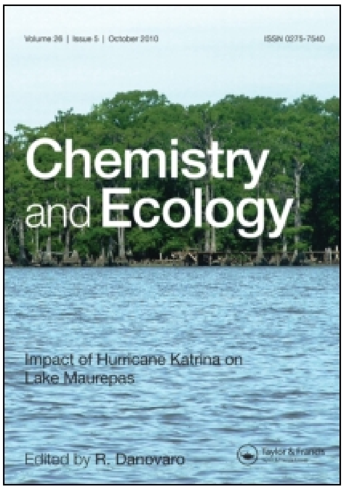

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Ante Barić[a]; Ivona Marasović[a]; Miroslav Gacčić[a]
[a] Institute of Oceanography and Fisheries, Yugoslavia

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EUTROPHICATION PHENOMENON WITH SPECIAL REFERENCE TO THE KAŠTELA BAY

ANTE BARIĆ, IVONA MARASOVIĆ and MIROSLAV GAČIĆ

Institute of Oceanography and Fisheries, Split, Yugoslavia

(2 May 1991)

The paper discusses the eutrophication phenomenon as a result of pollution from land-based sources with special reference to the experience gained in the Kaštela Bay Project.

The Bay of Kaštela is a semi-enclosed bay of a total volume of 1.4 km^3. It receives a great amount of untreated waste water, both domestic and industrial.

Results of the analyses of long-term data series of dissolved oxygen, nutrients, transparency and phytoplankton have shown a continuous increase of eutrophication in the Bay. While the concentration of oxygen in the euphotic layer increases due to a higher phytoplankton productivity, in the bottom layer it decreases as a result of the activity of heterotrophic bacteria. The nitrogen/phosphorus ratio in sea water has decreased, and today is much lower than in the open sea. From the Secchi-disc data it is clear that transparency has also decreased for the last three decades. Primary production as well as phytoplankton biomass has also increased. The structure of phytoplankton community has been changed and dinoflagellate species have become dominant rather than diatoms.

KEY WORDS: Eutrophication, nutrients, waste discharges, primary production, phytoplankton.

INTRODUCTION

In its most general sense, the term eutrophication is an increase of the trophic levels beyond the conditions previously existing in a given ecosystem, and results from an unusually high input of nutrients into the euphotic layer. This high input of nutrients may be due to natural processes (upwelling, inflow of unpolluted rivers) or to human activity. The former case is a natural phenomenon while the latter is anthropogenic eutrophication.

Natural eutrophication is basically a slow process (time scale of 10^3 to 10^4 years) allowing the ecosystem to adapt to changes.

As distinct from natural eutrophication, anthropogenic eutrophication (time scale of 10 or less years) causes much faster changes to which a particular ecosystem cannot adapt and this produces harmful effects.

The factors which affect eutrophication are numerous and interrelated, so that a change of a single factor can alter relationships in the entire ecosystem.

Since the main objective of the Kaštela Bay Project is to determine the bay's assimilative capacity for urban waste waters, most attention is directed to nutrients (input "load" and concentration in sea water) and to parameters which are most frequently used in studying the eutrophication process (oxygen content, transparency and phytoplankton).

CHARACTERISTICS OF THE KAŠTELA BAY

Kaštela Bay is a semi-enclosed bay with an inlet of relatively large cross-section (the

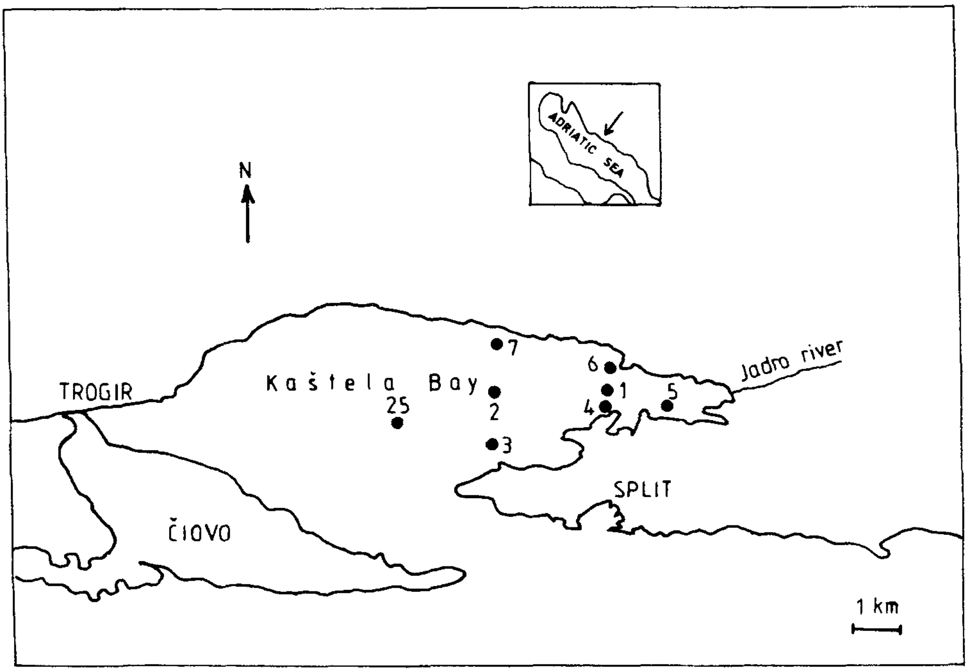

Figure 1 Map of the Kaštela Bay

deepest part of the bay is in the inlet itself – about 50 m deep) (Figure 1). The total volume of the Bay is 0.4 km^3 and the average depth is about 23 m. The shallowest parts of the Bay are the eastern and western corners. The main freshwater inflow is via the small river Jadro, with an average annual inflow of 10 m^{3}s^{-1}. The river mouth is located in the eastern part of the bay. In addition, several submarine springs contribute to the water budget of the Bay, even though to a smaller extent.

The narrow coastal strip of the Bay is a highly developed area with various uses (housing, industries, harbour, tourism, etc.). The towns of Split and Trogir, as well as several villages, are located there with more than 300,000 inhabitants. The population has increased sixfold over the last 45 years. Intensive industrialization and urbanization have not been followed by development of the necessary urban infrastructure. Thus, in practice, large quantities of urban and industrial waste waters are released untreated into the Bay.

The temporal distribution of temperature shows a cooling of the sea surface from November to March (Buljan and Zore-Armanda, 1979). The surface temperature is lower than that of the deeper layers during this period. The surface temperature is at a minimum in February and at a maximum in August. The water column is most homogeneous in March, and in April the developing thermocline can be observed. In October this usually disappears due to the vertical mixing generated by the wind.

