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MED POL**

UNITED NATIONS ENVIRONMENT PROGRAMME



FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS

**FINAL REPORTS ON RESEARCH PROJECTS DEALING WITH
EUTROPHICATION PROBLEMS**

**RAPPORTS FINAUX SUR LES PROJETS DE RECHERCHE TRAITANT DES
PROBLEMES DE L'EUTROPHISATION**

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This volume is the seventy-eighth issue of the Mediterranean Action Plan Technical Reports Series.

This series contains selected reports resulting from the various activities performed within the framework of the components of the Mediterranean Action Plan: Pollution Monitoring and Research Programme (MED POL), Blue Plan, Priority Actions Programme, Specially Protected Areas and Regional Marine Pollution Emergency Response Centre for the Mediterranean.

Ce volume constitue le soixante dix-huitième numéro de la série des Rapports techniques du Plan d'action pour la Méditerranée.

Cette série comprend certains rapports élaborés au cours de diverses activités menées dans le cadre des composantes du Plan d'action pour la Méditerranée: Programme de surveillance continue et de recherche en matière de pollution (MED POL), Plan Bleu, Programme d'actions prioritaires, Aires spécialement protégées et Centre régional méditerranéen pour l'intervention d'urgence contre la pollution marine accidentelle.

PREFACE

The United Nations Environment Programme (UNEP) convened an Intergovernmental Meeting on the Protection of the Mediterranean (Barcelona, 28 January - 4 February 1975), which was attended by representatives of 16 States bordering the Mediterranean Sea. The meeting discussed the various measures necessary for the prevention and control of pollution of the Mediterranean Sea, and concluded by adopting an Action Plan consisting of three substantive components:

- Integrated planning of the development and management of the resources of the Mediterranean Basin (management component);
- Co-ordinated programme for research, monitoring, exchange of information and assessment of the state of pollution and protection measures (assessment component);
- Framework convention and related protocols with their technical annexes for the protection of the Mediterranean environment (legal component).

All components of the Action Plan are inter-dependent and provide a framework for comprehensive action to promote both the protection and the continued development of the Mediterranean ecoregion. No component is an end in itself. The Action Plan is intended to assist the Mediterranean Governments in formulating their national policies related to the continuous development and protection of the Mediterranean area and to improve their ability to identify various options for alternative patterns of development and to make choices and appropriate allocations of resources.

The Co-ordinated Mediterranean Research and Monitoring Programme (MED POL) was approved as the assessment (scientific/technical) component of the Action Plan.

The general objectives of its pilot phase (MED POL - Phase I), which evolved through a series of expert and intergovernmental meetings, were:

- to formulate and carry out a co-ordinated pollution monitoring and research programme taking into account the goals of the Mediterranean Action Plan and the capabilities of the Mediterranean research centres to participate in it;
- to assist national research centres in developing their capabilities to participate in the programme;
- to analyse the sources, amounts, levels, pathways, trends and effects of pollutants relevant to the Mediterranean Sea;
- to provide the scientific/technical information needed by the Governments of the Mediterranean States and the EEC for the negotiation and implementation of the Convention for the Protection of the Mediterranean Sea against Pollution and its related protocols;
- to build up consistent time-series of data on the sources, pathways, levels and effects of pollutants in the Mediterranean Sea and thus to contribute to the scientific knowledge of the Mediterranean Sea.

Based on the recommendations made at various expert and intergovernmental meetings, a draft Long-term (1981-1990) Programme for Pollution Monitoring and Research in the Mediterranean (MED POL-Phase II) was formulated by the Secretariat of the Barcelona Convention (UNEP), in co-operation with the United Nations Agencies which were responsible for the technical implementation of MED POL-Phase I, and it was formally approved by the Second Meeting of the Contracting Parties of the Mediterranean Sea against pollution and its related protocols and Intergovernmental Review Meeting of Mediterranean Coastal States of the Action Plan held in Cannes, 2-7 March 1981.

The general long-term objectives of MED POL-Phase II were to further the goals of the Barcelona Convention by assisting the Parties to prevent, abate and combat pollution of the Mediterranean Sea area and to protect and enhance the marine environment of the area. The specific objectives were designed to provide, on a continuous basis, the Parties to the Barcelona Convention and its related protocols with:

- information required for the implementation of the Convention and the protocols;
- indicators and evaluation of the effectiveness of the pollution prevention measures taken under the Convention and the protocols;
- scientific information which may lead to eventual revisions and amendments of the relevant provisions of the Convention and the protocols and for the formulation of additional protocols;
- information which could be used in formulating environmentally sound national, bilateral and multilateral management decisions essential for the continuous socio-economic development of the Mediterranean region on a sustainable basis;
- periodic assessment of the state of pollution of the Mediterranean Sea.

The monitoring of, and research on, pollutants affecting the Mediterranean marine environment reflects primarily the immediate and long-term requirements of the Barcelona Convention and its protocols, but also takes into account factors needed for the understanding of the relationship between the socio-economic development of the region and the pollution of the Mediterranean Sea.

Research and study topics included initially in the MED POL - Phase II were:

- development of sampling and analytical techniques for monitoring the sources and levels of pollutants. Testing and harmonization of these methods at the Mediterranean scale and their formulation as reference methods. Priority will be given to the substance listed in the annexes of the Protocol for the prevention of pollution of the Mediterranean Sea by dumping from ship and aircraft and the Protocol for the protection of the Mediterranean Sea against pollution from land-based sources (activity A);

- development of reporting formats required according to the Dumping, Emergency and Land-Based Sources Protocols (activity B);
- formulation of the scientific rationale for the environmental quality criteria to be used in the development of emission standards, standards of use or guidelines for substances listed in annexes I and II of the Land-Based Sources Protocol in accordance with Articles 5, 6 and 7 of that Protocol (activity C);
- epidemiological studies related to the confirmation (or eventual revision) of the proposed environmental quality criteria (standards of use) for bathing waters, shellfish-growing waters and edible marine organisms (activity D);
- development of proposals for guidelines and criteria governing the application of the Land-Based Sources Protocol, as requested in Article 7 of that Protocol (activity E);
- research on oceanographic processes, with particular emphasis on surface circulation and vertical transport. Needed for the understanding of the distribution of pollutants through the Mediterranean and for the development of contingency plans for cases of emergency (activity F);
- research on the toxicity, persistence, bioaccumulation, carcinogenicity and mutagenicity of selected substances listed in annexes of the Land-Based Sources Protocol and the Dumping Protocol (activity G);
- research on eutrophication and concomitant plankton blooms. Needed to assess the feasibility of alleviating the consequences and damage from such recurring blooms (activity H);
- study of ecosystem modifications in areas influenced by pollutants, and in areas where ecosystem modifications are caused by large-scale coastal or inland engineering activity (activity I);
- effects of thermal discharges on marine and coastal ecosystems, including the study of associated effects (activity J);
- biogeochemical cycle of specific pollutants, particularly those relevant to human health (mercury, lead, survival of pathogens in the Mediterranean Sea, etc.) (activity K);
- study of pollutant-transfer processes (i) at river/sea and air/sea interface, (ii) by sedimentation and (iii) through the straits linking the Mediterranean with other seas (activity L);

The Contracting Parties at their 6th Ordinary Meeting (Athens, October 1989) agreed to:

- (a) Re-orient the research activities within MED POL in order to generate information which will also be useful for the technical implementation of the LBS protocol in addition to supporting monitoring activities;

- (b) replace as from 1990 research activities A-L by the following five new research areas:

Research area I - Characterization and measurement

This area will include projects which cover the characterization (identification of chemical or microbiological components) and measurement development and testing of methodologies of specified contaminants;

Research area II - Transport and dispersion

This area will include projects which aim at improving the understanding of the physical, chemical and biological mechanisms that transport potential pollutants from their sources to their ultimate repositories. Typical topics will be atmospheric transport and deposition, water movements and mixing, transport of contaminants by sedimentation and their incorporation in biogeochemical cycles. Priority will be given to the provision of quantitative information ultimately useful for modelling the system and contributing to regional assessments;

Research area III - Effects

This area will include projects relevant to the effects of selected contaminants, listed in Annexes I and II of the LBS and Dumping protocols, to marine organisms, communities and ecosystems or man and human populations. Priority will be given to effects and techniques providing information useful for establishing environmental quality criteria;

Research area IV - Fates/Environmental transformation

This area will include projects studying the fate of contaminants (including microorganisms) in the marine environment such as persistence or survival, degradation, transformation, bioaccumulation etc. but excluding transport and dispersion which is dealt in area II;

Research area V - Prevention and control

This area will include projects dealing with the determination of the factors affecting the efficiency of waste treatment and disposal methods under specific local conditions as well as the development of environmental quality criteria and common measures for pollution abatement;

- (c) define target contaminants or other variables at periodic intervals depending on the progress of implementation of the LBS protocol;

- (d) select project proposals on the basis of their intrinsic scientific validity, their Mediterranean specificity, and encourage whenever possible bilateral and multilateral projects among Mediterranean countries from the north and the south of the basin.

As in MED POL - Phase I, the overall co-ordination and guidance for MED POL - Phase II is provided by UNEP as the secretariat of the Mediterranean Action Plan (MAP). Co-operating specialized United Nations Agencies (FAO, UNESCO, WHO, WMO, IAEA, IOC) are responsible for the technical implementation and day-to-day co-ordination of the work of national centres participating in monitoring and research.

The present volume includes final reports on research projects dealing with eutrophication problems. Final editing and compilation of this volume was done by Mr. G.P. Gabrielides, FAO Senior Fishery Officer (Marine Pollution) while Ms V. Papapanagiotou, FAO Secretary, was responsible for the typing.

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LONG-TERM EUTROPHICATION OF THE NORTHERN ADRIATIC SEA:
EVIDENCE AND CONTROL

by

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ABSTRACT

Eutrophication of the northern Adriatic Sea has been investigated using data on dissolved oxygen (DO) from 1911 until 1982. It is concluded that DO increased in the surface layer and decreased in the bottom layer in all seasons except winter. DO changes have been attributed to an increase of anthropogenic nutrient inflow starting from 1955-'66. Horizontal maps of DO near the surface and on the bottom show a gradient from river Pô towards the middle of the northern Adriatic. A simple box model has been constructed and applied to explain the cause of DO changes in the seasonal dynamics. The main cause seems to be the increase of nutrient inflow. It has been concluded that the only reliable measure to decrease undesirable DO decrease near the bottom is a decrease in anthropogenic nutrient inflow into the northern Adriatic Sea.

1. INTRODUCTION

Scientists have repeatedly observed that the (eutrophic) state of the Northern Adriatic Sea (N.A.) is changing. General public also noticed massive phytoplankton blooms, massive appearance of gelatinous material and occurrence of high concentrations of jellyfish, all of which affect their ability to use the sea as a recreational area. Many tourists have cancelled their vacations and more will do so in the future if something is not done to restore the previously pleasant bathing, diving and recreational area. Fishermen also noticed changes that affect their activity, such as disappearance of benthic fauna.

The following questions are frequently asked:

- a) Are the observed changes significant in some sense?
- b) Are the changes permanent or temporary?
- c) What are the causes of these changes?
- d) What can we do to eliminate unpleasant changes?
- e) When will the consequences of our measures be visible?

It is well known that a shift from oligotrophic toward an eutrophic state induces, among others, an increase in the average primary production, phytoplankton density, increase in organic matter content, and a decrease in diversity of biological species.

Eutrophication includes a number of processes whose rate changes following an increase in nutrient inflow to a coastal ecosystem. The increase in nutrient inflow may be either natural or man made i.e anthropogenic. We also speak of an eutrophication state. The state may be characterized by various measures. Sometimes a single variable is used and at other times some collective measure is formulated which may be a function of concentration of biological and/or chemical species in an ecosystem. None of the measures used so far is exhaustive. Since our data are limited, the measure is necessarily a partial one. The Greek origin of terms oligotrophic and eutrophic mean respectively an "underfed" and an "overfed" ecosystem. The term eutrophic should not be taken literally because it does not mean that in an eutrophic ecosystem every biological entity is well fed.

By a long-term we mean an interval which is beyond yearly variations and, since we are most interested to find whether changes in the N.A. are man induced, our meaning of a long-term will be bounded by existing relevant data. Data on dissolved oxygen (DO) concentration, which will be used as a measure of eutrophication in this paper, date back to 1911.

Another approach to eutrophication has been to study the occurrence of three more or less related phenomena: phytoplankton blooms, hypoxia on the bottom and massive appearance of gelatinous material (mucilage). Although we shall return to each one of these phenomena, let us mention the well known fact that phytoplankton blooms have occurred in historical time far back from our "long-term interval" and are often quoted as counter-examples to those who advocate that recently observed algal blooms are a consequence of anthropogenic influence. Hypoxia on the bottom has also been found in oligotrophic waters and hence one can not state that it is always a consequence of a chain of events that starts with eutrophication. Recently, CEC has conducted a workshop on Eutrophication-Related Phenomena in the Adriatic Sea and in Other Mediterranean Zones (CEC, 1990). During this meeting a number of research attempts have been summarized, hence, one could say, the proceedings of this meeting represent the latest understanding of the three phenomena mentioned above. In the proceedings, Fogg (1990) states: "The mucilage is evidently produced under certain conditions and eutrophication is not involved".

In the present report we attempt to show the opposite i.e. that in the Northern Adriatic (N.A.) eutrophication is a necessary condition for massive appearance of mucilage.

Štirn et al. (1974) were the first to discover long-term changes in DO concentrations in N.A.. They analyzed data on DO concentration from 1911 until 1973 for the whole Adriatic. Although they found no significant trends, their frequency analysis of data for N.A. led them to conclude that in the period 1960-73 the frequency of low DO concentrations near the bottom increased and the frequency of high DO concentrations decreased in comparison to the respective frequencies in the interval 1928-33.

2. MATERIALS AND METHODS

2.1 The area of study

The northern Adriatic extends from the gulf of Trieste south approximately to the line Ancona - Pula. It is closed from three sides and open towards the middle Adriatic. The mean (station) depth is about 33.5 m (Degobbis and Gilmartin, 1990) (see Fig. 1). Several rivers flow into the N.A.. The largest rivers are situated along the Italian coast. The rivers bring a substantial supply of nutrients which mix with the oligotrophic waters incoming from the middle Adriatic. As a result, the N.A. is among the most productive areas in the Mediterranean (Kveder *et al.*, 1971; Štirn *et al.*, 1974). With the discharge of $\sim 1500 \text{ m}^3 \text{ s}^{-1}$, river Pô is the largest single source of fresh water. Since the concentration of nutrients in its water is from 50 to over 100 times higher than the concentrations in the open waters of the middle Adriatic, it represents the largest source of nutrients to the N.A.. The drainage area of river Pô hosts the largest human population and the largest industrial and agricultural area of any other river entering the Adriatic sea.

