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Eutrophication of the Izmit Bay, Marmara Sea*

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The elongated Bay of Izmit is one of the most heavily polluted semienclosed basins in Turkey. From systematic data obtained during field studies between 1984 and 1988, it is clear that two distinct water masses are present throughout the year. The brackish water which originated in the Black Sea forms a 10 to 15 m thick surface layer. Its salinity and temperature vary from 22–24 ppt and 20–24 °C in summer, to 26 ppt and 7 °C, in winter. Marine water, which arrived from the Mediterranean, underlies the permanent pycnocline and has much more stable properties: salinity and temperature ranges are 37.5–38.5 ppt and 14–15 °C, respectively.

Since the phytoplankton production is limited to the upper layer, including the halocline, nutrients have low surface concentrations in productive seasons and a higher concentration in winter. There is a sharp concentration increase in the halocline to high, almost constant, value in the lower layer. Phytoplankton biomass, in terms of chlorophyll-*a* concentration, has been found to be as large as 33 μg/L during spring in the more eutrophic inner part of the bay. In March 1988, the production reached the peak value of 3.3 g C/(m^2 day) with the mean annual rate of at least 2 to 4 times larger than in the Marmara and Black Seas. Dissolved oxygen concentration decreases in the halocline and varies seasonally be-

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* Dedicated to Marko Branica on the occasion of his 65th birthday.

tween 0.5–2.0 mL O_2/L in the subhalocline waters of the inner bay. Though phosphate and nitrate occasionally limit the phytoplankton production in the bay, reactive silicate is the major limiting nutrient due to large inputs of N and P relative to the silicate content. This finding suggests that the removal of phosphate should be significant before any decrease in phytoplankton production could be expected.

INTRODUCTION

Eutrophication that results from the inflow of nutrients discharged by land based sources has been a major problem in many coastal waters. The most conspicuous manifestations are the occurrence of algal blooms,[1,2] mucilage[3] and hypoxia in lower layers.[4,5] Practically the same discharges may affect the trophic state differently; this depends on coastal circulation and the existence of stratification.[6] Permanent stratification reduces horizontal advection in the lower layer.[7,8] In addition, it blocks vertical transport of oxygen to the bottom layer.[9]

Existence of large nutrient inputs from land-based sources discharging into the Izmit Bay is believed to be the major cause of eutrophication while permanent halocline that limits vertical mixing and induces a slow water exchange between segments of the bay and the adjacent Marmara Sea, are believed to be the major conditions favouring eutrophication.[10]

Although several studies have discussed treatment alternatives of waste effluents to the Izmit Bay,[10,11] very limited work has been published based on the results of systematic measurements of oceanographic characteristics and limiting nutrients.[12–14]

In this paper, selected results of examination of physical and biochemical data obtained from 31 stations during 32 cruises between 1984 and 1988 are presented together with the results of bioassay studies performed to determine nutrients that limit phytoplankton growth.

FIELD OF STUDY

The Izmit Bay is 45 km long (from the eastern boundary to Çatal Burnu), and varies in width from 1.8 to 9 km. It has an area of 261 km^2 (Figure 1). The bay may be divided into three subregions (western, central and eastern) connected to each other by two narrow openings. The central bay comprises the largest (154 km^2) and the deepest (205 m) part of the basin. The eastern part (37.5 km^2 and maximum depth of 37 m) is connected to the central part through the 1.8 km opening at Gölcük Burnu, while the