Tidal current components are very weak since the tidal sea level amplitudes are only about half a meter.

The residual current field variations and the water exchange with the adjacent basin is mainly wind-driven (Gačić, 1980). According to some recent results (Gačić *et al.*, 1987), about 70% of the current field variance could be related to the local wind forcing. The rest could be attributed to the remote forcing through the Bay inlet. The average renewal time is about a month (Zore-Armanda, 1980) while in strong wind conditions it can be as short as five days. Since the wind field is highly variable, and during the cold part of the year related to the passage of mid-latitude cyclones, the current field displays variability on the weather time scale. These weather or synoptic time scales are typically from two to five days and therefore, in strong wind conditions, the entire bay volume can be renewed during a single weather cycle.

During the warmest part of the year (July through September) cyclones do not pass over the area and wind field variations are mainly generated by diurnal warming (sea breeze). Wind forcing is relatively weak and since also the freshwater inflow is low, the residual current field is very weak. Consequently, the renewal time is rather long.

Even in earlier times when the Bay was not so heavily polluted, it was a highly productive basin. Strong effluent discharges which have occurred in the area for several decades have brought great changes to the ecosystem of the Bay. Apart from toxic pollutants which have been released, the substantial loads of nutrients have significantly increased the productivity of the basin, resulting in changes in both abundance and diversity of phytoplankton and zooplankton species. As a result of these changes, some effects have been noted:

- red tide phenomena;
- temporary oxygen depletion in the bottom layer;
- local mass fish kills.

NUTRIENT INPUTS TO THE BAY

Atmospheric Input

The amount of phosphorus from the atmosphere is insignificant. Generally, its total input from the atmosphere has been assessed at somewhere between 1 and 2 percent of the total input to the ocean, or some 5 mg/y-m^2 (SCOPE, 1976). In coastal waters, particularly close to large industrial conglomerations, its input can be higher. Rain contains on the average 0.08 mgl^{-1} of phosphorus, which, considering the annual mean rainfall in this area of 837 mm (Institute of Oceanography and Fisheries, unpublished data) means that some 4 t of phosphorus from the atmosphere reach the Bay each year.

Atmospheric input of nitrogen compounds is more important, especially near large urban areas where nitrogen oxides in the air appear in greater concentrations. Likewise, in the proximity of agricultural land, ammonia content is greater due to the advection from highly fertilized areas. The average amount of nitrogen in rain water is estimated at 0.7 mg l^{-1}, and thus the annual input of various forms of nitrogen into the Kaštela Bay is about 36 t.

Input by River and Runoff

The annual mean nutrient input by the river Jadro has been estimated at 206 ty^{-1} of total phosphorus (Margeta *et al.*, 1990). The total nitrogen and phosphorus inputs in the runoff was estimated at 59 and 19.7 t/y^{-1}, respectively (Margeta *et al.*, 1990).

Municipal Waste Water

Apart from human faeces, municipal waste waters contain domestic and industrial wastes. The nutrient content in municipal wastes depends on the level of water treatment. The whole volume of municipal waste waters is released untreated to the Kaštela Bay. The two main sewerage systems are on the eastern side of the Split peninsula and they release some 6.4 × 10^6 m^3 per year of waste water (Štambuk – Giljanović *et al.*, 1987). A number of smaller outlets release additional 3.2 × 10^6 m^3 y^{-1} of municipal and industrial waste water in the Bay. The average composition of waste water discharged into the sea by two main sewerage systems is shown in the Table 1.

The annual total amount of nitrogen and phosphorus discharged into the sea in different forms by these two sewage systems is estimated at 160 t nitrogen and 31 t phosphorus. If it is assumed that the mean contents of the remaining waste water releases are equal to the mean contents of the two main waste water systems, then the total annual amount of nitrogen and phosphorus entering the Bay would be 240 t and 46 t, respectively.

Industrial Waste Water

Nutrients can be found also in the waste waters of some industries, such as food production. In the southeasternmost part of the bay a separate outlet discharges waste water from a brewery, a slaughterhouse and a dairy, containing considerable quantities of organic matter. The amount of industrial waste water and its quality is given in Table 2.

Table 1 The average composition of the waste water discharged at two main outlets

Parameter *Sewer*	*Lora*	*Duje*
Flow m^3y^{-1}	3.3 × 10^6	3.1 × 10^6
Suspended matter mgl^{-1}	71	39
N_{tot} mgl^{-1}	36.3	12.3
N-NH_4 mgl^{-1}	21	8.3
N-NO_2 mgl^{-1}	0.02	0.005
N-NO_3 mgl^{-1}	0.1	0.045
P_{-tot} mgl^{-1}	6	3.5

Table 2 Industrial waste waters discharged into the Kaštela Bay (Margeta *et al.*, 1990)

Parameter *Type of industry*	*Dairy*	*Brewery*	*Slaughter-house*	*Other*
Flow m^3y^{-1}	1.73×10^5	3.50×10^5	2.96×10^5	2.0×10^6
Suspended matter ty^{-1}	581	65	96	213
BOD ty^{-1}	470	461	209	422
N-$_{tot}$ ty^{-1}	10	20	4.3	18.5
P-$_{tot}$ ty^{-1}	1.1	2.8	3.5	2.7

Total Input of Nitrogen and Phosphorus

Annual total input of nitrogen and phosphorus from land-based sources to the Kaštela Bay is estimated at 593.6 t and 101.3 t, respectively. The proportion (%) of each of these sources is given in Figure 2. Urban waste waters and freshwater input from the Jadro River are the most important sources of freshwater runoff and also contribute significantly to the nutrient input to the Bay, especially for phosphorus.

EUTROPHICATION INDICATORS

The Oxygen Concentration in the Bay

Oxygen content has been monitored at the central sampling station of the Bay of Kaštela ever since 1953 (Buljan and Zore-Armanda, 1966). Annual mean values of oxygen concentration in the surface and bottom layers are shown in Figure 3. Up to the beginning of the 1970s, oxygen content was lower in the bottom than in the surface layers, normal for shallow oligotrophic seas. Since then, there has been a noticeable increase of oxygen content in the surface layer, and a slight decrease in the bottom layer. At the same time, an increase in primary production has been recorded.

Data on oxygen content in the eastern part of the Kaštela Bay, which receives most of the municipal and industrial waste discharges, as well as the waters of the river Jadro, fully confirm this. In this part of the Bay in the summer, the water is stagnant and water exchange is considerably less than in the Bay as a whole (Zore-Armanda) *et al.*, 1976). Oxygen content in the surface layers at the stations in the eastern part of the Bay, close to pollution sources, was much higher than the bottom layer concentrations (Figure 4).