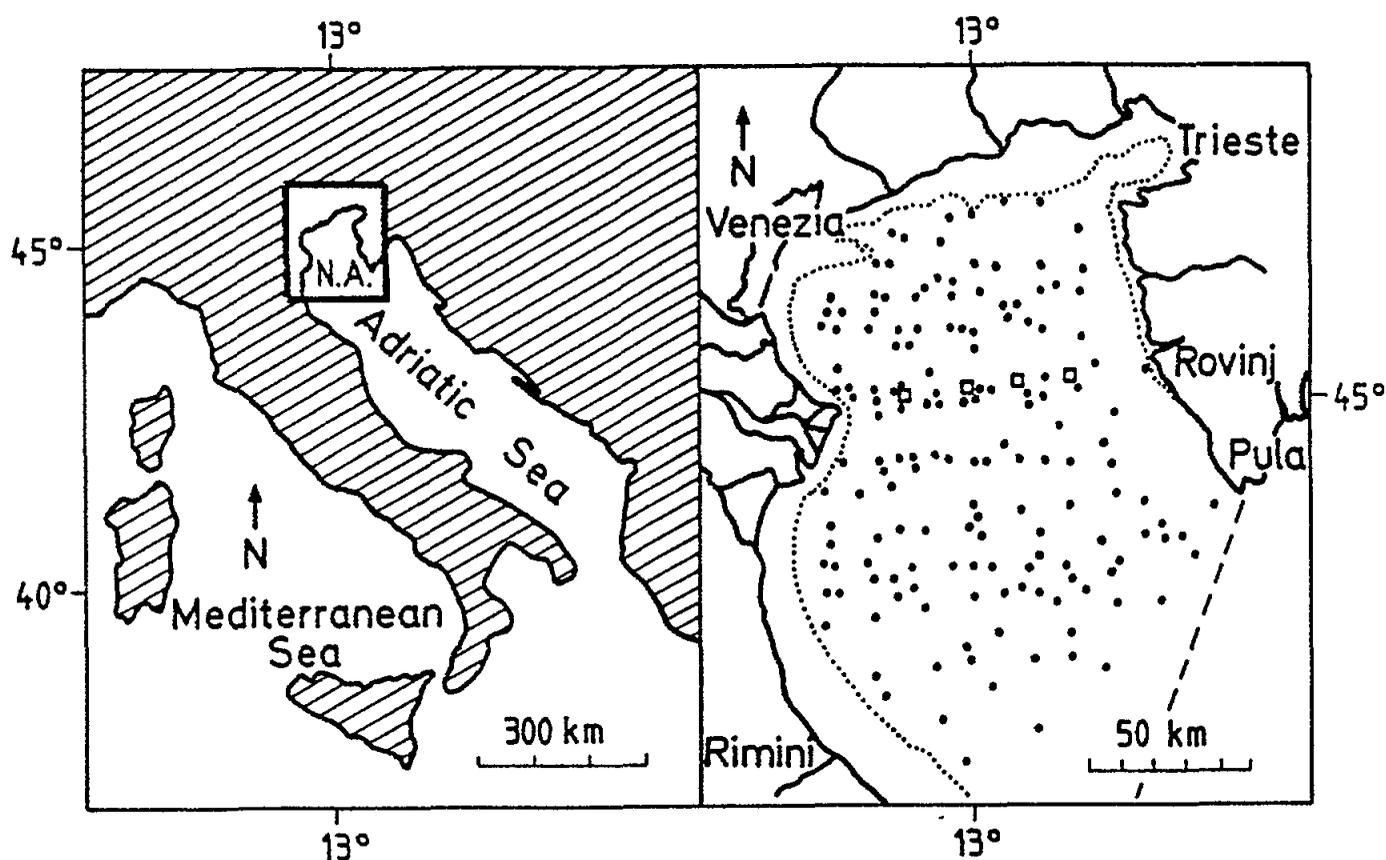


Fig. 1 Northern Adriatic Sea. Depth of 20 m is denoted with the dotted line. Locations of all stations are denoted. Some stations were visited only once while others were visited monthly or seasonally. The four stations on the transect Pô delta - Rovinj during 1973 are denoted with small squares

Intensive spring and autumn blooms of phytoplankton appear mostly in the western area which is under the direct influence of river Pô (Revelante and Gilmartin, 1976).

The circulation regime in the N.A. is not very well known. Still, many would agree that during winter there exists a cyclonic circulation (counter-clockwise) throughout the water column. As a consequence, the exchange time of water in the aquatorium is shorter in winter than in summer. Here, the exchange time is defined as the time interval needed that one volume of water equal to the volume of the N.A. is exchanged with the rest of the sea (Legoviã 1991). The interval is shorter than the interval needed to completely replace water from the N.A. with new water from the middle Adriatic. From summer towards winter, the water is cooled from the surface, vertical mixing increases and finally destroys summer stratification. This process is completed approximately by the end of October. From winter towards summer, the circulation weakens and concurrently the thermocline is formed.

During summer, vertical mixing across the thermocline is slower than in either layer. In this sense the thermocline "separates" the upper 20 m layer from the layer below. During July - August the cyclonic circulation is weak and the exchange rate between N.A. and the rest of the Adriatic decreases. Let us denote residual currents at 8 m below the surface as "surface currents" and currents at 5 m above bottom (30 to 35 m below surface i.e. below the summer thermocline) as "bottom currents". Then, according to data from two measurement periods: 23 May - 30 June and 19 August - 14 October 1986 (Brana and Kuzmanoviã 1987), we find: a) the intensity of surface currents in the summer to be about 80% of the intensity in winter; b) the intensity of bottom currents in winter to be about 40% of the intensity of surface currents in winter and c) the intensity of bottom currents in summer to be about 20% of the intensity of surface currents in winter.

2.2 Data and methods

2.2.1 Data on oxygen content for the period 1911-1982

The following oceanographic parameters have been measured since 1911: temperature, chlorinity and DO concentration. DO concentration was measured by the Winkler method (Winkler, 1888).

It is interesting to consider graphs by Štirn et al. (1974) on DO from 1911 until 1973 for the whole Adriatic. Results show an important point: variability in natural conditions is so large that a very careful filtering technique is needed to possibly reveal trends - if they exist at all.

The filtering technique devised and applied by Justiã et al. (1987) is used here:

- a) To decrease the scatter due to rather variable point sources located along the coast; only DO concentrations farther than the 20 m isobath were considered.
- b) To distinguish between the completely mixed water column, the formation of stratification, a stratified water column and the process of destratification, the four seasons were treated separately.

- c) Since oxygen production is mainly occurring near the surface, where higher values are expected, and oxygen consumption is mainly occurring near the bottom, separation between surface and bottom data is necessary. Obviously if these would be analyzed together the differences would cancel out and obscure possible trends.

Furthermore, we would expect that if there are differences in oxygen concentration between the upper and lower layer, these differences would be more pronounced in the extreme points of the two layers, that is, on the surface and close to the bottom. DO concentration close to the bottom would not only be smaller due to oxygen demand of the degradation processes but also because of a smaller primary production. If primary production is higher near the surface, a greater concentration of phytoplankton would result. In turn, this would absorb light and hence less light would be available near the bottom. For these reasons, all data between the two layers are neglected and the two extreme points are considered: 0.5 m below the surface and the first data point above the bottom, which turned out to be approximately 2 m above the bottom.

- d) Finally it was assumed that the DO concentration from one year to another is cyclic so that winter from one year may be compared to winter of the next year. Note that a deviation from this assumption would reveal a trend.

The data used include the following sources: Brückner (1914); Picotti and Vatova (1942); Vatova (1948); Picotti (1960); Trotti (1969); Franco (1972); Gilmartin *et al.* (1972a); Gilmartin *et al.* (1972b); Cescon and Scarazzato (1979); Franco (1982); HIRM (1982) and data from the Centers for Marine Research, Rudjer Bošković Institute.

2.2.2 Development of hypoxia on the transect delta Pô- Rovinj during 1973

Data were taken approximately bi-weekly but, since the same station was visited every second time, approximately monthly transects can be considered. Data were published by Gilmartin *et al.* (1972a,b) and represent the best data set in a year on the N.A. that is available in open literature.

Oxygen transects are plotted using an objective analysis method.

2.2.3 Horizontal maps of oxygen during 1973

Investigation of areas of higher DO concentration and DO deficiency using the above data source is performed by an objective analysis method.

2.2.4 Dynamics of oxygen content in northern Adriatic

Dynamics of DO concentration is studied using a simple box model which has been constructed from literature data and data from N.A..

3. RESULTS AND DISCUSSION

3.1 DO concentrations in the surface layer

Seasonal changes of DO concentrations near the surface between the years 1911-13 and 1972-82 are shown in Figure 2. During winter there is no

significant difference in DO concentration between the two periods. The difference is largest during spring, however it persists throughout summer and autumn.

3.2 DO concentration near bottom

Changes in the near-bottom water (2 m above the bottom) between the 1911-13 and 1972-82 periods are shown in Figure 2. With regards to 1911-13, DO concentrations in the near-bottom waters of N.A. during 1972-82 is smaller in all seasons of an average year. The difference is largest in the summer, smaller in autumn and spring and the smallest in winter.

3.3 Long term trends 1911-1984

The above results are in agreement with the results of Justić *et al.* (1987) who used a larger data set:

- a) Winters from 1911 to 1984 change very slowly in surface layer. The DO concentration increases with a rate of $0.005 \text{ cm}^3 \text{ O}_2 \text{ l}^{-1}$.

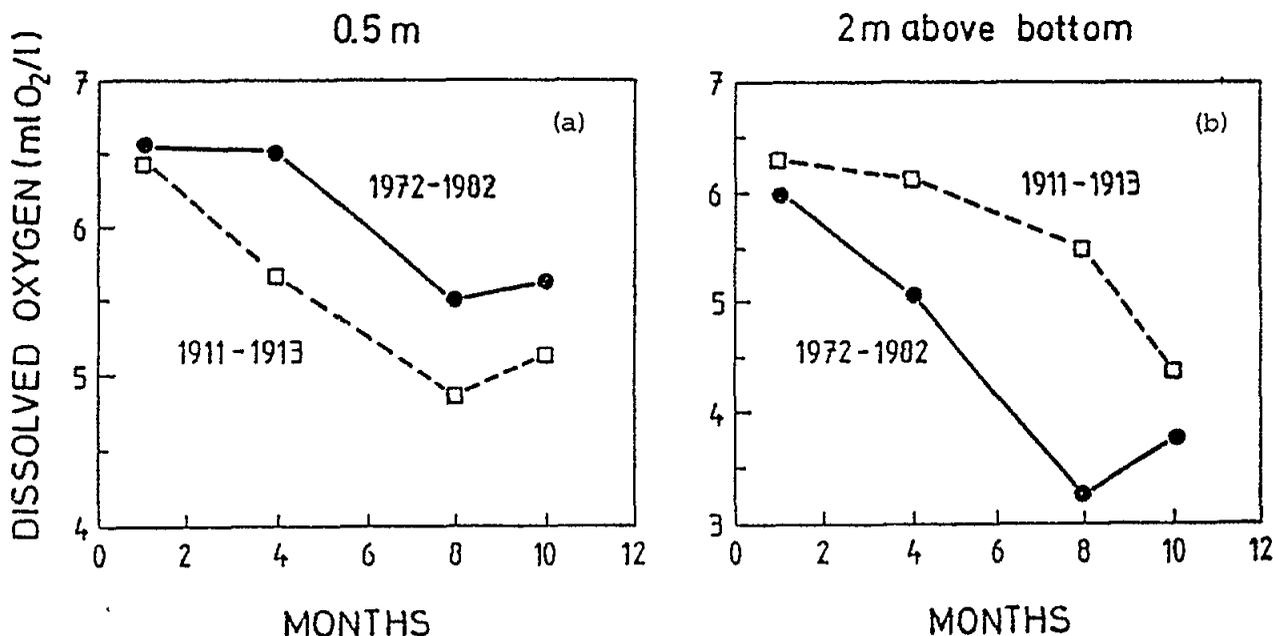


Fig. 2 Seasonal DO concentration near the surface and near the bottom during (a) 1911-1913 and (b) 1972-1982

- b) In spring, DO concentration near the surface increases by the rate of $0.02 \text{ cm}^3 \text{ O}_2 \text{ l}^{-1}$ per year. Near the bottom it decreases with the rate of $0.01 \text{ cm}^3 \text{ O}_2 \text{ l}^{-1}$.
- c) In summer, DO concentration near the surface increases by the rate of $0.015 \text{ cm}^3 \text{ O}_2 \text{ l}^{-1}$ per year. Near the bottom it decreases with the rate of $0.03 \text{ cm}^3 \text{ O}_2 \text{ l}^{-1}$ i.e. three times the rate in spring.

- d) In autumn, DO concentration near the surface increases by the rate of $0.012 \text{ cm}^3 \text{ O}_2 \text{ l}^{-1}$ per year. On the bottom it decreases with the rate of $0.02 \text{ cm}^3 \text{ O}_2 \text{ l}^{-1}$ i.e. two times the rate in spring.
- e) In addition, it was found that the data showed mostly insignificant to barely significant trend until 1955. No data were available from the period between 1955 and 1965. Data from 1966 until 1982 are responsible for the entire trend of DO increase near the surface and the decrease near the bottom.

The validity of the above results may be questioned on the grounds that location of stations varied during the time interval while there exists an east-west trend in DO concentrations. Together these may have made trends in time spurious (Degobbis, private communication). A separate analysis performed on several representative stations from a very small area where the maximum of data have been collected on the examined time interval, revealed a significant trend in time.

Identification of 1955-65 as a start of a significant trend of increase in DO concentration at the surface and a decrease near the bottom has been explained using the following hypothesis:

H1: in those years widespread fertilization and usage of detergents containing phosphorus compounds started. The increase in usage of nutrients, led to an increase in nutrient inflow into N.A. The increase in nutrient inflow is responsible for the existing trends in DO concentration.

According to H1 an increase in nutrient inflow caused a trend towards higher primary production close to the surface and, as a consequence, the higher concentration of oxygen resulted. At the bottom, the DO concentration started to decrease due to a higher flux of organic matter from the upper layer (settling of phytoplankton) and consequently higher flux of decomposition (not the rate). This resulted in higher demand of DO and hence a smaller concentration. To a smaller extent, primary production near the bottom decreased because of less light i.e. shading from higher concentrations of phytoplankton in the upper layer. This conclusion follows from the finding that Secchi disk depth is decreasing (Justiæ 1988). In our opinion, supply of oxygen from the surface by vertical mixing must have increased (since higher concentration is found near the surface than earlier and vertical mixing rates did not change) but this is apparently not sufficient to match a very large biological oxygen demand near the bottom.