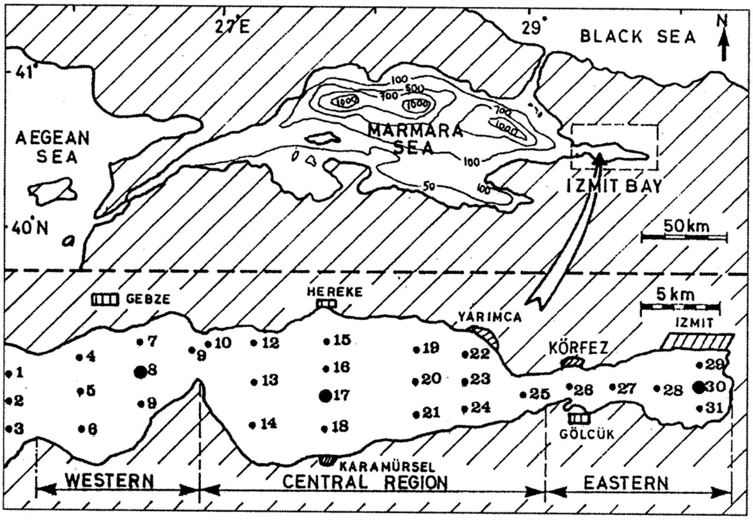

Figure 1. Location and geometry of the Marmara Sea and the Izmit Bay. Network of stations where vertical profiles of selected parameters have been measured and samples taken.

central part is connected to the outer, western part, through a 2.7 km opening at Dil Burnu.

In the area surrounding the bay, more than 250 large industrial plants have been built since 1965. Most of them discharge their liquid wastes into the bay after pretreatment. Population increase in the region causes an additional rise of untreated sewage discharges into the bay. In recent years, periodic red-tide events have been observed. In addition to land-based sources, special and hazardous wastes from increased ship traffic have most probably contributed to further deterioration of water quality.

The bay exchanges the water with the Marmara Sea which is itself stratified and receives water in the upper layer from the Black Sea through the Bosphorus strait. The water in the lower layer originates from the Mediterranean Sea.[15]

Easterly winds that originate from the Black Sea region dominate from August to October.[16] Their monthly mean is 3 m/s with a maximum daily speed of 7 m/s. From November to March, southerly winds often persist for several days with speeds up to 20 m/s and may produce storm waves and surges.

The average annual precipitation and evaporation are 700 mm and 600 mm, respectively.[17] Total riverine input from several creeks amounts to 15 m^3/s.

EXPERIMENTAL

In order to understand the spatial and temporal variations of the oceanographic parameters and nutrients, the station network, illustrated in Figure 1, was visited systematically by the R/V Arar of Istanbul University and by the R/V Bilim of the Middle East Technical University. Water samples were collected from standard depths by means of Nansen bottles. Either a SeaBird or an InterOcean probe was used to measure temperature, salinity and dissolved oxygen.

Samples for analysis of silicates were kept at 4 °C, whereas the other samples were frozen to –20 °C and stored for not longer than two weeks. Nutrients were analyzed using the Technicon Autoanalyzer II system and following the standard methods.[18,19] The nutrients analyzed were silicate, nitrate + nitrite, orthophosphate. Errors of analytical techniques were:

2.5 $\mu g(PO_4)/L$, 2 $\mu g\ (NO_3)/L$, 2 $\mu g(SiO_4)/L$, 0.1 μg (Chl-*a*)/L. The samples for bioassay studies of limiting nutrients were collected two meters below the sea surface at Stations 2, 8, 10, 17, 22, 23, 27 and 30. The samples for phytoplankton production were collected at depths where surface irradiance was reduced to 75 %, 25 %, 10 %, and 1 % at four stations. Samples were processed according to the procedure suggested by Gargas.[20] Prior to nutrient enrichment, subsamples were prefiltered through a 0.2 mm net. Then, they were incubated on a shaker at *in situ* temperature for 15 hours under continuous light of 500 µE. Subsequently, ^{14}C spiked aliquots were incubated for 2 hours and filtered through 0.2 µm membrane filters. The growth of phytoplankton was determined by the ^{14}C uptake rate using an HP 1550 liquid scintillation counter.

RESULTS AND DISCUSSION

To a large extent, oceanographic properties of the water in the bay follow the changes in the Marmara Sea. This means that they are influenced by the exchange between the Black Sea and Aegean Sea.