During the "red tide" development in the eastern part of the Bay in 1980, values of oxygen content were very low, both in the bottom and surface layers (Marasović and Vukadin, 1982). A minimum value of 0.58 ml l^{-1} was recorded from the bottom layer.

Transparency

Sea water transparency, generally measured with the Secchi disc, is the indicator commonly used for the eutrophication process study. Specifically, light scattering by

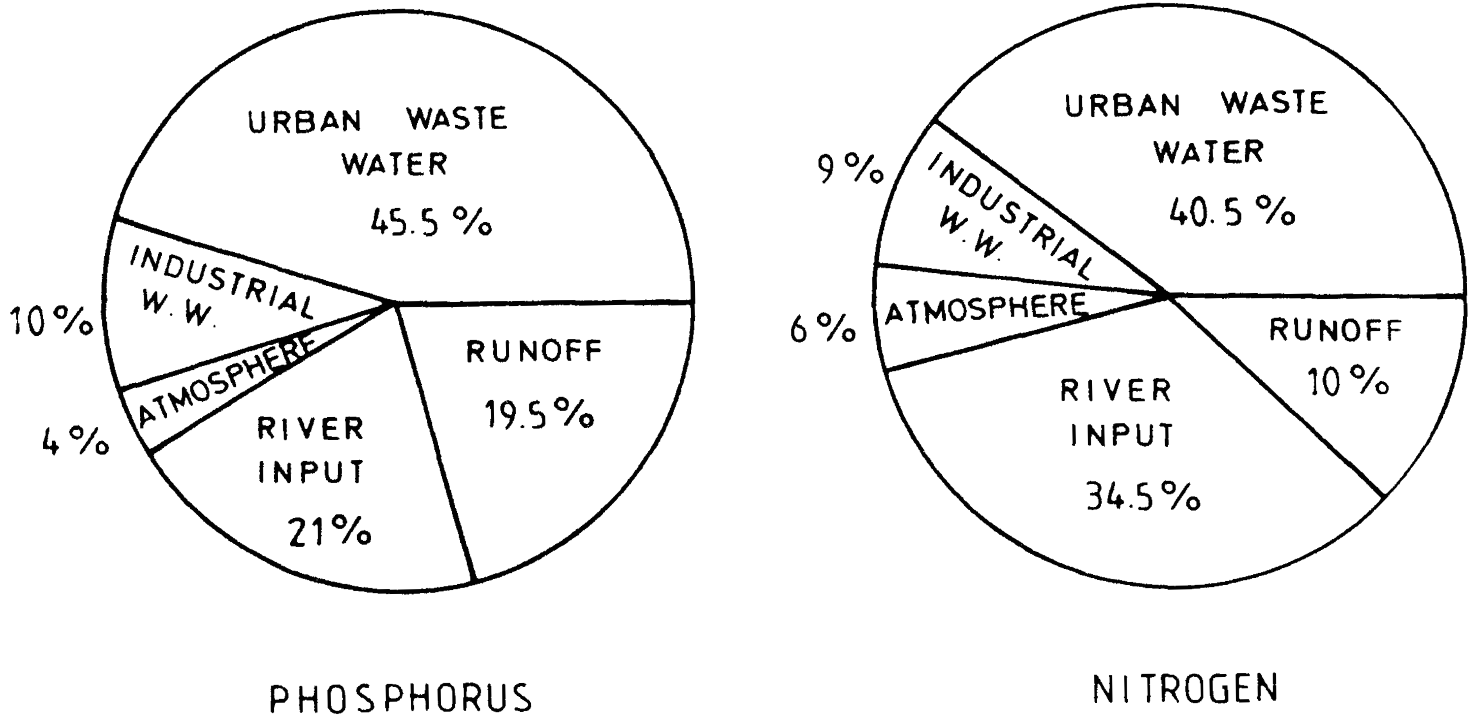

Figure 2 Main sources of nitrogen and phosphorus

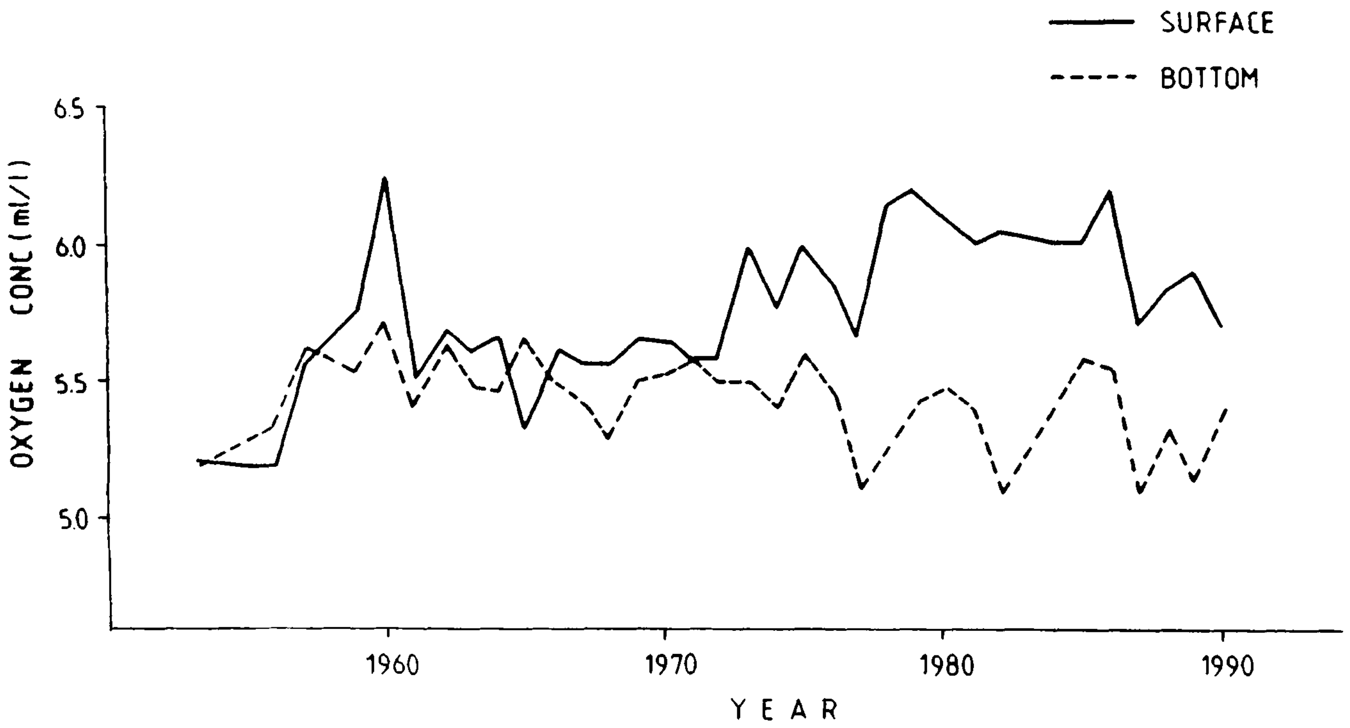

Figure 3 Average annual values of dissolved oxygen in the surface and bottom layer at the central sampling station in the Bay.