Much of the variance in the data may be explained by vertical mixing between surface and near bottom water. When the DO difference between the two waters is small, like in the interval 1911-55, the variance is small. As the difference between the two layers increases the variance in each layer increases.

Small or no difference in DO concentration during winter between the two periods is a result of: a) a small change in primary production during winter. Obviously during winter, phytoplankton production is less dependent on nutrients than on temperature and possibly light; b) a slow decomposition rate near the bottom, although the flux must have increased; c) a counter-clockwise circulation in this season with faster renewal of water from Middle Adriatic,

and d) a larger vertical mixing of water in this season (when compared to summer) precludes both a build-up near the surface and the deficiency of DO in near-bottom water.

3.4 Development of DO supersaturation in the water column and hypoxia near the bottom during 1973 on the transect from the delta of river Pô to Rovinj

The first station is located 20 km off the delta and the last station is located 20 km off Rovinj (Fig. 1). Four stations are located along a distance of 50 km.

The dynamics of DO concentration in the water column from April 26 to December 6 are shown in Fig. 3.

Near the surface, DO concentration starts from saturation in winter although slightly higher DO concentration is often measured near river Pô. On April 26 no indication of bloom is visible except that at the surface 107% DO is recorded at the station closest to river Pô. On May 11 (not shown) 119% of DO saturation was found at the depth of 15 m at the station nearest to river Pô and 110% was found at the depth of 5 m at the next station. Twelve days later on May 23, values from 109 to 128% DO saturation were measured near the surface. During the rest of spring and summer, higher DO concentrations moved 10 to 20 m below surface.

Hypoxia near the bottom starts from the side of river Pô and as summer approaches it spreads toward Rovinj. On October 11, according to these graphs, and this particular year, we have the smallest value of oxygen near the bottom. A gradient from the river Pô towards Rovinj is clearly visible. Consideration of the last three graphs in Fig. 3 shows how hypoxia disappears: incoming water from middle Adriatic on the side of Rovinj forces the water toward the side of river Pô out of N.A.. In addition vertical mixing which also intensifies brings oxygen-rich water from surface to the bottom.

3.5 Horizontal distribution of DO concentration

Horizontal distribution of DO concentrations have been made for measurements during 1973. An example of distributions at the surface (0 m) and near the bottom approximately 2 m above bottom for 17-21 July 1973 are shown in Figures 4a and 4b, respectively.

Higher concentrations of DO near the surface are often found near river Pô delta and extends either towards Rovinj or along south east i.e. along the Italian coast, depending on prevailing currents.

Hypoxia near the bottom is often seen as a smeared-out image of the distribution at the surface except that here smaller DO concentration is located near river Pô delta.

3.6 Causes of long-term changes in DO concentration

The hypothesis H1 (above) has not yet been proven. It remains to be determined whether nutrient load to N.A. has increased, and if so, to what extent. If it has increased, then higher concentrations of nutrients would be

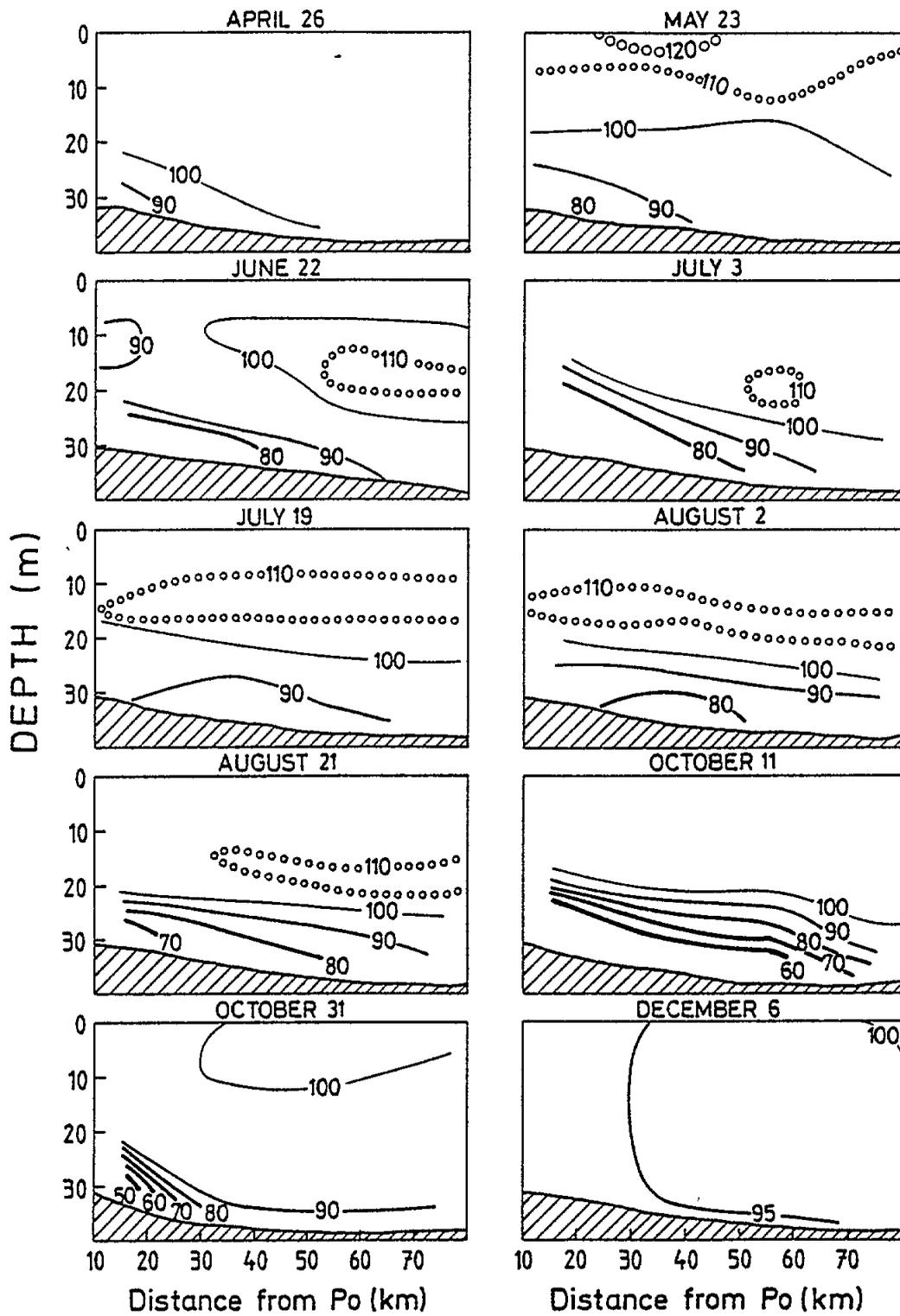


Fig. 3 Development of DO supersaturation in the water column and hypoxia near the bottom (in % of the saturation value) from April 26 until December 6, 1973 on a transect between river Pô delta and Rovinj

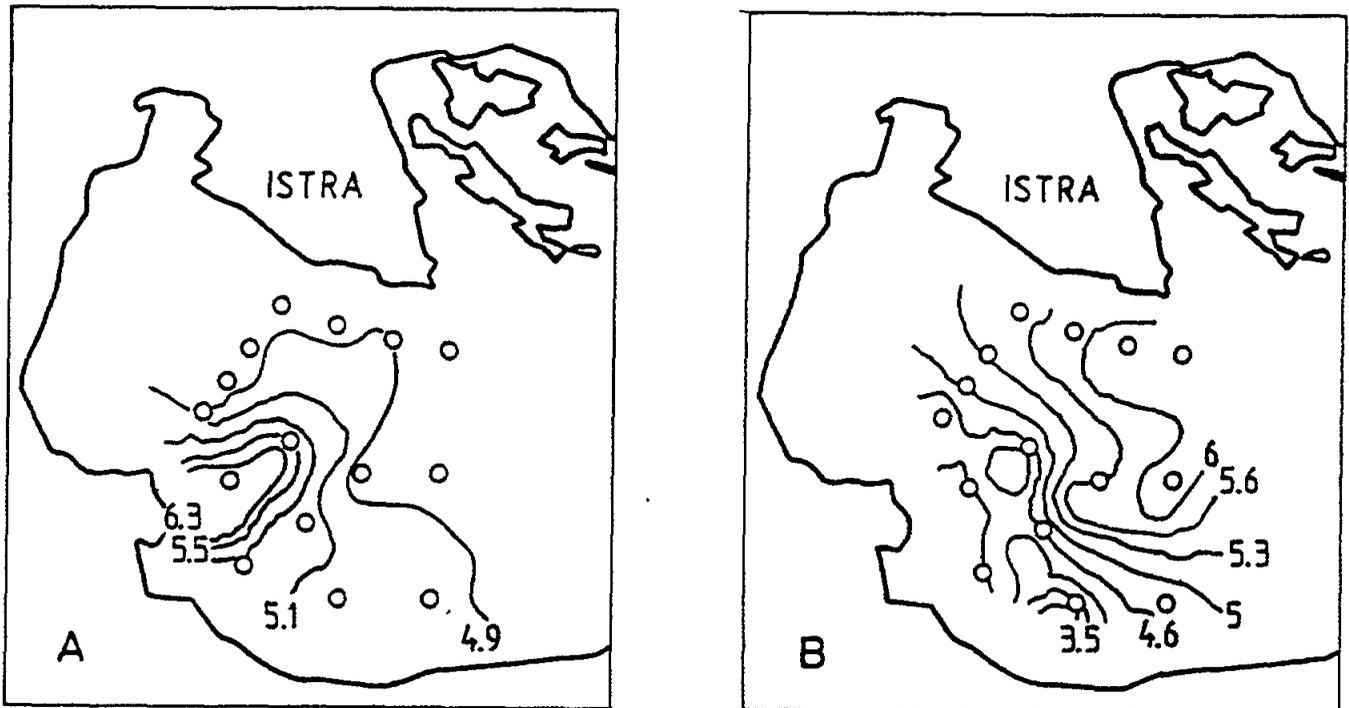


Fig. 4 DO concentration (ml DO l^{-1}) in northern Adriatic, 17-21. July 1973. A) surface water; B) water 2m above bottom

expected in a wider area of N.A. due to a normal dispersion. This would induce higher primary production and hence higher DO concentration in a wider area.

The direct procedure would be relatively simple: calculate total load and subtract from it the anthropogenic part. If the anthropogenic part cannot explain the observed changes, a search for other parameters should be initiated.

As it has been shown by Degobbis and Gilmartin (1990), to calculate the total load directly and precisely is virtually impossible. The reason is simple: all relevant data do not exist. Still, carefully combining existing data and using literature values of nutrient contribution per inhabitant, Degobbis and Gilmartin came to following estimates:

Nitrogen inflow $\approx 23.6 \cdot 10^9 \text{ mol N y}^{-1}$ ($= 331 \cdot 10^3 \text{ t y}^{-1}$)

Phosphorus inflow $\approx 0.9 \cdot 10^9 \text{ mol P y}^{-1}$ ($= 27.9 \cdot 10^3 \text{ t y}^{-1}$)

Silica inflow $\approx 8.4 \cdot 10^9 \text{ mol Si y}^{-1}$ ($= 23.6 \cdot 10^3 \text{ t y}^{-1}$)

It must be mentioned that not all existing sources have been accounted for, and that the average estimates were computed from a mixture of data and sources from the late sixties until the beginning of the eighties i.e in the time interval when nutrient inflow was increasing. From this perspective, they

represent a lower bound to the true inputs. On the other hand, not all nutrients measured in rivers and streams end up in N.A. water column, some is consumed earlier and is buried in the sediment of rivers and streams. Still, these are not only the best estimates to date but, we believe, that they are closer to the true value than the usual order of magnitude estimates.

Let us consider the data on production of P-fertilizers, phosphorus acid and N-fertilizers in Italy (Justiæ 1988). The production of phosphoric acid started in 1957 with 50 Kt P y⁻¹ and steadily increased to 500 Kt P y⁻¹ by 1970, when it started to decrease to 450 Kt P y⁻¹ by 1985. Production of P-fertilizers started in 1949 with 150 Kt P y⁻¹ and increased to 430 Kt P y⁻¹ by 1979, it then started to decrease and reached 300 Kt P y⁻¹ by 1985. Production of N-fertilizers started in 1949 with 50 Kt N y⁻¹ and increased to 600 Kt N y⁻¹ by 1979 when it started to decrease to 420 Kt N y⁻¹ by 1985.

The question is how the increase in production of nutrients from the fifties to 1968 translates into an increase of the load to N.A.? Direct data do not exist and an indirect method must be devised. Prior to that, let us consider the situation from 1968 to 1985 since for this period relevant data exist. To summarize, in this period production of N-fertilizers has increased 2.5 times while production of phosphoric acid and P-fertilizers have increased 25% and 50% respectively.

According to Marchetti et al. (1989), for the nutrient load carried by the river Pô, the major single source of nutrients to N.A., between 1968 and 1985 the inflow of total mineral nitrogen increased 2 times and the inflow of orthophosphate has increased 2.5 times. If river Pô would carry nothing else but a part of produced nutrients, then it would follow that it carries about 20% of mineral N from produced N-fertilizers and about 1% of orthophosphate from P-fertilizers.

Let us now assume that river Pô carries a significant quantity of nutrients which may be natural and therefore constant. If that would be the case then a doubling of nutrient production could not result in a doubling of the concentration of nutrients in river Pô. Instead, it would result in a much smaller increase in concentration. The fact that doubling production causes doubling in the concentration in river Pô means that natural concentration of nutrients in river Pô would be zero. On the other hand, we know that the natural concentration of nutrients in river Pô is greater than zero, hence it must be insignificant. Since this is an order of magnitude analysis, it follows that the natural concentration of nutrients in the river Pô is at least an order of magnitude smaller than the present concentration.

Another piece of evidence comes from Gržetiæ et al. (1991) who compare the inflow of rivers Krka, Rijeina and Bakar Bay ground waters (all from east Adriatic coast) to rivers entering N.A.. If one compares the average concentrations of these rivers to the average concentration of N.A. rivers (weighted with respect to the inflow of each), one comes to the following conclusion:

Concentration factor (dimensionless)	total		
	mineral N	PO ₄	SiO ₂
N.Adriatic rivers/ relatively pristine rivers from eastern adriatic coast	4.2	18.45	5.2
Pô/Krka	9	46	5

Let us mention that neither of considered rivers nor ground waters from east Adriatic coast are entirely pristine i.e. all of them contain an anthropogenic contribution. Despite the rough approach, the concentration factor above shows clearly how far are rivers entering N. A. from natural values. It is necessary to state that river Pô heavily weights in these estimates since it has the highest concentrations and by far the highest rate of water discharge.

The ratio of nutrient concentrations in river Pô to river Krka is in agreement to the above order of magnitude analysis.

