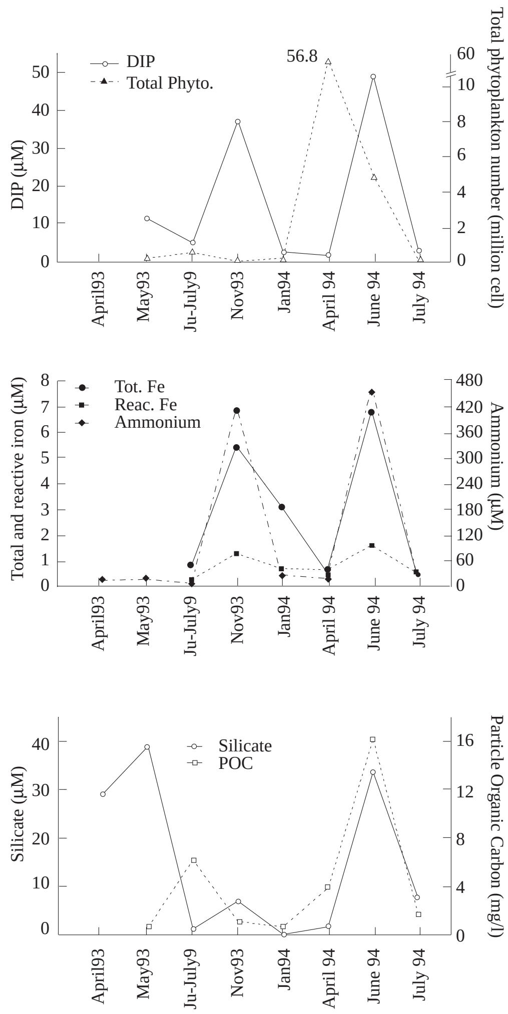

Figure 4. The distribution of phosphate, total phytoplankton number, ammonium, total and reactive iron, silicate and POC at Sta 1 surface waters.

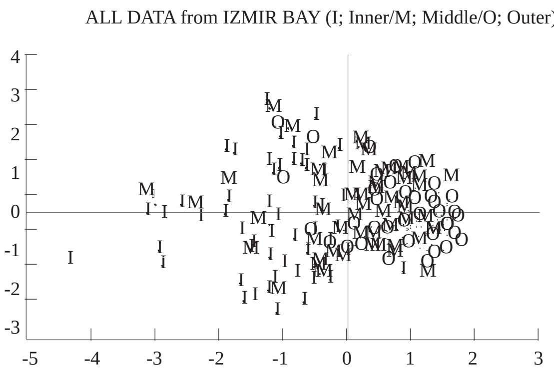

Figure 5. Plot of samples taken throughout the bay during the survey against values for first two principal components; Z_1 and Z_2 for ecological variables.

Conclusion

Owing to inadequate light conditions in the inner part of the bay, it is likely that the high amount of DIP cannot be utilized or produced by the mineralization of an increasing load of particulate organic matter entering Izmir Bay at a very high rate. Whatever the actual reason, it is obvious that the DIP is transported to the middle part of the bay, and thereby enhances the bloom (Table 2; at Station 3).

It seems that the fate of DIP in the bay is determined by the phytoplankton blooms as well as by the physico-chemical processes. The differences in species dominancy and composition appeared to be an important factor for controlling the distribution of DIP in the euphotic layers throughout the bay. The physiological state of phytoplankton is as important as its abundance. In general, the harmony between phytoplankton blooms and DIP concentration was found in the euphotic zone. Nevertheless, the following points should be focused on for understanding the specific interactions of phytoplankton species with DIP and for obtaining more specific and concrete results:

- the effects of different algae species, i.e., species-dependent DIP uptake rates
- the effects of light, DO, temperature and water movement
- effects of biotic factors, i.e., grazing and bacterial activity

on the distribution of phosphorus fractions.

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