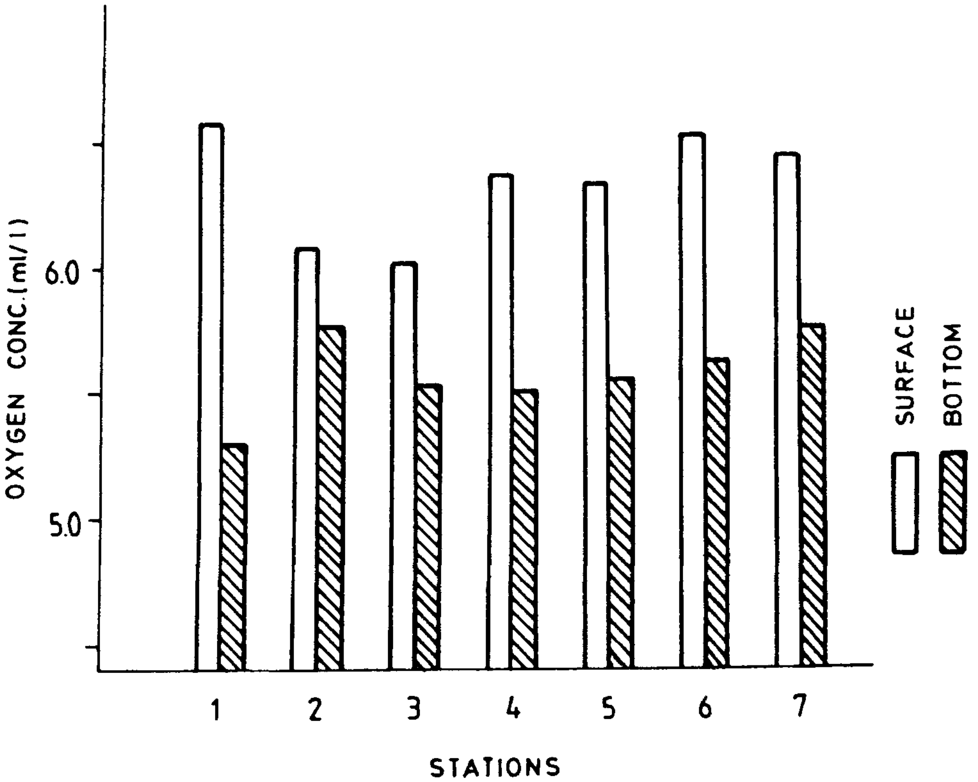

Figure 4 Average values of oxygen content in the surface and the bottom layer in the eastern part of the Bay.

plankton diminishes the depth of light penetration. The light penetration in deep layers is reduced with intensified eutrophication. However, reduced transparency can also be caused by the presence of suspended particles of abiotic origin. In coastal waters, this occurs frequently near river mouths, or after abundant rain when runoff carries large quantities of suspended matter to the sea.

Measurements of sea water transparency at the Kaštela Bay central station have been made since 1953 (Buljan and Zore-Armanda, 1966 and 1979). Annual mean values are shown in Figure 5. Individual Secchi disc values are highly variable as well as the derived annual means, especially in the first part of the measurement period. This variability can be explained as the impact of suspended matter reaching the sea in runoff and by the river Jadro. However, the available data show clearly a small but statistically significant decrease of transparency over a period of 37 years. This decrease in transparency is attributed to the growing eutrophication in the Kaštela Bay due to pollution.

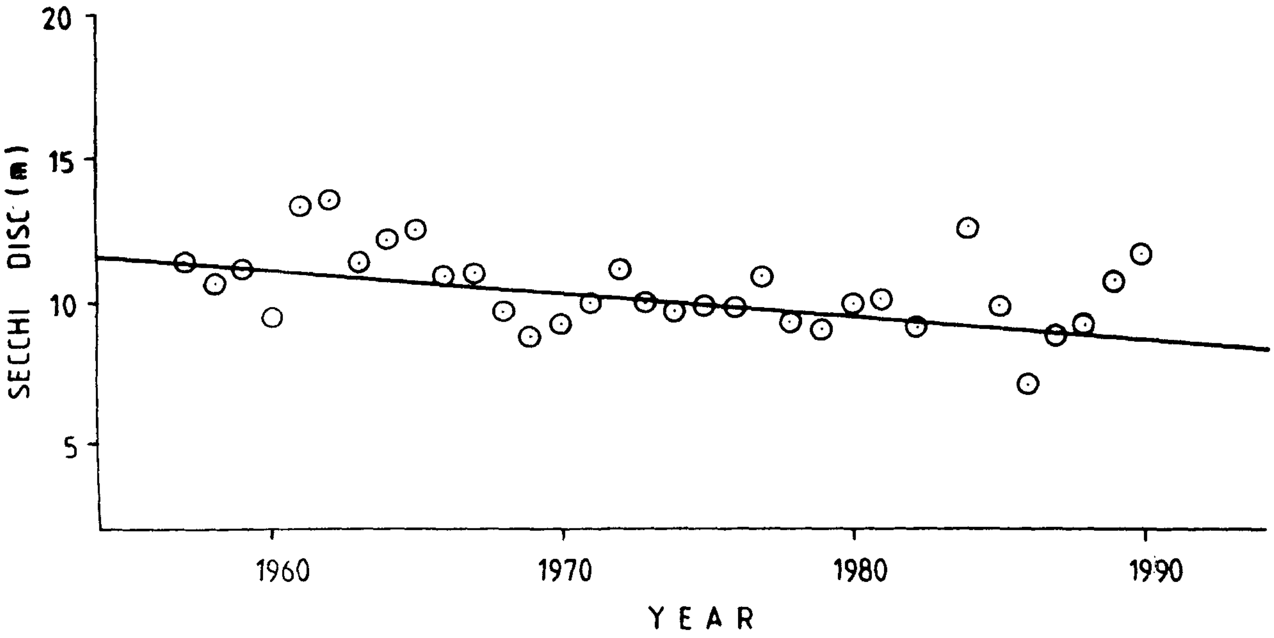

Figure 5 Average annual values of transparency (Secchi disc)

Nutrients

Although the stronger inflow of nutrients in a specific marine ecosystem is the cause of the eutrophication, levels of dissolved nutrients in sea water are generally not a reliable indicator of eutrophication, or of pollution. The measured concentrations of dissolved nutrients in sea water are the result of a series of physico-chemical and biological processes, which are interrelated and controlled by different factors. Changes occurring in these processes can significantly affect nutrient concentrations. Therefore, data on nutrient concentrations in the sea water are not necessarily a sufficient indication of eutrophication.