Since the major source of fresh-water to N.A. carries an order of magnitude higher nutrient concentration than the natural, we consider that hypothesis H1 is proven.

Hence, the cause of eutrophication in N.A. since 1945 is clearly anthropogenic as the change of nutrient inflow is not a fraction of the natural inflow but an order of magnitude increase.

3.7 Consequence of increase of primary production in the upper layer

Among others, the three parameters that have been measured frequently in N.A. and which represent integrals of primary production are: chlorophyll-a, oxygen and dissolved organic matter.

One would expect that the three would be correlated at least in the surface layer. Indeed oxygen concentration and chlorophyll-a are correlated. From data in Jeftić and Smodlaka (1978), one easily finds: $DO (\%) = 87.2 + 5.43 \text{ Chl-}a (\mu\text{g l}^{-1})$; $R=0.91$.

Dissolved organic material produced by phytoplankton has been measured as surfactant activity (Žutić et al., 1981). Dissolved organic matter (DOC) and its surface active fraction are higher in N.A. than in open waters of the rest of the Adriatic and Mediterranean (Aosovič et al., 1985). Surface active organic matter (S.A.) correlates well with DO concentration ($R = 0.93$), (Žutić and Legović 1990).

Since we had only DO concentration as a long-term parameter, we concluded so far: increase in DO concentration \Rightarrow increase in Chl-a \Rightarrow increase of DOC.

From the above we conclude that primary production must have increased.

Increase in primary production over the long-time interval means that we expect phytoplankton blooms which occur in spring, summer and autumn to cover a much larger area.

From data in our disposal we were not able to find evidence that phytoplankton blooms in N.A. are more frequent in recent years. However, using a model of phytoplankton dynamics, we have shown that in general, if nutrient inflow to an area is high, previously inexistent autumn bloom becomes regular (Legoviæ and Justiæ 1984a, 1984b).

The most visible recent phenomenon in the N.A. is occurrence of massive quantities of gelatinous material or mucilage. This material occurs in the order of 1 to 50 million tons during the largest events. So far the cause for the appearance of this material was sought in specific hydrodynamic and meteorological conditions prevailing over N.A. (Degobbis *et al.*, 1979; Degobbis, 1989). While it is obviously true that during calm weather and weak currents, phytoplankton can reach higher densities, and in the later stage, a higher flux ($\text{g C m}^{-2} \text{ s}^{-1}$) of mucilage is reached in a confined area, it also follows from a biological common sense that high densities of phytoplankton can not occur over a wide area whatever the meteorological conditions are, if sufficient amount of nutrients were not present previously. For example, the same conditions that prevailed in summer 1988 over N.A. when an extensive bloom occurred (Degobbis, 1989) also prevailed over middle Adriatic, but still the concentration of phytoplankton and later of the mucilage production, reached highest values in N.A.

Another interesting phenomenon occurs in the last ten years and has attracted a lot of public attention and lately research effort too. High densities of jellyfish *Pelagia noctiluca* have been observed beginning with year 1977. Although this phenomenon has not been exclusively linked to an increase in primary production of the area, the increase in primary production and its various consequences (increase in dissolved organic matter, phytoplankton and zooplankton concentration in the upper layer) and overfishing of predators to *Pelagia noctiluca* are among factors contributing to the increase in density of this jellyfish (Legoviæ 1987; 1991).

3.8 Consequences of oxygen decrease on the bottom

Low dissolved oxygen concentrations close to the bottom of the Northern Adriatic may eliminate organisms living on the bottom or organisms which have a bottom attached phase in their life cycle. Benoviæ *et al.* (1987) presented a comprehensive data set which shows a correlation between oxygen depletion near the bottom and disappearance of meroplanktonic hydromedusan species in the N.A. In this respect the mean oxygen concentration is neither critical nor decisive, it is the minimum oxygen concentration which matters. Data analyzed by Justiæ *et al.* (1987) indicate that the concentration may fall below 0.5 ml DO l^{-1} at 2 m above the bottom. Since data closer to the bottom were not in our disposal. We may only speculate what concentrations may be found there. In any case we do expect smaller oxygen concentrations, and, according to the evidence by Stachowitsch (1984) the deficit is sufficient to cause mass mortalities. In 1974 mass mortality of benthic macrofauna was recorded in the central part of the gulf of Trieste (Fedra *et al.*, 1976). Similar events were observed north of Rimini in September and October 1985 (Chiaudani *et al.*, 1983a,b). In the gulf of Trieste mass mortality of benthic

animals was observed in September 1980 and 1983 when the affected area was estimated to cover about 50 km² (Stachowitsch, 1984; Faganeli et al., 1985). Mass mortality has so far been linked to a combination of climatic and hydrological conditions but data presented above (Fig. 2) indicate a long-term ecological change, and hence we expect that these events occur over a larger area than before 1945. Crema et al. (1991) found a number of effects that frequent catastrophic events induce on the structure of macrofaunal communities. Expectations and conclusions based on long-term trends hold on the average. Although, natural changes in nutrient inflow continue to exist from one year to another, year-to-year changes are magnified recently due to the high anthropogenic nutrient concentrations in incoming fresh waters.

3.9 Dynamics of oxygen content near the bottom

3.9.1 A simple box model

The model is constructed for simulating effects of higher production and higher stratification on the DO concentration near the bottom (Justiæ 1989).

The formulations adopted in the model are the following:

3.9.1.1 Primary production and sedimentation of organic matter

Seasonal dynamics of primary production in N.A. are known with precision from detailed studies using incubators (Gilmartin and Revelante, 1980; Smolaka, 1986), from in situ studies (Kveder et al., 1971) and from expressions relating the two (Precali, 1983).

The integrated value of the intensity of primary production (PI) in the euphotic zone during the year is calculated on the basis of the potential primary production (Po) in the surface layer. Daily values are obtained for the interval between 6 AM and 6 PM. The hypothesis was used that daily intensity follows a parabola with a maximum at 12 h. It was also assumed that primary production decreases exponentially with depth. The coefficient of attenuation, k is calculated from Secchi disk depth, z_s:

$$PI = \int_0^{z_{eu}} P(z) dz, \text{ where } : P(z) = P_o * e^{-k*z} \text{ and } k = c/z_s. \quad (1)$$

The value of the constant c is 1.5. For the euphotic depth, z_{eu}, we took z_{eu} = 3*z_s.

Integrated values of yearly primary production in the west area change from 90 to 115 gC m⁻² y⁻¹.

Based on results from other shallow ecosystems (Hartwig, 1976; Smetacek, 1980; Suess, 1980), the quantity of organic matter that sedimented to the bottom is proportional to the integral of primary production. On short time intervals (i.e. days) this dependence is not obvious due to a time lag between primary production and sedimentation.

It was found that the ratio between intensity of primary production and sedimentation is in the range from 0.1 at the beginning of the phytoplankton bloom, to 1.0 at the end of the bloom (Starešinić *et al.*, 1982). During winter and spring, diatom blooms sediment to the bottom relatively fast (Durbin and Durbin, 1981; Smetacek, 1984). On the contrary, during summer the percentage of organic matter that ends on the bottom is smaller mainly due to smaller sinking of nanoplankton and more intensive zooplankton feeding (Malone, 1980; Hobbie and Cole, 1984). The rate of organic detritus sedimentation varies between 0.2 and 100 m day⁻¹. The sinking speed depends on the size of particles, ratio between specific gravity and surface of the particles, the intensity of stratification and the state of the plankton community. Starešinić *et al.* (1981 and 1982) determined that the value of sedimentation flux in the Northern Adriatic varies from 40 mgC m⁻² day⁻¹ in the eastern part to 140 mgC m⁻² day⁻¹ in the western part. It follows that between 25% and 30% of primary production sediments to the bottom. On the basis of the above, the sedimentation process will be described in the following way:

$$S(t) = \acute{a} \text{ PI } (t - n) \quad (2)$$

where S(t) is sedimentation flux (mgC m⁻² day⁻¹), PI is daily integrated primary production (mgC m⁻² day⁻¹), \acute{a} is sedimentation rate (between 0.25 and 0.3 day⁻¹, t is time in days and n is time needed for the biomass to reach the bottom.

3.9.1.2 Benthic respiration

Benthic respiration, R, will be formulated as a first order process:

$$R(t) = 2.01 * k_b (T, O_2) * F(t) \quad (3)$$

where R is in dm³O₂ m⁻² day⁻¹, k_b - parameter which determines dependence of respiration on temperature and concentration of oxygen in the bottom layer, F(t) is quantity of organic matter that is available for decomposition (gC m⁻²). The value of F(t) is:

$$F(t) = \int_{t_0}^t [S(t') - R(t')] dt' \quad (4)$$

S(t') and R(t') are sedimentation rate and benthic respiration rate, respectively.

Benthic respiration depends on temperature and concentration of dissolved oxygen and is given by:

$$\begin{aligned} k_b (T, DO) &= k_o (T/T_{max})^a \text{ if } DO > 1.5 \text{ cm}^3 \text{ DO dm}^{-3} \\ k_b (T, DO) &= k_o (T/T_{max})^a * (DO/1.5)^b \text{ otherwise} \end{aligned} \quad (5)$$

where T_{max} - maximum value of temperature in the bottom layer while a and b are constants. From experimental data (Hargrave, 1969; Nixon *et al.*, 1980; Officer *et al.*, 1984) it follows that the value of the exponent a is between 2 and 3 while exponent b is around 2. It has been determined that oxygen concentration regulates respiration only for values smaller than 1.5 cm³ DO dm⁻³ (Pamatmat, 1971).

Seasonal cycle of temperature will be represented by:

$$T = 15 - 6 \cos (2 \delta (t - \theta) / 365) \quad (6)$$

where θ is a phase shift. The maximum temperature value in the bottom layer is around 20EC.

When the temperature is around 20EC and DO concentration is above $1.5 \text{ cm}^3 \text{ O}_2 \text{ dm}^{-3}$, the value of the k_b function is close to k_0 which is between 0.001 and 0.005.

Formulas (1-6) enable one to calculate benthic respiration as a function of integrated value of sedimentation of organic matter, temperature and concentration of oxygen in the bottom layer. Using $k_0 = 0.003$ and a range of sedimentation between $17\text{-}40 \text{ gC m}^{-2} \text{ y}^{-1}$, benthic respiration is between 0.05 and $0.11 \text{ gC m}^{-2} \text{ day}^{-1}$. If we assume that decomposition and sedimentation follow the Redfield ratio ($\text{MC}/\text{MO}_2 = 0.288$ by weight) then the mean value of oxygen consumption varies between 0.14 and $0.32 \text{ g O}_2 \text{ m}^{-2} \text{ day}^{-1}$. Depending on temperature, concentration of oxygen and sedimentation of organic matter, the above values may be 2 to 3 times larger. Hence, in the most productive areas of N.A. one should expect maximum values of benthic respiration of $1 \text{ g O}_2 \text{ m}^{-2} \text{ day}^{-1}$. This value is close to more productive marine ecosystems (Jorgensen, 1979; Officer *et al.*, 1984).

3.9.1.3 Vertical transport of oxygen

Vertical transport of oxygen is usually described by the Fick's transport:

$$D = k_z A \text{ MC}/\text{Mz}$$

where D is flux of oxygen ($\text{dm}^3 \text{ O}_2 \text{ m}^{-2} \text{ day}^{-1}$), k is coefficient of vertical turbulent diffusion ($\text{m}^2 \text{ day}^{-1}$), A is the area of the diffusion surface (m^2), and C is DO concentration ($\text{dm}^3 \text{ O}_2 \text{ m}^{-3}$). The main problem in the application of Fick's transport is to determine the values for turbulent diffusion k_z . Since direct determination is very difficult, temperature is often used (Jassby and Powell, 1975; Imboden, 1979; Quai *et al.*, 1980; Abott *et al.*, 1984). In order to apply the model for transport of oxygen to the bottom layer for varying degrees of stability of the water column, we shall use a nonlinear relationship for the dependence of k_z on the intensity of stratification (Gargett, 1984):

$$k_z = 86400 a_0 N^{-1}, \text{ where}$$

$$N = [(g/\delta) (\text{Ms}/\text{Mz})]^{0.5}$$

k_z is coefficient of turbulent diffusion ($\text{m}^2 \text{ day}^{-1}$), N is Brunt-Vaisala frequency (s^{-1}), g is gravitational constant (9.81 ms^{-2}), δ is mean density in the water column, Ms/Mz is density gradient (kg m^{-4}) and $a_0 = 1.1 \cdot 10^{-7} \text{ m}^2 \text{ s}^{-2}$.

3.9.2 Simulations of the model

3.9.2.1 An average year

Figure 5 shows the typical dynamics of DO concentration on the bottom according to data (a) and according to the model (b). Since the results of the

model are found within one standard deviation from the data, we judge that the correspondence between the model and the data is acceptable. The integrated primary productivity over the year is 90 gC m^{-2} .