Figures 2, 3 and 4 show the vertical distribution of parameters in the western, central and eastern parts of the bay, respectively. Although, the data shown do not encompass all the variability that exists in oceanographic and eutrophication parameters, seasonal changes in the upper and lower layer are visible as well as the gradient from the western to the eastern part of the bay.

Surface temperature during summer ranges between 20 and 24 °C with the maximum in July. During winter, the minimum temperature of 7 °C is reached in January in the western part.

Surface salinity ranges between 21 ppt and 26 ppt with the maximum in January or February. The decrease of surface salinities starting from spring is caused by a larger brackish water inflow from the Black Sea through the Bosphorus. The arrival seems to be completed from May to July, depending on the intensity and time of snow-melting in the catchment area of the Danube river which enters the Black Sea. Although these seasonal

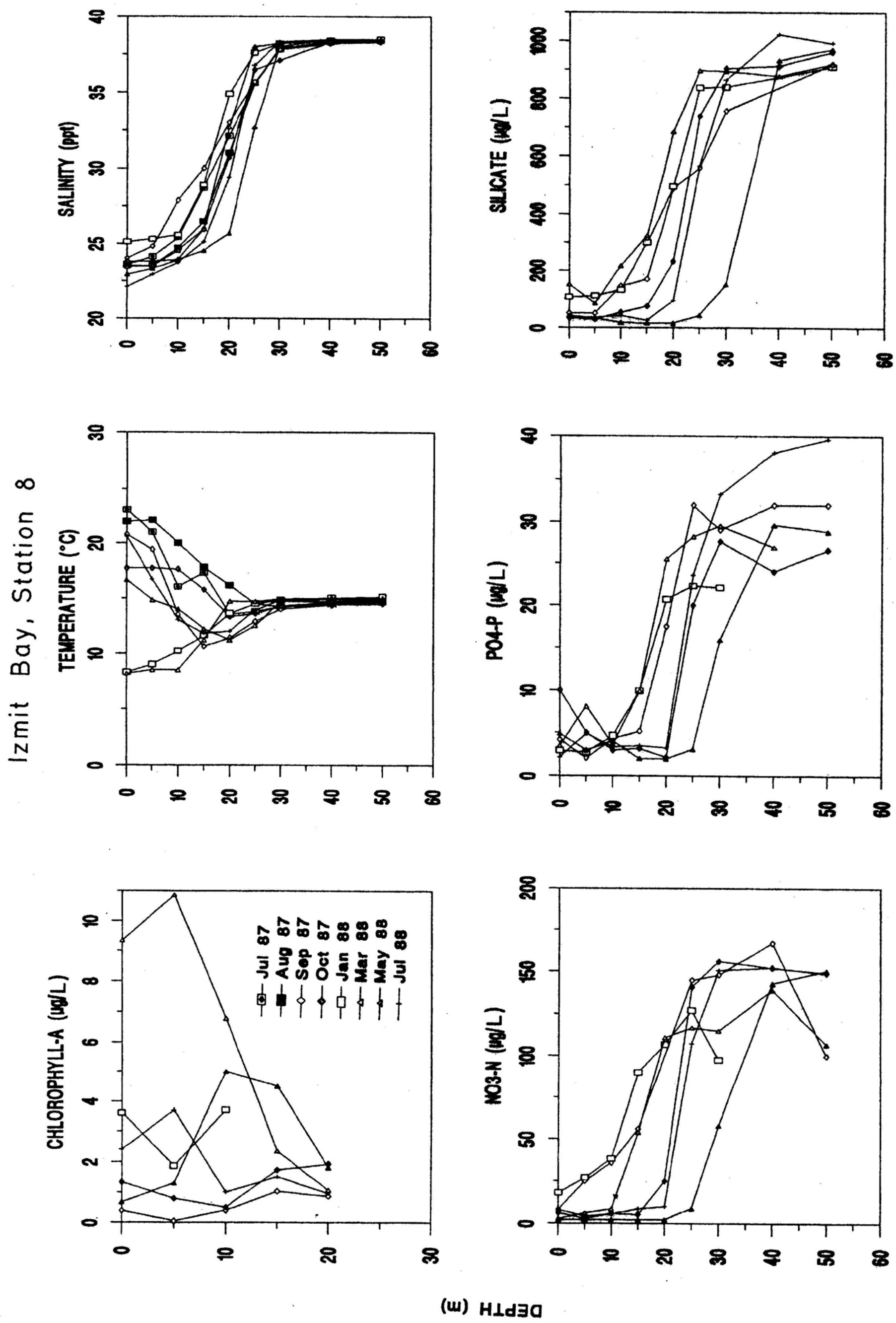

Figure 2. Vertical profiles of Chlorophyll-*a*, temperature, salinity, NO_3, PO_4 and SiO_2 at Station 8 in the western region of the Izmit Bay.