Nutrient contents in the Bay have been observed at the central station since 1971 and phosphate and total phosphorus since 1962 (Buljan and Zore-Armanda, 1966 and 1979). As shown by published data, the $P\text{-}PO_4$ concentration increased up to the beginning of the 1970s, followed by a gradual decrease, $N\text{-}NO_3$ and $N\text{-}NO_2$ concentrations were gradually falling over the whole period of measurement. Pucher-Petković and Marasović (1988) calculated the ratio of nitrogen to phosphorus, showing that this ratio has fallen, reaching a value of 23, still higher than the optimum value for the phytoplankton growth, but significantly below the value determined for the open middle Adriatic. The reduced ratio of nitrogen to phosphorus is in accordance with the observation that the Kaštela Bay receives large quantities of nutrients in which the nitrogen/phosphorus ratio is 6.

Data on mean nutrient concentrations in the surface and bottom layers at three stations in the eastern part of the Bay are shown in Figure 6. Nitrate content in the surface layer at all stations exceeds that in the bottom layer. This is also true for the ammonia content. Nitrite content at all stations is significantly higher in the bottom than in the surface layer. Phosphate concentrations at all stations, except station 5, are higher in the surface layer than in the bottom layer. These data confirm the well-known fact that in polluted coastal areas municipal waste waters are an important source of nitrates and phosphates, as these waste waters are discharged in large volume to the studied area. Lower surface salinities are consistent with this.

Apart from other nutrients, nitrites are produced in the sea water by bacterial decomposition of dead organisms at the sea bottom, leading to concentrations higher in the bottom layer from where they are transported to the upper layers by vertical mixing.

Phytoplankton

The first observations on the phytoplankton of the Kaštela Bay were made some fifty years ago (Ercegović, 1936, 1940). Systematic studies of phytoplankton, together with some other biotic and abiotic parameters, have been carried out ever since 1956. The last twenty years have shown some changes such as a gradual increase in primary production, phytoplankton density, timing of seasonal cycles, as well as changes in the taxonomic structure of the phytoplankton community. For the last ten years these changes have become more serious since red tides now occur every summer, accompanied by occasional kills of marine organisms.

The first sign of increased eutrophication in the Bay is manifest as an increase in primary production. For the period 1962–1967 primary production in the Bay was estimated to be 150 g C $m^{-2}y^{-1}$ (Pucher-Petković and Zore-Armanda, 1973), and for the following ten years as about 200 g C $m^{-2}y^{-1}$. An even higher level of primary production, 235 g C $m^{-2}y^{-1}$, has characterized the last decade (Figure 7) (Pucher-

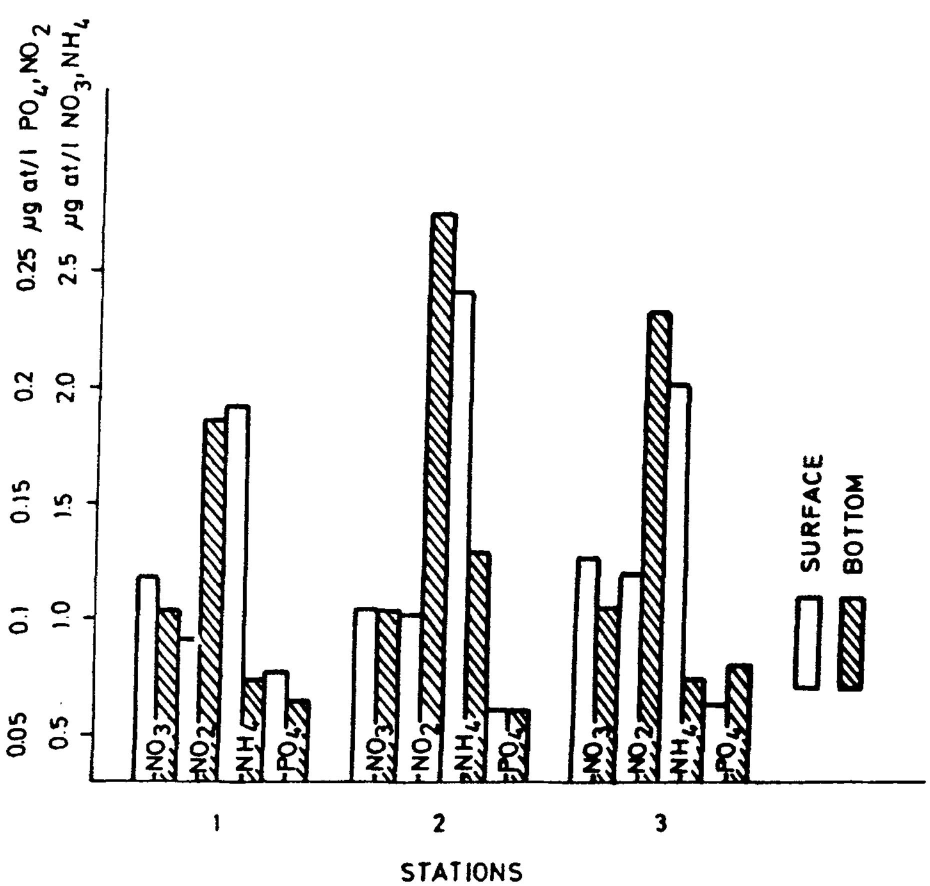

Figure 6 Nutrient concentrations in the surface and the bottom layer in the eastern part of the Bay.

Petković and Marasović, 1988). On the basis of these values the Bay may be placed in the fifth category of productivity according to the Koblentz – Mishke's (1970) classification of world seas.

The results of long-term studies on the phytoplankton biomass in the Bay have been available since 1977. They confirm the results on phytoplankton density as well as on primary production. Namely, the concentrations of chlorophyll α in biomass have shown an increase since 1977 (Figure 8).

The average value of the chlorophyll biomass during the long-term (1977–1990) is 1.11 mg Chl α m^{-3}. Even though a year to year decrease in chlorophyll biomass has been recorded, it should be emphasized that since 1983 the annual mean value has never dropped below the mean value of the 10-year interval. This could indicate that, in addition to natural factors, the long-term fluctuations of the phytoplankton biomass are a consequence of pollution of the Bay.