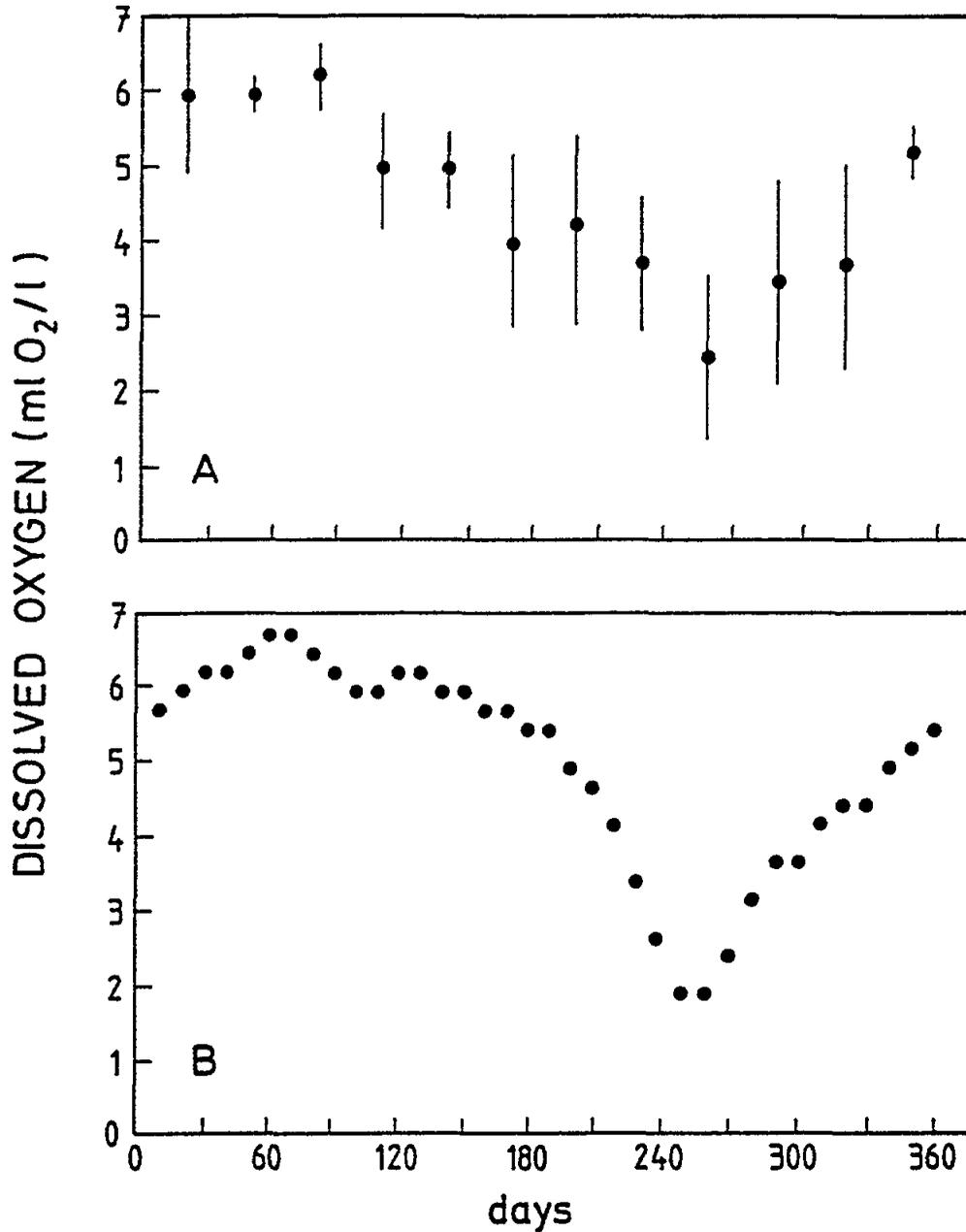


Fig. 5 Seasonal dynamics of DO concentration near the bottom: A) mean values and standard deviations for a western subregion of N.A. during 1972-82; B) model results

3.9.2.2 Effect of doubled primary productivity during one summer month

When the primary productivity integrated over one month is doubled, this perturbation roughly corresponds to a moderate phytoplankton bloom. But since we know that the effect on the concentration of dissolved oxygen near the bottom will vary depending upon the month in which the bloom occurs, we have investigated the appearance of a bloom during each of the following months separately: May, June (Fig. 6) and July and August (Fig. 7).

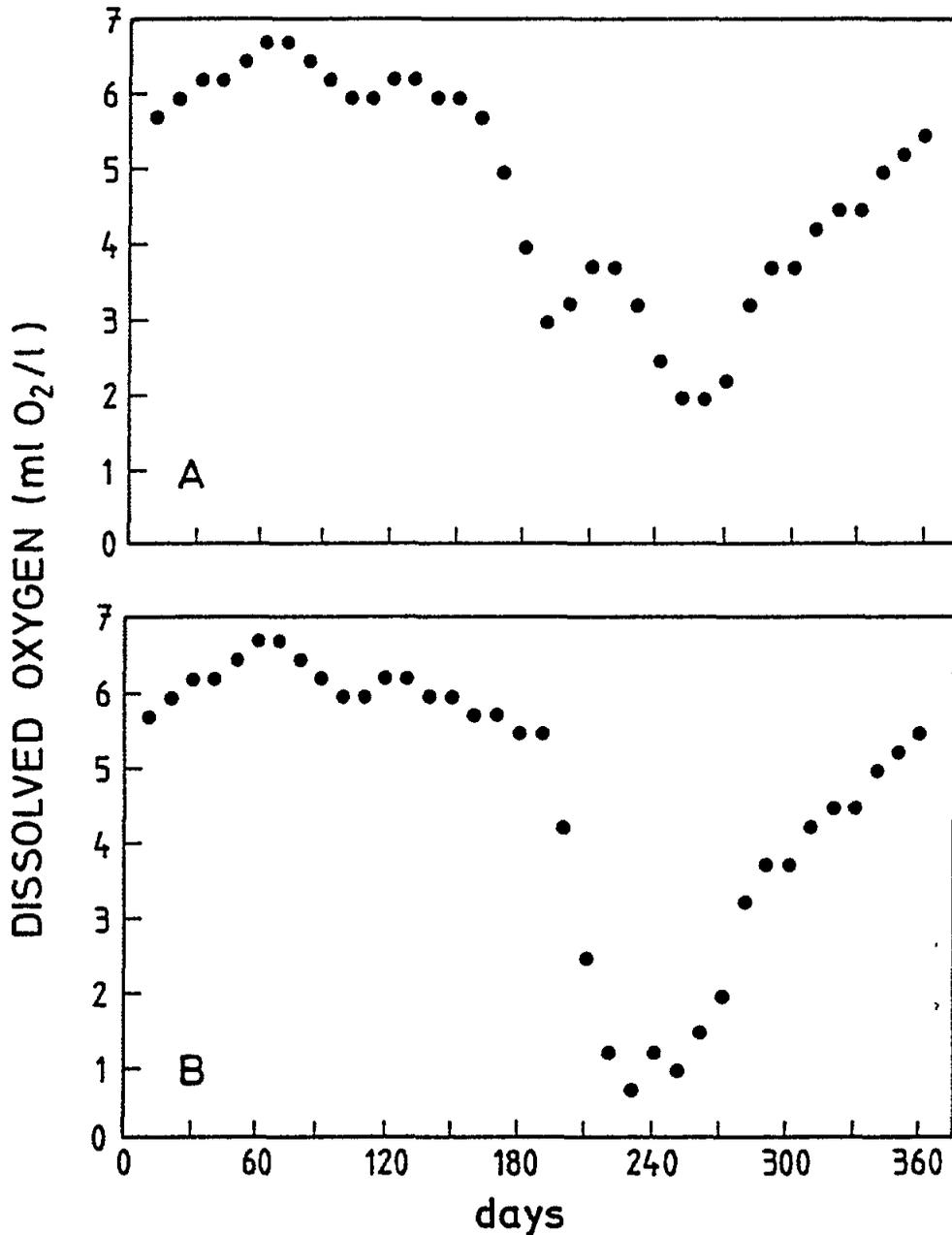


Fig. 6 Seasonal dynamics of DO concentration near the bottom according to the model in case primary production is doubled during: May (A) and June (B)

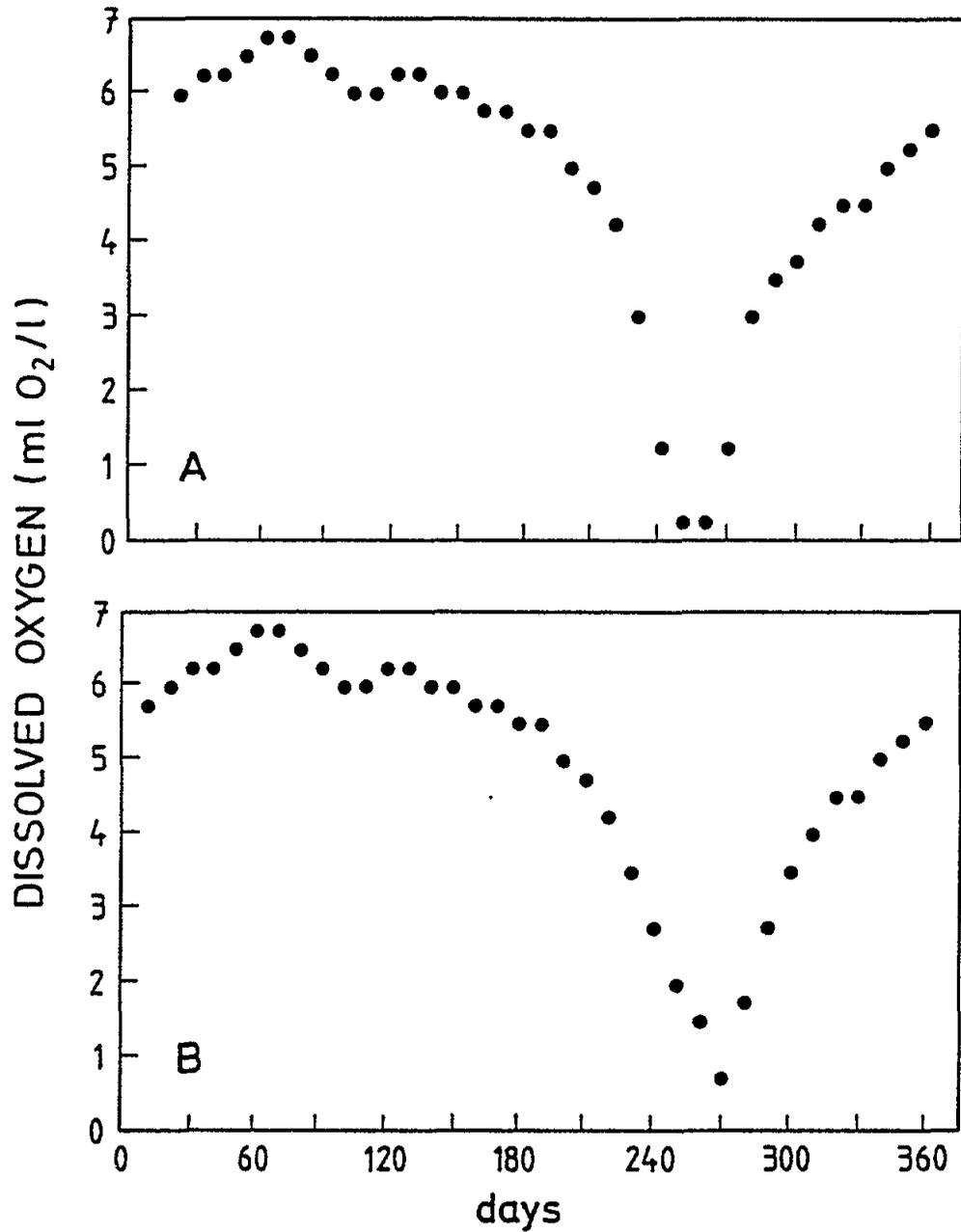


Fig. 7 Seasonal dynamics of DO concentration near the bottom according to the model in case primary production is doubled during: July (A) and August (B)

We see that the appearance of a bloom during May does not cause the concentration of dissolved oxygen near the bottom to fall below 2 ml O₂ l⁻¹. However, a bloom during June, July or August will cause greater hypoxia on the bottom. Particularly dangerous is the bloom which occurs during July. Such a bloom is likely to cause benthic mortality of organisms. A bloom in July which causes primary productivity in the surface layer three times greater in comparison to the average year will cause hypoxia on the bottom and benthic mortality of greater proportions.

3.9.2.3 Effect of a higher stratification during summer

Simulations were performed in which vertical stratification is increased by one standard deviation above the mean value. This perturbation is made to test the following hypothesis: Hypoxia on the bottom occurs because of calm weather and higher than usual vertical stratification which decreases transport of oxygen from the surface layer to the bottom layer.

Results show that the above increase in vertical stratification with respect to the normal year cannot cause significantly lower DO concentration near the bottom.

3.9.2.4 Conclusion from the model

Results from the model suggest that the dominant mechanism of hypoxia occurrence on the bottom is: a significant phytoplankton bloom above thermocline, subsequent sinking of the organic matter across the thermocline and its decomposition on the bottom.

3.10 Control

Based on evidence, causes and mechanisms of undesirable changes of N.A. ecosystem, what control would be feasible?

First, nutrient inflow which comes from sewage waters must be decreased. These waters must be chemically and biologically treated and nutrients must be controlled prior to their release into rivers that carry them to the sea. The idea that we can throw wastes to rivers because they have a self-purifying ability must be abandoned. For all those who still believe in it we suggest the following: When they take water from the stream they should release it upstream of the point of intake.

Second, strict measures must be taken to persuade the agriculture segment of the society to use much less nutrient fertilizers since obviously a significant part of it is wasted. Scientists should develop precise measures of quantity of nutrients that need to be used on agricultural lands. These measures must be soil specific and crop specific. Especially important is to develop new practices in applying fertilizers, so that crops are grown but nutrients are not lost.

3.11 Answers to questions stated in the introduction

a) Are the observed changes significant?

If we define the state as DO concentration, then we can say that the state did not change from 1911 until today only during winter. In spite of nutrient inflow, primary production during winter is slow, degradation on the bottom is slow too (because of low temperatures). In addition strong vertical exchange of water brings aerated water to the bottom.

In all other seasons the change is obvious. In late summer DO concentration near the bottom becomes so low that it causes massive mortalities of the remaining benthic fauna. This we believe is significant.

Regular peaks of algal concentrations which occur in N.A. during late spring, summer and autumn became intensive phytoplankton blooms occupying a large area of N.A. In the late stages of these blooms impressive masses of mucilage appear. These are very likely to occur during quiet weather when waters of N.A. circulate slower. Mucilage in such masses would not occur were it not for such a large nutrient inflow. This is also one significant change.

The counter argument that mucilage had appeared in historical times is very easy to explain. All rivers entering N.A. vary naturally. When large quantities of water are washed after spring rains and melting of snow, as well as waters after first autumn rains, they bring a pulse of nutrients from which a bloom will occur but this bloom will certainly be smaller than if these rivers wash a well fertilized agricultural area and bring much higher quantity of nutrients. So, we do not doubt that blooms and mucilage have occurred in historical times. We do doubt, however, that they have so often covered such a large area as they did during the last decade.

b) Is N.A. changing permanently or the changes are temporary?

The change which we observe will stay in N.A. until anthropogenic nutrient sources are reduced. The state of N.A. is dynamically responding to the increase of nutrient load.

c) What is the cause of this change?

The cause of these changes is obviously anthropogenic in the sense that they would not occur to such an extent if nutrient load were not so high.

d) What can be done to restore the ecosystem?

The only way to reverse the observed changes is to decrease nutrient inflow to N.A. The consequences of a significant nutrient reduction would be visible in a few years time. The reason is simple: large phytoplankton blooms and subsequent mucilage formation occur after nutrient pulses from river Pô. If these pulses are reduced, less extensive blooms would occur.

CEC Workshop (1990) suggested that nutrient inflow should be reduced by 50% to improve the situation. We agree that the situation would improve whatever the reduction would be, except that the effect of 50% reduction would be barely detectable. We have to remember that it has taken scientists over 40 y to recognize long-term changes when nutrient inflow has increased an order of magnitude.

4. CONCLUSIONS AND RECOMMENDATIONS

Analysis of oxygen change between 1911-13 and 1972-84 showed that the North Adriatic ecosystem has changed towards a more eutrophic state. We expect significant episodes such as extensive phytoplankton blooms, extensive mucilage formations and mass mortality of benthic animals to occur more often in N.A. than before. As a consequence, a further decrease in fishery yield of benthic fishes may also be expected.