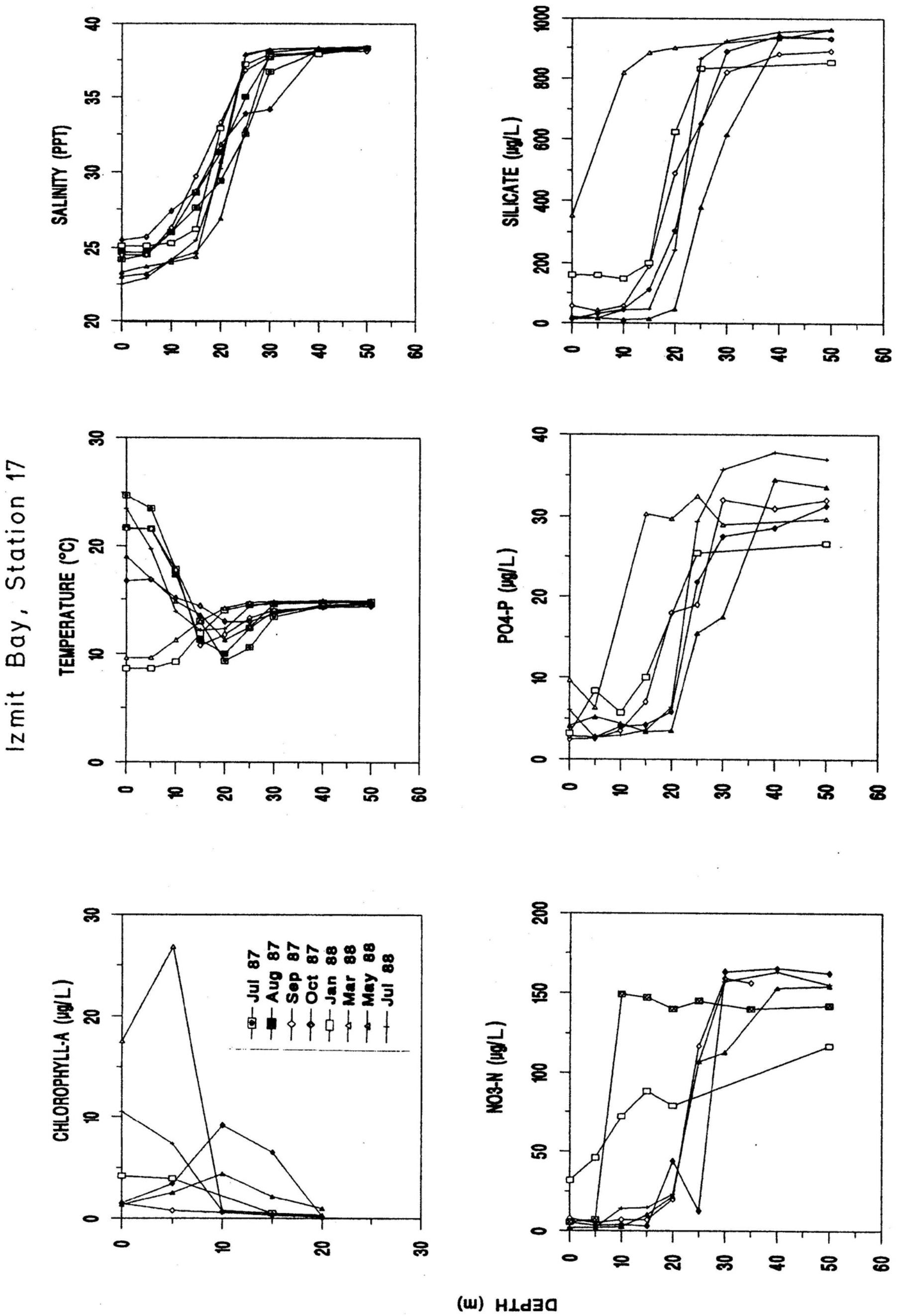

Figure 3. Vertical profiles of Chlorophyll-*a*, temperature, salinity, NO_3, PO_4 and SiO_2 at Station 17 in the central region of the Izmit Bay.