According to numerous indicators, including primary production assessment, the Kaštela Bay could be categorized as a highly eutrophic area. Chiaudani *et al.* (1982) suggested a classification on the basis of maximum surface concentrations of chlorophyll α. Kaštela Bay, with its maximum surface concentration of chlorophyll α (7.8 mg Chl α m^{-3}), may be categorized as eutrophic, while its eastern part, with

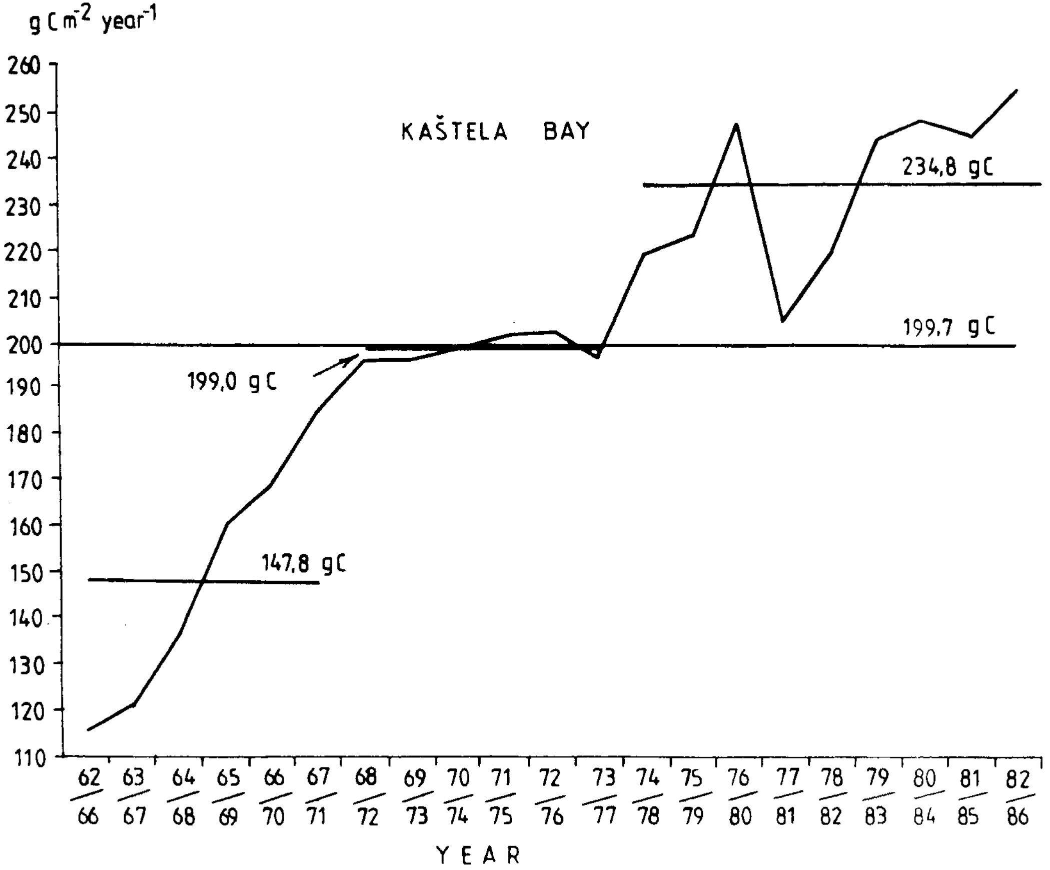

Figure 7 Fluctuations of the gross primary production in the Kaštela Bay over a period of twenty four years, presented through five-year running means (after Pucher-Petković and Marasović, 1988).

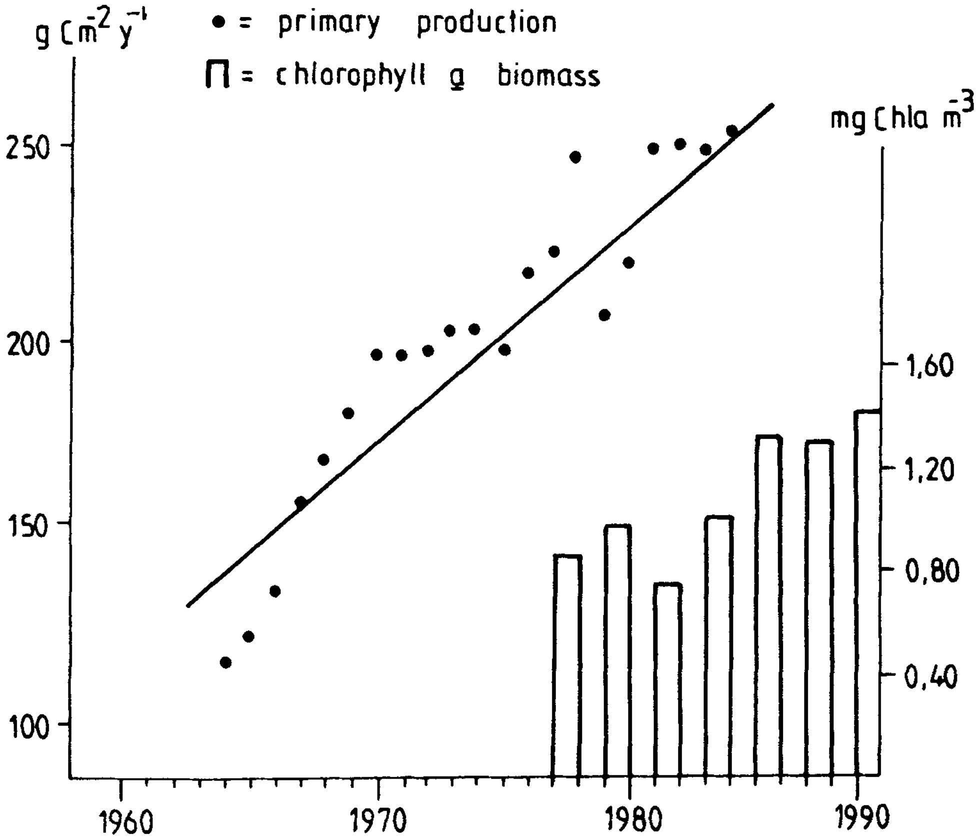

Figure 8 Increase of the primary production and chlorophyll α biomass in the Kaštela Bay.

a maximum concentration of approximately 200 mg Chl α m^{-3}, is highly eutrophic.

The bacterial biomass growth ranges from 1.57 to 61.68 mg C m^{-3}, and density of total bacteria and heterotrophs is an order of magnitude higher in the Bay than in the open sea (Krstulović, 1987). Accordingly the Bay may also be categorized as very productive.