The only cure to decreasing the induced change in primary production is to reduce the inflow of nutrients to N.A.

The recommendation for monitoring, concerns parameters which document the change of the eutrophic state. Primary production, chlorophyll-a, dissolved oxygen near the bottom and surfactant activity (as a reliable measure of DOM) are not in the list of parameters to be measured within the Mediterranean Long-Term Pollution and Research Programme. We recommend that these parameters be measured.

Except for an excellent study by Faganeli et al. (1985), properties of the N.A. ecosystem near the bottom have been poorly investigated so far. Since it is clear that massive mortalities of benthic organisms are connected to oxygen depletion at the bottom, biweekly measurements during summer and seasonal measurements of dissolved oxygen at a fine vertical resolution should be established.

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A STUDY OF PHYTOPLANKTON POPULATIONS OF THE RIVA TRIGOSO BAY
(Gulf of Genoa) IN RELATION TO EUTROPHICATION FEATURES
OF THE WATER

by

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ABSTRACT

This study concerns the examination of phytoplankton populations and water eutrophication in the Riva Trigoso Bay (Gulf of Genoa).

Samples were taken monthly from April 1988 to May 1989 at a fixed station; the phytoplankton study took place on an annual basis examining diatoms and dinoflagellates in particular; furthermore, the phytoplanktonic biomass and cell density were evaluated, and the water temperature, salinity and pH were measured.

The study of seasonal variations of phytoplankton biomass and species composition has emphasized the oligotrophic characteristics of the Riva Trigoso Bay waters.

1. INTRODUCTION

It is well established that waters derived from the hinterland and particularly urban and industrial discharges can produce increasing eutrophic conditions in coastal waters. The aim of this research was to determine the seawater characteristics in a coastal zone of the Gulf of Genoa which is affected by human activities and the flow of waste waters. Eutrophication was evaluated by determining the phytoplankton biomass and the seasonal trend of diatoms and dinoflagellates.

2. MATERIALS AND METHODS

The area under examination (Fig. 1) was the Riva Trigoso Bay (Gulf of Genoa) which was chosen as a result of the following features:

- the discharge into the Bay via the Petronio stream, of both urban and agricultural wastes
- the presence of a submarine city sewer system (east of Punta Manara, 500 m distance at a depth of 37 m), that also receives discharges from naval docks;
- an increase in the summer tourist population;
- the existence of fishing activities (both recreational and professional).

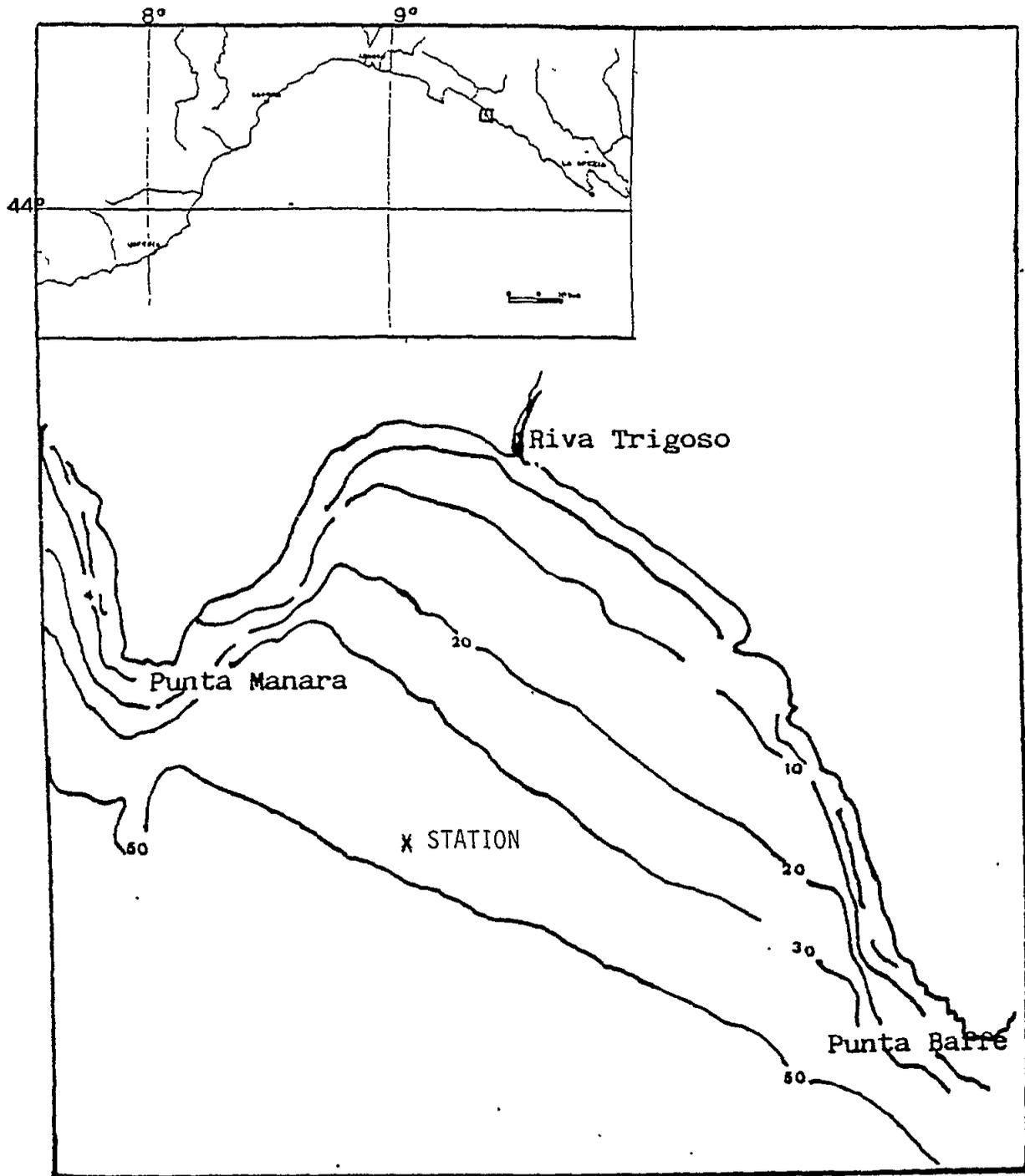


Fig. 1 The sampling area in the gulf of Genoa

Sampling was carried out at a fixed station (depth 40 m) during April 1988 to May 1989; 46 samples were collected in total; some hydrological parameters (temperature, salinity, pH) were also measured.

The phytoplankton biomass was studied by determining the chlorophyll-*a* concentration and by counting the number of cells per litre; furthermore, a systematic classification of phytoplankton species was performed.

The water samples were collected using a membrane pump; temperature measurements were taken "*in situ*"; salinity and pH values were measured in the laboratory, using standard methods (FAO, 1975).

The chlorophyll-*a* concentration was estimated according to the method of Strickland and Parsons (1960). The systematic analysis of phytoplankton (diatoms and dinoflagellates) was performed according to Utermöhl (1958).

3. RESULTS

Table 1 shows the collective data on hydrological parameters. Surface water temperature varied from 12EC (February 1989) to 23EC (July 1988) and at the deeper layers (17m and 36m) from 13EC (December 1988, February and March 1989) to 21EC (July 1988). A vertical water stratification, causing a variation of 1 to 2EC between depths was noted in summer 1988.

Table 1

Temperature, salinity and pH values
at three depths in Riva Trigoso Bay.

PARAMETERS DEPTH DATE	TEMPERATURE (EC)			SALINITY			pH		
	surf.	17m	36m	surf.	17m	36m	surf.	17m	36m
20.04.88	15.0	-	-	36.00	-	-	8.15	-	-
26.05.88	21.0	-	-	36.33	-	-	8.00	-	-
20.06.88	21.0	-	-	-	-	-	-	-	-
18.07.88	23.0	21.0	20.0	36.35	36.21	36.12	7.95	8.02	8.06
03.10.88	20.0	20.0	20.0	37.10	37.35	37.30	8.24	8.28	8.30
17.11.88	17.5	18.0	18.0	37.05	37.75	37.50	8.36	8.32	8.33
19.12.88	13.0	13.0	13.0	36.19	36.96	37.30	8.12	8.06	8.05
02.02.89	12.0	13.0	13.0	37.17	37.60	37.47	8.29	8.31	8.28
30.03.89	14.0	13.5	13.0	37.43	37.33	37.49	8.32	8.28	8.28
30.04.89	15.0	-	-	-	-	-	-	-	-
04.05.89	16.0	15.5	15.5	37.04	37.63	37.24	8.13	8.19	8.16

From October to December 1988 water homeothermic conditions were observed. In February a temperature inversion was noted and a decrease of surface temperature, which however increased from March onwards.

With respect to salinity a fluctuation from 36‰ at the surface (April 1988) to 37.75‰ at 17 m (November 1988) was noted. The pH values coincide at all studied depths, with a minimum of 7.95 (surface, July 1988) and a maximum of 8.36 (36 m, December 1988).

The surface concentration of chlorophyll-*a* (Table 2) varied from 0.07 µg l⁻¹ (December 1988) to 1.38 µg l⁻¹ (April 1988), while at greater depths these values varied from 0.10 µg l⁻¹ (July 1988, February 1989) to 0.56 µg l⁻¹ (May 1989).

Phytoplankton (Table 2) was abundant in March, April and May 1989 between 36 m and the surface, and decreased during the following months, except in July 1988 (8861 cells l⁻¹) in surface waters.

Table 2

Chlorophyll-*a* concentrations (µg l⁻¹) and phytoplankton density (diatoms plus dinoflagellates in cells per litre) at the 3 sampling depths in Riva Trigoso Bay.

DATE	Chlorophyll- <i>a</i>			Phytoplankton		
	surface	17m	36m	surface	17m	36m
20.04.88	1.38	-	-			
26.05.88	0.49	0.46	0.47			
20.06.88	0.55	-	-	2866	-	-
18.07.88	0.35	0.10	0.46	8861	566	1308
03.10.88	0.28	0.22	0.50	2833	1509	2871
17.11.88	0.29	0.29	0.29	2706	1884	2091
19.12.88	0.07	0.46	0.50	2689	4503	3204
02.02.89	0.52	0.46	0.10	754	1187	1520
30.03.89	0.30	0.13	0.50	17552	13614	9878
30.04.89				17080	-	-
04.05.89	0.32	0.56	0.36	16075	16208	3678

In winter a homogeneous cell density was noted, while during spring and summer, a greater phytoplankton stratification was noted at the surface. In particular, diatoms were always found at a 75% percentage (Table 3); in June 1988 only they were replaced by dinoflagellates (86.8%).

Tables 4 and 5 show the species list and percentage of diatoms and dinoflagellates. In the surface layer the following species prevailed (>15%): Asterionella glacialis, Chaetoceros curvisetus, Leptocylindrus danicus, Nitzschia closterium, Nitzschia delicatissima, Rhizosolenia alata,

Thalassiothrix frauenfeldii, Prorocentrum micans; at 17 m : Asterionella glacialis, Leptocylindrus danicus, Nitzschia seriata, Nitzschia delicatissima, Dactyliosolen blavyanus; at 36 m: Leptocylindrus danicus, Nitzschia closterium, Nitzschia delicatissima, Nitzschia seriata, Thalassiothrix frauenfeldii and Bacillaria paradoxa.

Table 3

Percentage of diatoms and dinoflagellates at the three sampling depths in Riva Trigoso Bay.

DEPTH DATE	DIATOMS			DINOFLAGELLATES		
	surface	17m	36m	surface	17m	36m
20.06.88	13.1	-	-	86.8	-	-
18.07.88	89.0	74.9	95.3	10.9	25.0	4.6
03.10.88	79.5	80.4	91.1	20.5	19.6	8.9
17.11.88	92.2	93.4	91.4	7.8	6.6	8.6
19.12.88	96.3	98.4	98.4	3.7	1.6	1.6
02.02.89	85.8	87.1	97.1	14.2	12.9	2.9
30.03.89	98.1	99.7	99.4	1.9	0.3	0.6
30.04.89	97.9	-	-	2.1	-	-
04.05.89	94.0	97.7	98.4	6.0	2.3	1.6

As far as the percentage composition of phytoplankton in surface waters is concerned, during 1988 the prevailing species were: Prorocentrum micans (48.1%) and Goniodoma polyedricum (11.8%) in June, Leptocylindrus danicus (18.2%) and Rhizosolenia stolterfothii (17.4%) in July, Leptocylindrus danicus (7.9%) in October, Nitzschia closterium (3.7%) and Thalassiothrix frauenfeldii (3.9%) in November, Nitzschia closterium (19.1%) and Thalassiothrix frauenfeldii (26.4%) in December. During 1989 Nitzschia closterium (7.6%) prevailed in February, Nitzschia delicatissima (41.4%) and Chaetoceros curvisetus (19.1%) in March and Thalassiothrix frauenfeldii (35.5%) and Asterionella glacialis (14.8%) in April.

Table 6 shows the "Shannon-Weiner index" for the sampled phytoplankton.

4. DISCUSSION

The study of seasonal variations of the phytoplankton biomass and species composition has emphasized the oligotrophic characteristics of the Riva Trigoso Bay waters. The data obtained concerning chlorophyll-*a* concentrations substantially agree with some studies performed in other sea areas of the Ligurian Sea (Jacques, 1967; Nival *et al.*, 1976; Carli *et al.*, 1980; Bruzzone *et al.*, 1982; Cattaneo and Fabiano 1982; Fabiano *et al.*, 1984; Innamorati *et al.*, 1987) which are presumably not affected by eutrophication.

Table 4

Percentage frequency of diatoms; surface layer (* stands for # 0.1%).