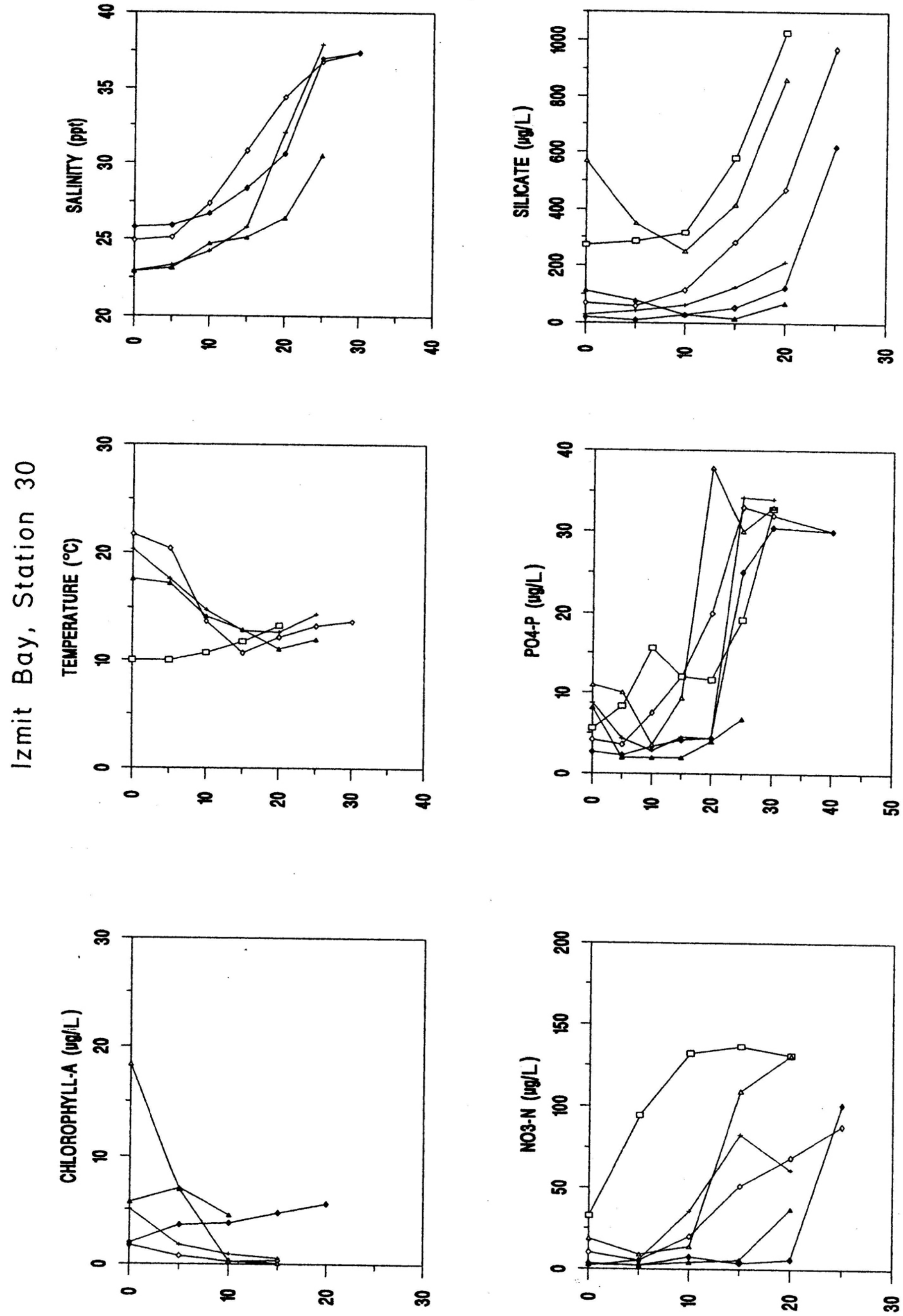

Figure 4. Vertical profiles of Chlorophyll-*a*, temperature, salinity, NO_3, PO_4 and SiO_2 at Station 30 in the eastern region of the Izmit Bay.

changes are felt throughout the upper layer of the Izmit Bay, a comparison of salinity in the upper layer along the longitudinal axis indicates an increase towards the eastern part of about 2 to 3 ppt. This means that there exist intermittent entrainment inflows from the lower layer, which contribute from 10% to 15% of the existing water.

The Mediterranean water in the bottom layer flows through the bay without much change and is characterized by approximately 37.5 to 38.5 ppt salinity and 14 to 15 °C temperature throughout the year.

Since the Sea of Marmara forms a transition between the Black Sea and the Aegean Sea, chemical and biological characteristics of the Izmit Bay are also significantly influenced by the two adjacent water masses. The permanent halocline which separates the water of the Black Sea origin from that of the Mediterranean origin plays an important role in both vertical and horizontal distribution of biochemical parameters within the Bay of Izmit.

In the upper layer, nutrient concentrations are relatively low and show seasonal fluctuations (Figures 2, 3 and 4). Concentration of ortho-phosphate in the surface water is from 2.0 to 8.0 μg/L in the productive spring and autumn periods. Enrichment during the winter vertical mixing and accompanying the low primary production in this season results in concentrations as high as 30 μg/L for nitrate, 12 μg/L for phosphate and 0.6 mg/L for silicate.

Along the longitudinal axis, on the average, nitrate, phosphate and silicate are all increasing from the western towards the eastern part. The gradients follow the ratio between lower and upper concentration so that the largest gradient is in the silicate and the smallest in ortho-phosphate concentration.

In deep waters of the bay, the dissolved N/P ratio in weight is always less than 5 (*versus* 7 in the Marmara Sea) while ortho-phosphate and nitrate + nitrite concentrations range between 25–40 μg/L and 90–150 μg/L, respectively. The highest nutrient concentration in the bottom waters was observed in the summer months following the productive spring season and sinking of phytoplankton to the lower layer. During winter months, concentrations of all three nutrients decrease due to the entrance of water from the Mediterranean and much smaller production and sinking of organic nutrients through the halocline.

The silicate distributions in the bay are generally consistent with the nitrate and ortho-phosphate variations. Low silicate concentrations in the surface layer (< 50 μg/L) from May to July indicate that diatoms dominate the primary production in the bay. This has been confirmed by recent observations in the Marmara Sea and Izmit Bay.[21] In the lower layer, the concentration increases steadily from spring to autumn and reaches a value of 1 mg/L due to a high input of silicate material from the surface through sinking of diatoms and slow water exchange with the Marmara Sea.