Before 1970, the seasonal cycle of phytoplankton in the Bay was characterized by a spring and fall/winter maximum and a summer minimum. Since 1970, a third phytoplankton maximum has been recorded during summer, replacing the summer phytoplankton minimum (Figure 9), with the opportunistic phytoplankton species *Nitzschia seriata, Skeletonema costatum and Leptocylindrus danicus* becoming dominant (Figure 10); prior to 1972 these species were absent or very rarely found. The number of common species has decreased from 39 to 25 (Pucher-Petković and Marasović, 1980) and coincided with the increase of “opportune” species abundance. Similar changes have been shown for the zooplankton community (Regner, 1987), where *Acartia clausii* has become the dominant copepod species.

By the end of summer 1980, the occurrence of “red tide” in the Bay was observed for the first time (Marasović and Vukadin, 1982). Since then a “red tide” bloom has been observed regularly every summer, always provoked by the dinoflagellate

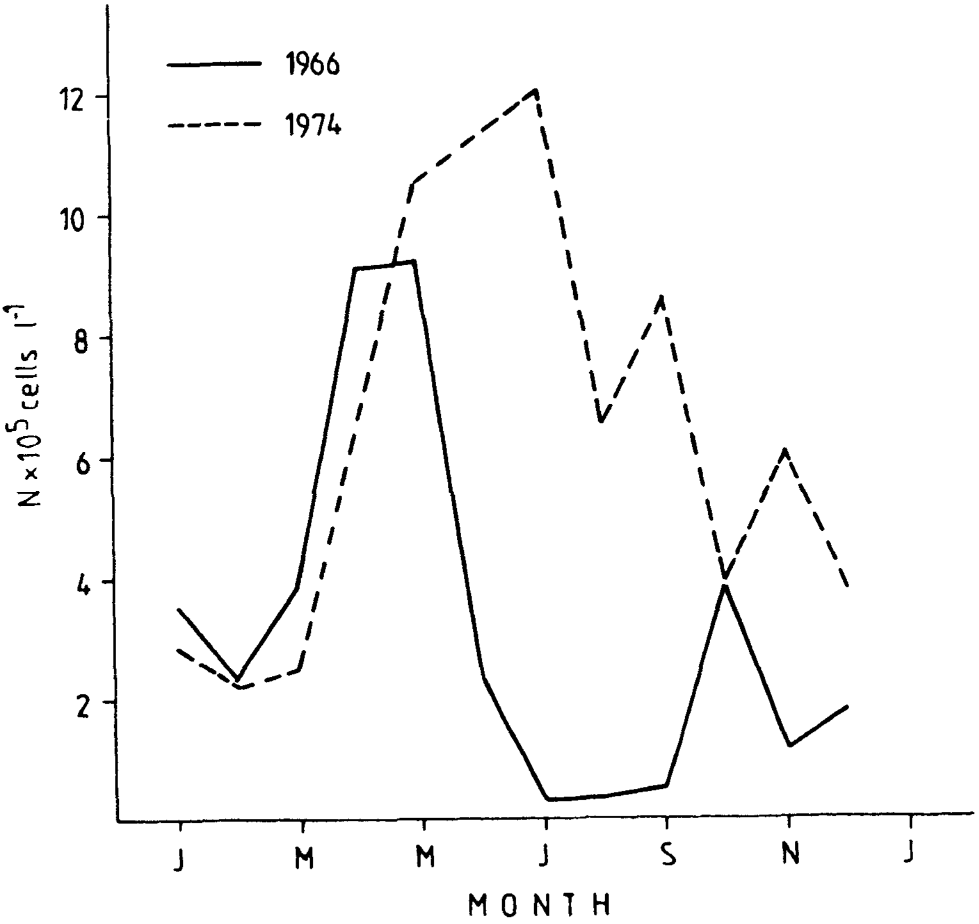

Figure 9 Seasonal fluctuations in 1966 and 1974 of the total phytoplankton in the Kaštela Bay (after Pucher-Petković and Marasović, 1980).

species *Gonyaulax polyedra* Stein (Marasović, 1989; Marasović *et al.*, 1991). Occasionally, the "red tide" bloom has caused kills of demersal fish and shellfish as in 1980, 1985, 1987, 1989, and 1990. *Gonyaulax polyedra* is a suspected toxic organism but its toxicity has never been established with certainty. It is believed that the kills of marine organisms in the affected area were due to the very low oxygen levels in sea water (1 ml l^{-1}) as a consequence of the decomposition of phytoplankton.

The fact that dinoflagellates have become a significant component of the total phytoplankton population in the Kaštela Bay is the most important result of the long-term studies. Earlier investigations showed that up to the beginning of the seventies, diatom speicies were the dominant phytoplankton group (70–99%) (Pucher-Petković, 1973; Homen, 1979). The decreased ratio of diatoms to dinoflagellates (D/DF) (Figure 11) shows clearly that diatom dominance in the Bay has been declining