DATE	1988					1989			
	June 20	July 18	Oct. 03	Nov. 17	Dec. 19	Feb. 02	Mar. 30	Apr. 30	May 04
DIATOMS									
<u>Amphora spp.</u>	-	-	3.0	0.5	1.7	1.1	0.6	1.3	0.5
<u>Asterionella glacialis</u>	-	-	0.2	-	-	-	1.2	14.8	18.9
<u>Asterolampra marvlandica</u>	-	-	*	*	0.2	-	-	-	-
<u>Biddulphia mobiliensis</u>	-	-	-	-	0.5	-	-	0.2	*
<u>Biddulphia sinensis</u>	-	-	-	-	0.2	-	-	-	-
<u>Cerataulina bergonii</u>	-	14.4	-	-	1.1	-	0.8	0.3	0.2
<u>Chaetoceros curvisetus</u>	-	-	-	-	-	-	19.1	5.1	2.6
<u>Chaetoceros decipiens</u>	-	2.3	-	-	0.5	-	3.2	2.8	5.7
<u>Chaetoceros densus</u>	-	-	-	0.3	0.7	-	-	-	-
<u>Chaetoceros ingolfianus</u>	-	-	-	2.5	-	-	-	-	-
<u>Chaetoceros peruvianus</u>	-	-	0.2	*	0.2	-	*	0.2	0.2
<u>Chaetoceros spp.</u>	-	5.2	1.2	0.7	1.8	6.4	1.2	0.3	1.3
<u>Cocconeis spp.</u>	-	-	2.8	0.5	0.4	-	*	0.2	*
<u>Coscinodiscus spp.</u>	*	-	2.7	4.8	4.6	9.0	-	2.5	2.0
<u>Dactyliosolen blavvanus</u>	-	6.0	0.8	-	0.2	-	1.8	1.6	1.0
<u>Dactyliosolen mediterraneus</u>	-	-	3.5	0.9	-	-	0.3	-	*
<u>Diploneis sp.</u>	-	-	-	-	-	-	-	-	*
<u>Dytilum brightwellii</u>	-	-	-	-	0.9	-	-	*	-
<u>Grammatophora sp.</u>	-	-	-	-	-	-	-	*	*
<u>Guinardia flaccida</u>	*	-	-	-	-	-	-	-	*
<u>Hemiaulus hauckii</u>	0.6	1.5	1.3	0.2	0.2	-	1.1	0.2	0.1
<u>Hemiaulus spp.</u>	-	-	-	-	-	-	0.3	-	-
<u>Leptocylindrus danicus</u>	-	18.2	7.9	1.8	1.0	2.6	5.4	0.7	1.8
<u>Leptocylindrus minimum</u>	-	-	3.4	-	2.4	-	*	-	-
<u>Licmophora spp.</u>	0.9	0.7	3.4	1.3	0.5	1.3	0.7	0.8	3.1
<u>Navicula crabro</u>	-	-	-	0.5	-	-	-	-	-
<u>Navicula spp.</u>	0.7	-	17.6	3.4	13.9	1.3	1.0	3.8	2.0
<u>Nitzschia closterium</u>	-	-	6.2	3.7	19.1	7.6	0.7	0.6	1.5
<u>Nitzschia delicatissima</u>	-	-	1.4	-	0.7	-	41.4	1.1	1.7
<u>Nitzschia seriata</u>	-	-	-	-	1.9	-	3.4	1.2	4.0
<u>Plagioqramma pulchellum</u>	-	-	-	0.2	*	-	-	-	-
<u>Pleurosigma spp.</u>	-	-	*	0.5	1.8	0.4	*	*	*
<u>Rhabdonema adriaticum</u>	*	-	-	-	-	-	-	-	*
<u>Rhizosolenia alata</u>	-	12.1	4.2	-	*	-	5.6	0.9	4.5
<u>Rhizosolenia calcar avis</u>	-	0.7	2.0	-	-	-	*	*	*
<u>Rhizosolenia delicatula</u>	-	-	-	-	-	-	0.6	-	0.3
<u>Rhizosolenia fragilissima</u>	-	0.7	-	-	-	*	-	2.9	4.2
<u>Rhizosolenia imbricata</u>	-	-	-	-	-	-	1.5	-	4.8
<u>Rhizosolenia shrubsolei</u>	-	-	-	-	-	1.9	-	-	-
<u>Rhizosolenia stolterfothii</u>	-	17.4	*	-	-	3.0	0.9	*	0.2
<u>Rhizosolenia temperei</u>	-	-	-	*	-	-	-	-	-
<u>Rhizosolenia spp.</u>	-	-	0.3	0.3	-	1.0	-	-	-
<u>Skeletonema costatum</u>	-	-	-	-	6.3	-	*	6.2	0.2
<u>Striatella sp.</u>	-	-	-	-	-	-	-	-	0.2
<u>Thalassionema nitzschioides</u>	-	-	0.6	0.7	2.8	-	*	9.4	1.6
<u>Thalassiosira decipiens</u>	-	-	-	-	0.7	-	-	-	-
<u>Thalassiothrix frauenfeldii</u>	-	3.8	1.9	3.9	26.4	5.9	2.9	35.5	29.5
<u>Triceratium sp.</u>	-	-	-	-	-	1.3	-	*	-
unidentified diatoms	11.0	2.9	12.4	66.0	3.5	33.4	2.0	2.2	0.8

With respect to the abundance of diatoms and dinoflagellates the results agree with those of Rampi (1954) for the Punta Mesco sea area, where diatoms prevailed.

Furthermore, the observations presented in this study are also in agreement with Bernhard et al. (1969) who found, off the Cinque Terre zone, a diatom prevalence over dinoflagellates, throughout the year.

Table 5

Percentage frequency of dinoflagellates at the surface layer (* stands for # 0.1%).

DATE	1988					1989			
	June 20	July 18	Oct. 03	Nov. 17	Dec. 19	Feb. 02	Mar. 30	Apr. 30	May 04
DINOFLAGELLATES									
<u>Ceratium candelabrum</u>	*	-	-	-	-	-	-	-	-
<u>Ceratium declinatum</u>	-	-	0.5	-	*	-	-	*	-
<u>Ceratium furca</u>	5.7	0.5	0.3	-	-	-	*	0.2	0.3
<u>Ceratium fusus</u>	0.7	*	*	-	0.4	0.6	-	0.5	0.8
<u>Ceratium gibberum</u>	-	-	*	-	-	-	-	-	-
<u>Ceratium macroceros</u>	-	*	*	-	-	-	-	-	-
<u>Ceratium massiliense</u>	-	*	1.0	-	-	-	-	-	-
<u>Ceratium tripos</u>	1.6	-	-	-	-	-	-	-	-
<u>Ceratium sp.</u>	*	-	-	-	-	-	-	-	-
<u>Dinophysis caudata</u>	1.0	4.5	-	-	-	-	-	-	-
<u>Dinophysis spp.</u>	1.6	-	*	-	-	0.4	*	-	-
<u>Goniodoma polyedricum</u>	11.8	-	-	-	-	-	-	-	-
<u>Gonvaulax spp.</u>	0.4	-	-	0.7	-	0.4	0.6	-	-
<u>Ornithocercus quadratus</u>	-	-	-	-	-	0.4	-	-	-
<u>Oxytoxum scolopax</u>	-	-	-	-	*	0.4	-	-	-
<u>Oxytoxum tessellatum</u>	-	-	-	*	-	-	-	-	-
<u>Oxytoxum spp.</u>	0.7	0.7	2.4	1.8	0.7	0.4	-	-	*
<u>Peridinium cerasus</u>	-	-	-	-	-	0.4	-	-	-
<u>Peridinium conicum</u>	1.5	-	-	-	-	-	-	-	-
<u>Peridinium depressum</u>	0.7	-	-	-	-	0.4	-	-	-
<u>Peridinium diabolus</u>	0.4	-	-	-	-	-	*	*	*
<u>Peridinium divergens</u>	-	-	0.3	-	-	-	-	-	-
<u>Peridinium globulus</u>	-	*	-	-	-	-	-	*	-
<u>Peridinium longipes</u>	-	-	-	-	-	-	*	*	*
<u>Peridinium mediterraneum</u>	*	-	-	-	-	-	-	-	-
<u>Peridinium oblongum</u>	0.4	-	-	-	-	-	-	-	-
<u>Peridinium stenii</u>	1.3	-	-	-	-	-	-	-	-
<u>Peridinium spp.</u>	6.2	*	0.3	-	-	-	-	-	*
<u>Podolampas palmipes</u>	-	-	-	-	-	-	*	-	-
<u>Prorocentrum compressus</u>	0.4	-	0.6	-	-	-	-	-	-
<u>Prorocentrum micans</u>	48.1	0.2	0.3	-	*	0.6	0.2	0.4	2.6
<u>Prorocentrum spp.</u>	-	-	1.0	0.5	-	-	-	*	-
<u>Pyrocystis lunula</u>	-	-	*	-	-	-	-	-	-
<u>Pyrocystis obtusa</u>	-	-	*	*	-	0.4	-	-	-
unidentified dinoflagellates	3.7	4.5	13.0	4.5	2.2	9.7	0.8	0.7	1.5

Concerning the phytoplankton species composition, according to Rampi (1954), Prorocentrum micans prevailed in June, Leptocylindrus danicus in July, Nitzschia delicatissima and Thalassiothrix frauenfeldii in April, May and December.

A similar cell density of Thalassiothrix frauenfeldii was reported by Forti (1922) in Genova-Quarto and by Jacques (1967) in the Banyuls-sur-Mer area (only in April). Thalassiothrix frauenfeldii which is considered by Bernhard *et al.* (1969) as a discontinuous species, occurred very frequently in samples in the present study.

With respect to Leptocylindrus danicus the results of the present study are in agreement with other studies concerning the phytoplankton populations of the East Ligurian Sea (Bernhard *et al.*, 1969; Cattaneo and Fabiano 1982). The diversity index (Shannon and Weaver, 1949), estimated on

Table 6

Diversity index (Shannon and Weaver, 1949)
for diatoms and dinoflagellates in Riva Trigoso Bay.

DATE	SURFACE	17 m	36 m
20.06.88	2.59	-	-
18.07.88	3.13	3.70	2.07
03.10.88	3.89	4.67	3.98
17.11.88	3.26	3.37	3.80
19.12.88	3.31	3.38	3.60
02.02.89	3.71	3.12	3.55
30.03.89	2.86	2.64	2.77
30.04.89	3.13	-	-
04.05.89	3.52	3.51	3.56

diatoms and dinoflagellates together, excluding undetermined specimens, showed throughout an average value of 3.33 ± 0.54 (Table 6) and this value rarely varied during the studied period.

The lowest values were found in warm months (June, July), when there were not many phytoplankton species, but showed however a high individual density.

5. CONCLUSIONS

This study shows that the area under investigation is not affected by eutrophic phenomena, in spite of exogenous sources occasionally increasing the phytoplankton biomass.

However, the data obtained suggest that monitoring should be continued on a more frequent basis in order to obtain a better evaluation of the effect of environmental factors on the structure and dynamics of phytoplankton populations in coastal waters which are under the influence of human activities.

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A STUDY OF PLANKTONIC POPULATIONS IN RELATION TO THE EUTROPHICATION
STATE OF THE WATER IN A LIGURIAN SEA ZONE

by

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ABSTRACT

This study examines the water characteristics of a neritic zone in front of Genova (Ligurian Sea). Sampling was carried out during the spring to summer period of 1989, 1990 and 1991 at two stations. The depth of the first station was 20 m while the depth of the second one which was not fixed was 100 m during 1989 and 700 m during the samplings of 1990 and 1991. Some physico-chemical parameters, total bacteria, total and faecal coliforms and phyto- and zooplanktonic biotic communities were considered. On the whole, all recorded values show a generalized oligotrophic state of the water; nevertheless, an increasing trend of some parameters in the coastal station, probably due to anthropogenic causes, was occasionally indicated. Classification and ordination techniques were applied to define temporal and structural changes of the community.

1. INTRODUCTION

The research group of the Planktonology Chair (University of Genova), involved in this MED POL Phase II project, has for three years studied the water quality of a coastal zone in the Gulf of Genova (Ligurian Sea) affected by purified urban waste waters and freshwater inputs, by examining some eutrophication indicators, the bacteria, and the quantitative and qualitative compositions of phyto- and zooplankton populations.

Eutrophic phenomena are closely related to many factors, such as nutrient and organic matter increase (Aubert, 1988; Cruzado, 1988). Particularly, several pollutants often affect coastal areas of large cities, producing changes of water characteristics as well as turbidity and abnormal algal growth (Genovese, 1979).

2. MATERIALS AND METHODS

The research was carried out in two areas (coastal station ST1, depth of about 20 m; offshore station ST2, depth of about 100 m during 1989 and 700 m during 1990 and 1991) located in front of Genova-Sturla (Fig. 1). Sampling was carried out at the surface and at a depth of 10 m in both stations, in May, June, July and September 1989; June, August, September and October 1990; April, June, July, August and October 1991. The study included hydrological parameters (temperature, pH, salinity, dissolved oxygen), nutrients (nitrites,

nitrates, phosphates), chlorophyll-*a* analysis, bacterial count (heterotrophic, total and faecal coliforms), quantitative and qualitative composition of phytoplankton (diatoms, dinoflagellates) and zooplankton.

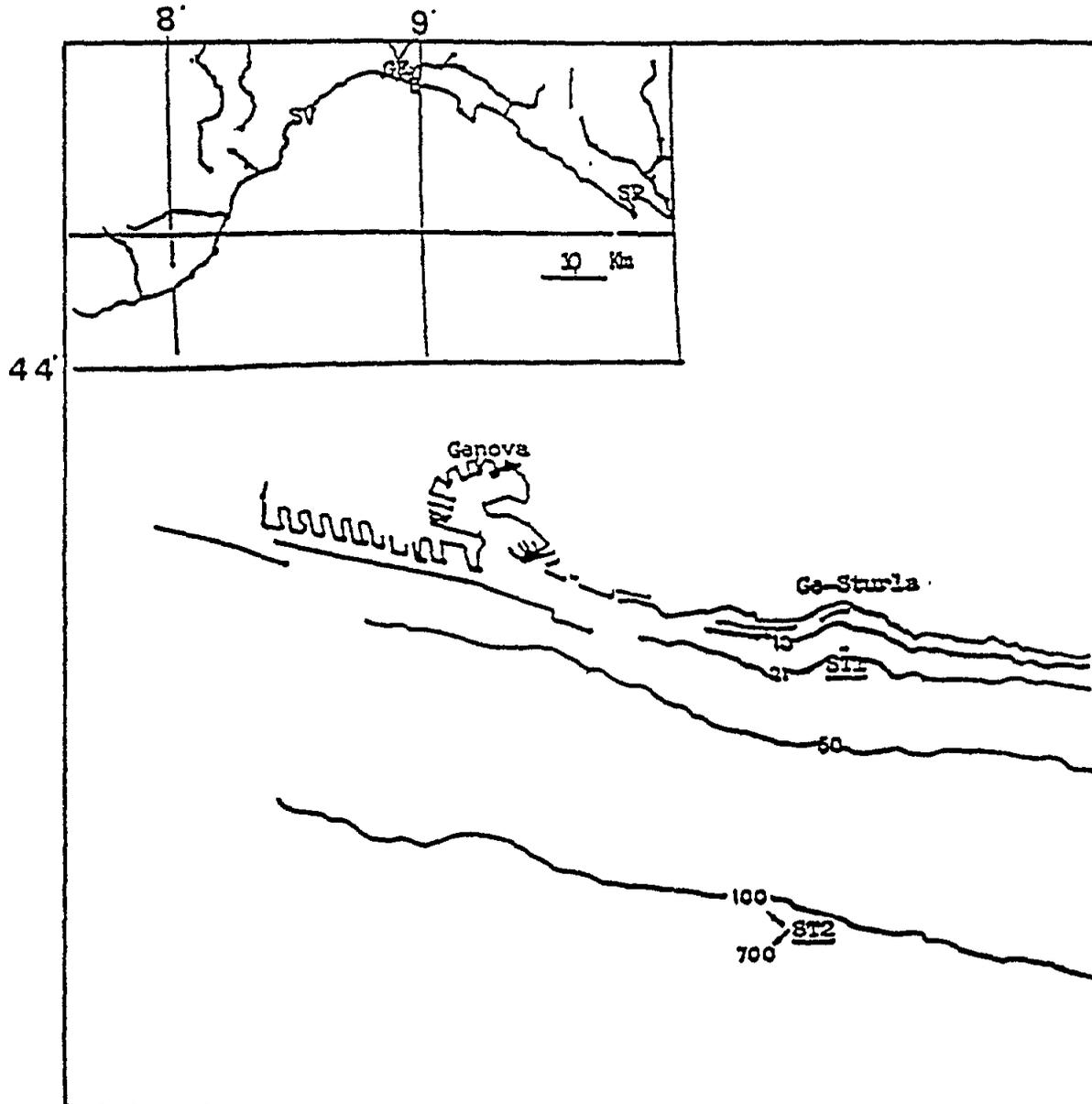


Fig. 1 Location of the sampling stations

Physico-chemical parameters and dissolved oxygen were measured using a multiparameter probe (Combibox CB 570, Vittadini, Milano); nutrients and chlorophyll-*a* were analysed according to Strickland and Parsons (1968), and bacteria by standard methods.