Horizontal distribution of chlorophyll-*a* demonstrates that phytoplankton biomass increases towards the eastern part of the bay. The highest chlorophyll-*a* concentration of 22 mg/m^3, was detected in March 1988 while the lowest value of 0.1 mg/m^3 was found in February 1987. However, even in January, chlorophyll-*a* values may be occasionally as high as the concentration in the productive months. Indeed, this has been observed after an entrainment event that was followed by a week of sunny and calm weather. Such high values are limited to the surface layer (from 0 to 5 m) due to the insufficient light intensity below that layer and are more likely to occur in the eastern part where the nutrient inflow rates are higher. From late summer to early autumn, photosynthetic production decreases significantly due to depletion of nutrients in the euphotic zone.

Dissolved oxygen (DO) concentration shows variations both in time and within the bay. DO content is near or exceeding the saturation level in the surface layer and exhibits a sharp decrease in the halocline (Figure 5). It reaches the minimum concentration (< 0.5 µg/L) immediately below the halocline, especially during summer periods, due to the large amounts of biodegradable organic substances sinking from the surface layer and a long residence time of bottom water. Consequently, the dissolved oxygen in the subhalocline waters of the eastern part decreases steadily from 2 to 2.5 mg/L, in the spring, to less than 0.5 mg/L by October. The lowest values of DO are found in the bottom layer of the eastern part.

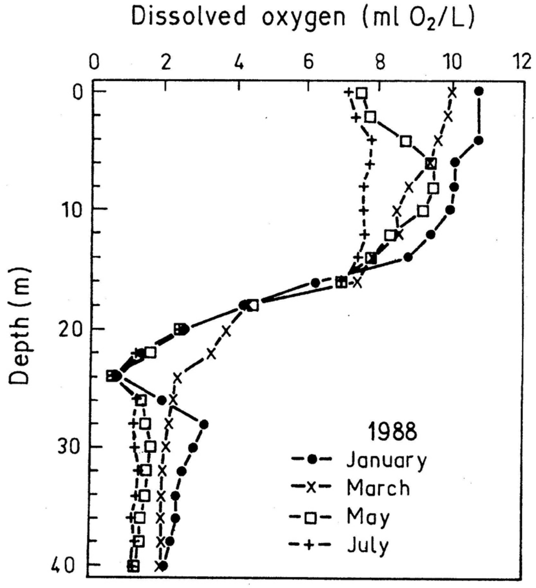

Figure 5. Vertical profiles of dissolved oxygen at station 17 during 1988.

Changes in environmental and hydrographic conditions determine the intensity of phytoplankton production in the bay. Nutrient inflow from land based sources and entrainment contribute to the increase of nutrient concentrations in the surface waters and thus late winter to early spring blooms occur both in the bay and in the Marmara Sea. However, these blooms are more intense in the Izmit bay. During summer, the phytoplankton production fluctuates more or less randomly, depending on the supply of nutrients from the lower layer, from the existing sources on the coast and from the zooplankton predation pressure.

Between 1987 and 1988, the annual primary production estimated from ^{14}C measurements was about 365 g C/m^2 in the central bay. This is about 2 times higher than the production in the western part (165 g C/m^2), Marmara and Black Seas. The largest production of 3327 mg/(m^2 day) was recorded in March 1988 at station 17. The production from this station was always higher than at the more polluted station 23, probably because of lower water transparency and inadequate physiological conditions for algal growth at the location where large quantities of toxic chemicals and suspended solids are discharged.[22] The lowest production rate occurred in the early autumn when the surface waters were depleted of nutrients and production values as low as 125 mg C/(m^2 day) were recorded in June 1987. at station 2. Because of the large particle discharge from land, the euphotic zone is limited from 10 to 25 m, depending on the location and season. However, the highest production rates were consistently observed in the water column that extends from the surface to 10% of the surface light intensity. From late summer to early autumn, this depth varies between 3 and 10 m. The smallest Secchi depths are found in the eastern part of the bay.