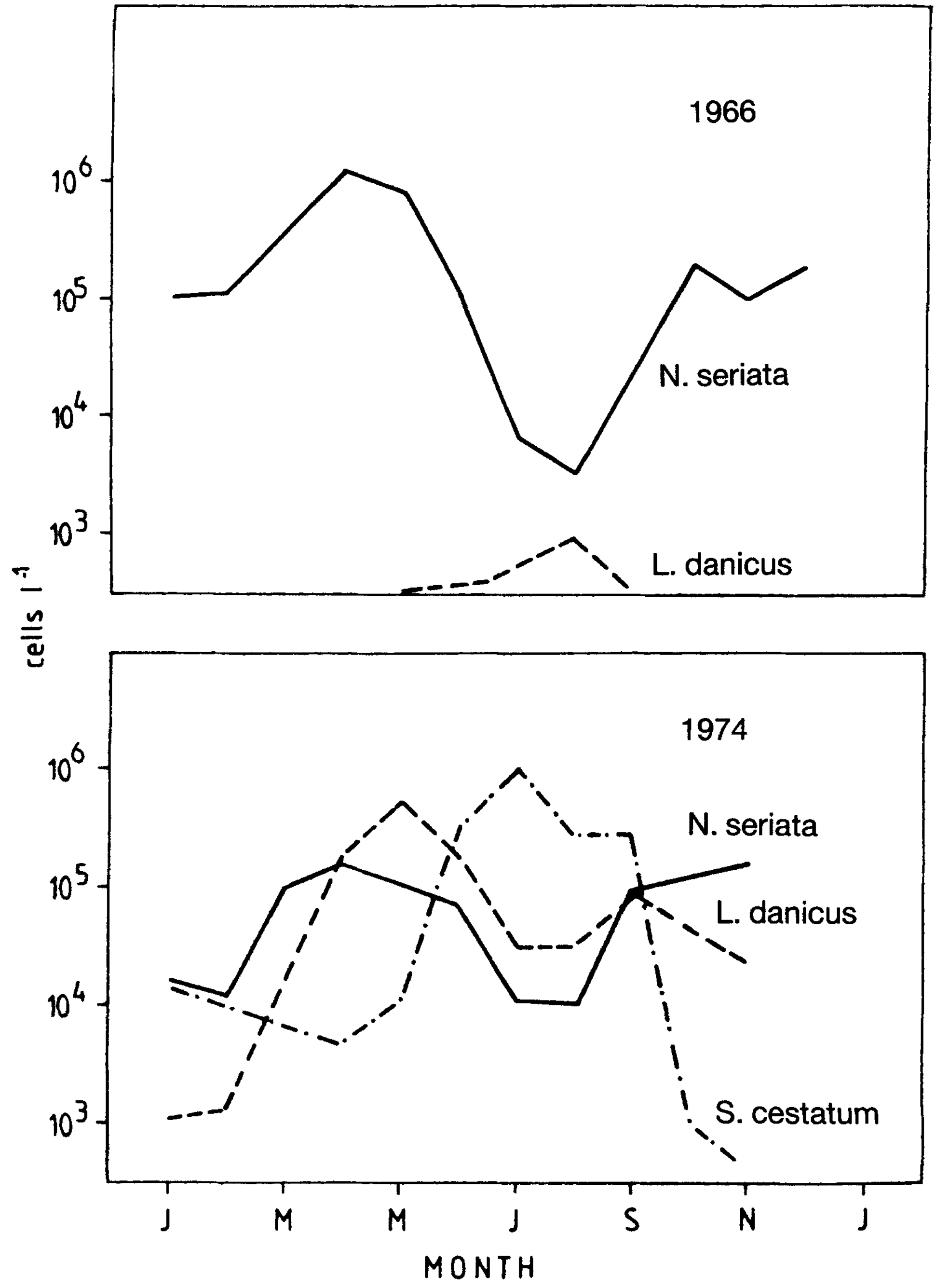

Figure 10 Seasonal fluctuations of the three dominant phytoplankton species in the Kaštela Bay (after Pucher-Petković and Marasović, 1980).

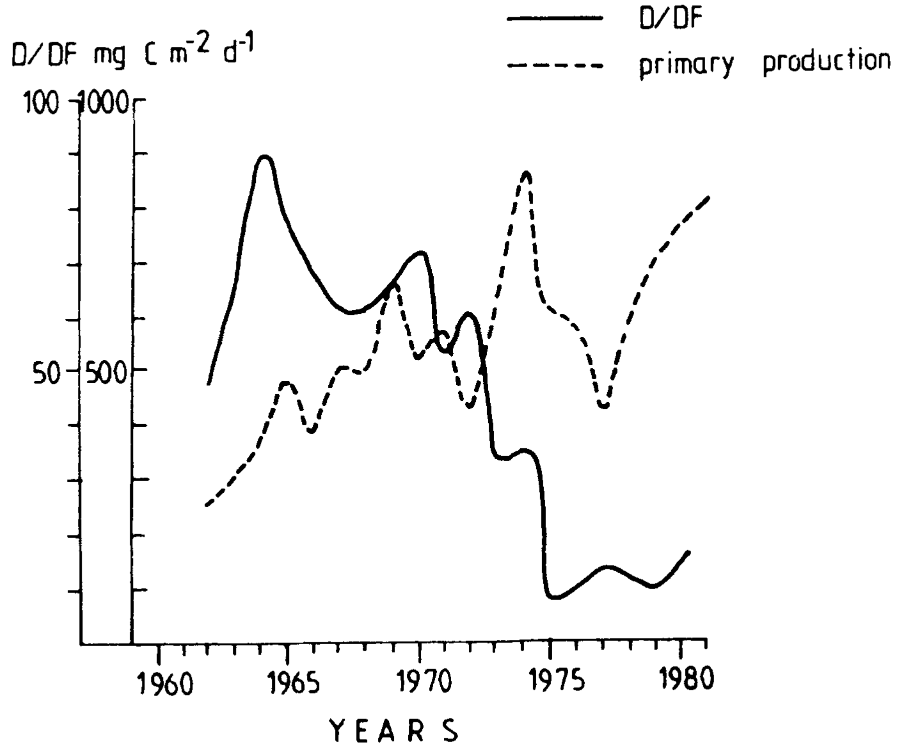

Figure 11 Ratio of diatoms and dinoflagellates cell numbers (D/DF) and primary organic production (six-monthly means, May to October).

since then. At the same time, the increased dinoflagellate contribution is followed by an increase of primary production. The relationship between these two curves clearly shows that during the first period, the diatom phytoplankton component was the determining factor of productivity, whereas later the dinoflagellates increased in importance. Platt *et al.*, (1970) and Tangen (1979) have suggested that dinoflagellates become a significant or even a dominant component of the phytoplankton population in waters subject to organic pollution.

CONCLUSIONS

On the basis of available physical, chemical and biological data (transparency, oxygen content, primary production, phytoplankton community structure and phytoplankton biomass) it is concluded that eutrophication in Kaštela Bay started in early 1970s and is still continuing. In the eastern part of the Bay the degree of eutrophication, due to physical and chemical characteristics of this area of the Bay, is much higher than that in the central and presumably the western part of the Bay.

Dissolved oxygen concentrations ranging between 3.7 and 5.6 ml l^{-1} are sufficient to meet the requirements of marine organisms, but smaller concentrations are detrimental. It is believed that oxygen concentrations in some communities close to the shore can persist below 3.5 ml $l^{-1}$for several hours without damage (Sournia, 1973) and the lethal concentration for most marine organisms is 0.9 ml l^{-1}.

Closed circulation is established in the eastern part of the Bay in summer and is influenced by peculiar physico-geological conditions which allows an excess development of autotrophic phytoplankton population due to the large nutrient inputs from discharge of waste waters. Subsequently this causes dramatic nyctohemeral oscillations of oxygen content from 10 ml l^{-1} (200% saturation) to <2 ml l^{-1} (<20% saturation) making this system exceptionally unstable, since both such high and low oxygen values adversely affect marine organisms (bubble disease and anoxia). It is not known, however, how long these concentrations persisted or how large was the area where oxygen content dropped below the lethal limit. It is anticipated, nevertheless, that with present pollution trends, the areas of such dramatic fall of oxygen can only be further extended and their duration prolonged in the future.

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