The relationship between the phytoplankton growth and nutrient concentration has been investigated to determine limiting nutrients. In comparison with the control, a positive response was measured in the ^{14}C uptake of natural assemblage of phytoplankton when phosphate was added to samples collected in July, August and September 1987. At station 2, the degree of limitation has a factor of 2.5 relative to the unenriched sample recorded in July and it declined to 2 in August. Responses of 0.5 and 1.7 were observed in July at stations 8 and 10, respectively. The highest uptake rates of 1.8 and 6 were found in September at stations 27 and 30, respectively. The nitrate spiked samples showed a 2-fold increase in the ^{14}C uptake rate relative to the unenriched control sample only during August at station 23. Enrichments with dissolved silicate demonstrated that it is the most important limiting nutrient for growth. The response of ^{14}C uptake changed significantly from a factor of 1 to 30 with respect to the unenriched control. The largest response to silicate enrichment appeared in samples from the eastern part of the bay. For example, at station 23, in August 1987, October 1987 and May 1988, the response of uptake increased by 2, 2.6 and 4, respectively. The enrichment of natural phytoplankton with both nitrogen and phosphorus resulted in a measurable increase in the ^{14}C uptake rate with respect to the enrichment with a single nutrient. The phenomenon has often been termed a synergistic effect. We propose a simpler explanation. Assume a population of phytoplankton cells that is in the Redfield ratio but where both nitrogen and phosphorus are low. Adding only phosphorus would not result in an increase of primary production because nitrogen is limiting. Likewise, adding nitrogen could not enhance primary production because phosphorus is limiting. When both nutrients are added, preferably in the Redfield ratio, the increase in primary production would be maximized.

CONCLUSIONS

The bay is occupied by two distinctly different water masses: the upper brackish water layer and the lower marine layer. Although the inner bay receives large quantities of waste waters enriched with nutrients, a small increase of inorganic nutrients in the surface waters is observed due to phytoplankton uptake. Chlorophyll-*a* concentration increases towards the eastern side of the bay. Nutrient concentrations and bioassay studies point to the phytoplankton limitation of growth by the following nutrients (in decreasing order of importance): silica, phosphorus and nitrogen. Due to the sinking and decomposition of large quantities of biogenic material through the halocline and slow exchange with the Marmara Sea, the lower layer in the eastern part is hypoxic throughout the year, but the least dissolved oxygen is found in the late summer.

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SAŽETAK

Eutrofikacija u zaljevu Izmit, Mramorno More

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Zaljev Izmit jedno je od najzagađenijih priobalnih područja u Turskoj. Iz terenskih podataka dobivenih od 1984. do 1988. g. vidi se da tijekom cijele godine u zaljevu postoje dvije vodene mase. Bočata voda koja potječe iz Crnog Mora zauzima površinski sloj od 10 do 15 m. Salinitet i temperatura variraju od 22 do 24‰ odnosno od 20 do 24 °C ljeti, te oko 26‰ odnosno i 7 °C zimi. Morska voda koja dolazi iz Sredozemnog mora, nalazi se ispod stalne piknokline. Njen salinitet je od 37,5 do 38,5‰, a temepratura od 14 do 15 °C.

Sadržaj hranjivih tvari nizak je u produktivnoj sezoni, a oko desetak puta viši zimi. Postoji naglo povećanje koncentracije u haloklini na visoku, gotovo konstantnu vrijednost u donjem sloju. Biomasa fitoplanktona (klorofil) dostiže vrijednost 33 μg/L tijekom proljeća u istočnom području zaljeva. U ožujku 1988, produkcija je dostigla vrijednost od 3,3 g C/(m^2 dan) a srednja godišnja produkcija je od 2 do 4 puta veća nego u Mramornom ili Crnom moru. Otopljeni kisik naglo pada ispod piknokline i u donjem sloju varira sezonski između 0,5 i 2 mg/L. Iako fosfat i nitrat ponekad ograničavaju rast fitoplanktona, silikat je glavna ograničavajuća hranjiva tvar. To se objašnjava velikim donosom fosfata i nitrata s obzirom na silikat. Slijedi da odstranjivanje fosfata iz otpadnih voda koje dolaze u more valja provesti temeljito prije no što se očekuje vidljivo smanjenje u produkciji fitoplanktona.