In order to analyse nutrients and phytoplankton, seawater samples were collected by a "Niskin" reversible bottle; seawater samples for bacterial analysis were collected in sterile bottles provided with a closing apparatus.

Zooplankton samples were collected with a standard net (FAO WP2, 200 µm). Phytoplankton was studied according to Utermöhl (1958) against sedimentation (24 hours). Zooplankton count and classification was performed as reported in Carli and Sertorio (1964).

The community diversity was measured using the Shannon-Weiner index (H') (Shannon and Weaver, 1949); equitability (J) was expressed as a Pielou evenness index (Pielou, 1966). The Bray-Curtis similarity measure (Bray and Curtis, 1957) was calculated from transformed data $Y_{ji} = \log(x_{ji} + 1)$, in order to balance contributions of rare vs. abundant species.

Classification was performed on all similarity matrices using the Average Linkage clustering technique (Sokal and Sneath, 1963). Ordination techniques (MDS: Multidimensional Scaling) were applied to map the results derived from the classification, according to the method described by Field *et al.* (1982) and Clarke and Green (1988).

Principal components analysis (PCA) was performed on the environmental data. The multivariate statistical analysis was carried out using the software package PRIMER developed at the Plymouth Marine Laboratory.

3. RESULTS AND DISCUSSION

3.1 Physico-chemical parameters

At the coastal station, surface temperatures ranged from 14.4EC (April 1991) to 25.3EC (July 1991), while at 10 m depth, temperatures varied from 15.1EC to 23.8EC in April and July respectively. Similar results were recorded at the offshore station, where surface values varied from 15.4EC to 25.2EC, in April and July 1991 respectively and at 10m depth from 15.1EC (April 1991) to 23.0EC (September 1990).

Substantially homogeneous pH values (from 8.00 at station ST1, to 8.40 at station ST2, both in September) were recorded for both surface water and at 10 m depth.

Salinity showed some surface variations at station ST1, ranging from 36.95‰ (September 1989) to 38.18‰ (September 1990) and at station ST2, ranging from 37.10‰ (April 1991) to 38.20‰ (August 1991); at 10 m the lowest salinity measurements occurred in October 1990 both at station ST1 (36.80‰) and at station ST2 (37.20‰) and the maxima in September 1990 at station ST1 (38.46‰) and in August 1991 at station ST2 (38.20‰). Summer salinity values were slightly lower at station ST1 than at station ST2, probably due to freshwater contributions.

The results for dissolved oxygen were similar for both surface water and 10m depth; on the whole values varied from 4.27 mg l⁻¹ (August 1990, surface) to 13.3 mg l⁻¹ (June 1989, surface).

The variations of physico-chemical parameters at station ST1 agree with available data recorded in neighbouring zones by other authors; in particular, Anselmi (1923) reports annual temperature values ranging from 14EC to 27.3EC in the surface layer of the sea area in front of Genova-Quarto dei Mille, and Sertorio (1956) reported temperature values, along the coastline

of Genova-Sturla, which are in general agreement with the data presented in this paper. The same can be stated for data obtained at station ST2 in comparison to values recorded by Bossolasco and Dagnino (1961) and Bossolasco *et al.* (1973).

Summer values of dissolved oxygen were lower than mean values recorded for both coastal and offshore waters of the Gulf of Genova (Fabiano *et al.*, 1986).

3.2 Nutrients and chlorophyll-a

At station ST1, N-NO₂ ranged from 0.02 (10 m, October 1990) to 1.22 µg-at l⁻¹ (surface, August 1991), N-NO₃ from 0.13 (10 m, April 1991) to 2.13 µg-at l⁻¹ (surface, October 1991) and P-PO₄ from 0.01 (10 m, August 1990) to 0.28 µg-at l⁻¹ (surface, July 1991).

At station ST2, N-NO₂ varied from 0.02 (10 m, June 1990) to 0.70 µg-at l⁻¹ (10 m, July 1991), N-NO₃ from 0.11 (10 m, June 1990 and August 1991) to 1.01 µg-at l⁻¹ (surface, October 1990) and P-PO₄ from 0.02 (10 m, July 1989) to 0.39 µg-at l⁻¹ (10 m, June 1990).

At station ST1, chlorophyll-a concentrations ranged from 0.01 µg l⁻¹ (May 1989 at 10 m) to 0.70 µg l⁻¹ (June 1990 at the surface), while at station ST2 values ranged from 0.01 µg l⁻¹ to 0.41 µg l⁻¹ (May 1989 and August 1989 both at 10 m, and October 1990 surface, respectively).

Nitrate concentrations (including NO₂) were generally lower than 1 µg-at l⁻¹, except in October 1991, when values reached 2.37 µg-at l⁻¹ at the coastal station.

Phosphates were always lower than 1 µg-at P-PO₄ l⁻¹ and showed slight differences between station ST1 and station ST2.

Chlorophyll-a was always lower than 1 µg l⁻¹ i.e. within the limit for non-eutrophic waters (Marchetti, 1984; Stirn, 1988). Values at the coastal station were generally higher than those recorded at the offshore station. The water eutrophication indicators agree with data recorded by other authors for neighbouring zones of the Ligurian Sea (Nival *et al.*, 1972; Bruzzone *et al.*, 1979; 1982; Carli *et al.*, 1980; Della Croce *et al.*, 1981; Fabiano *et al.*, 1984; 1986; Innamorati *et al.*, 1987).

3.3 Bacteria

Heterotrophic bacterial counts at station ST1 showed concentrations at 10 m depth to range from 2.2X10 (October 1991) to 5X10⁴ (June 1989) CFU ml⁻¹ (CFU is colony forming unit). Total coliform abundance varied from 1.8X10 (June 1989, 10 m) to 2X10³ (July 1989, surface) CFU 100 ml⁻¹ while the recorded values for faecal coliforms ranged from 0 (August 1990, surface), to 3X10² (July 1989, surface) CFU 100 ml⁻¹.

At station ST2, heterotrophic bacterial counts varied from 0.2X10 (October 1991, 10 m), to 2.6X10⁴ (August 1990, 10 m) CFU ml⁻¹ and total coliforms from 0 (recorded for more than one month) to 7.5X10² (July 1989, surface) CFU 100 ml⁻¹. Faecal coliforms were not present except in May and July at the surface (0.1X10 CFU 100 ml⁻¹).

Heterotrophic bacterial counts did not show significant variations at ST1; with the exception of June 1989 (10 m) and July 1989 (surface) recorded values were not over 10,000 CFU ml⁻¹; bacterial concentrations were generally lower at ST2 than at ST1. The results presented in this study are in general agreement with available data recorded by others for the Gulf of Genova (Carli *et al.*, 1979).

The total coliforms always showed concentrations lower than 2,000 CFU 100 ml⁻¹, except in July 1989 (ST1, surface). In general, bacteria are more plentiful at the surface than at a depth of 10 m, according to studies carried out in Adriatic coastal waters (De Martino *et al.*, 1989).

The high bacterial count recorded at the off-shore station during 1989 could be attributed to the different sampling location (100 m).

3.4 Phytoplankton and zooplankton

Phytoplankton cells were generally more abundant at ST1 than at ST2, except in September 1989. The cell density showed a wide range from 346 (September 1989) to 82,974 (June 1990) cells l⁻¹. During the sampling period there were fewer variations at the off-shore station, from 433 (July 1989) to 22,554 (June 1990) cell l⁻¹. Generally, diatoms prevailed over dinoflagellates; nevertheless, at ST1 the diatom/dinoflagellate ratio reversed in June and July 1991. The diatom maximum (61,412 cells l⁻¹ occurred in June 1990; however this value is remarkably lower than values recorded by Geraci *et al.*, 1986 for the nearby port of Genova (2X10⁶ cells l⁻¹) which is more affected by eutrophication. The phytoplankton population is generally characterized by the species: Chaetoceros spp., Guinardia flaccida, Leptocylindrus danicus, Licmophora dalmatica, Melosira spp., Nitzschia closterium, Nitzschia seriata, Rhizosolenia alata, Thalassionema nitzschioides, Thalassiothrix frauenfeldii, Ceratium furca, Dinophysis rotundata, Gonyaulax polygramma, Oxytoxum spp., Peridinium spp., Prorocentrum micans and Prorocentrum triestinum (Table 1). During this study Dinophysis rotundata, D. tripos and D. caudata were found, which are not responsible for toxic blooms in the Mediterranean Sea and are usually found in coastal waters (Lassus *et al.*, 1991).

Diversity (H') and evenness (J) showed the same range of variations at both stations during the three years. In particular during 1990, the diversity and equitability trends measured at the coastal station and at the off-shore station were quite similar (Fig. 2a).

The greatest abundance of zooplankton was found in 1989; during the examined period the abundance ranged from 325 (April 1991) to 6,217 (May 1989) ind. m⁻³ at ST1 and from 279 (July 1991) to 13,654 (May 1989) ind. m⁻³ at ST2. Adult copepods were the most abundant group with percentages of the total population between 30.5% in July 1991 to 100% in May 1989.

The most representative species were Paracalanus parvus, Clausocalanus arcuicornis, Clausocalanus furcatus, Temora stylifera, Centropages typicus, Oithona helgolandica and Corycella rostrata (Table 1).

With respect to diversity and equitability, even if with slightly appreciable differences, the higher diversity values were recorded in the offshore station (Fig. 2b).

Table 1

List of phytoplankton and zooplankton species found in the samples.

DIATOMS	DINOFAGELLATES	ZOOPLANKTON	COPEPODS
Amphora sp.	Ceratium arietinum	PROTOZOA	Calanus helgolandicus
Asterionella notata	Ceratium candelabrum	Foraminifera	Calanus spp.
Asterolampra sp.	Ceratium concilians	Radiolaria Phoeodaria	Eucalanus elongatus
Biddulphia mobiliensis	Ceratium declinatum	Ciliata Tintinnida	Rhincalanus nasutus
Cerataulina bergonii	Ceratium furca	CNIDARIA	Paracalanus parvus
Chaetoceros curvisetus	Ceratium fusus	Hydromedusae	Paracalanus nanus
Chaetoceros decipiens	Ceratium hexacanthum	Siphonophora	Paracalanus spp.
Chaetoceros didymus	Ceratium macroceros	ANNELIDA	Calocalanus styliremis
Chaetoceros ingolfianus	Ceratium massiliense	Alcyonidae	Calocalanus sp.
Chaetoceros peruvianus	Ceratium pentagonum	CRUSTACEA	Clausocalanus arcuicornis
Chaetoceros rostratus	Ceratium setaceum	Cladocera	Clausocalanus furcatus
Chaetoceros spp.	Ceratium tripos	Ostracoda	Clausocalanus spp.
Cocconeis spp.	Ceratium kofoidi	Copepoda	Stephos sp.
Coscinodiscus spp.	Ceratium sp.	Mysidacea	Temora stylifera
Dactyliosolen mediterraneus	Dinophysis acuminata	Pteropoda	Temora sp.
Eucampia zodiacus	Dinophysis caudata	CHAETOGNATA	Centropages hamatus
Grammatophora spp.	Dinophysis diegenis	Sagitta sp.	Centropages kroyeri
Guinardia flaccida	Dinophysis fortii	Tunicata	Centropages typicus
Hemiaulus hauckii	Dinophysis odiosa	Doliolum sp.	Centropages spp.
Hemiaulus sinensis	Dinophysis parva	Oikopleura spp.	Isias sp.
Lauderia borealis	Dinophysis parvula	Salpa sp.	Labidocera sp.
Leptocylindrus danicus	Dinophysis rotundata	LARVAE	Lucicutia flavicornis
Leptocylindrus minimus	Dinophysis tripos	Actinotriaria	Candacia longimana
Leptocylindrus sp.	Dinophysis spp.	Nemertes	Candacia spp.
Licmophora dalmatica	Gonyaulax birostris	Bryozoa	Acartia clausi
Licmophora spp.	Gonyaulax polyedra	Polychaeta	Acartia sp.
Melosira sp.	Gonyaulax polygramma	Cirripedia	Microsetella sp.
Navicula cancellata	Gonyaulax spinifera	Ostracoda	Oithona brevicornis
Navicula crabro	Gonyaulax spp.	Copepoda	Oithona helgolandica
Navicula forcipata	Goniodoma polyedricum	Euphausiacea	Oithona nana
Navicula northumbrica	Heterodinium sp.	Decapoda	Oithona plumifera
Navicula quadriseriata	Histioneis joergenseni	Gastropoda	Oithona spp.
Navicula spp.	Noctiluca scintillans	Bivalvia	Euterpina acutifrons
Nitzschia closterium	Ornithocercus magnificus	Echinodermata	Euterpina sp.
Nitzschia delicatissima	Oxytoxum caudatum	Fish larvae	Oncaea mediterranea
Nitzschia longissima	Oxytoxum constrictum	Fish eggs	Oncaea venusta
Nitzschia seriata	Oxytoxum coronatum		Oncaea spp.
Nitzschia spp.	Oxytoxum reticulatum		Sapphirina sp.
Pleurosigma spp.	Oxytoxum scolopax		Corycaeus spp.
Rhizosolenia alata	Oxytoxum variabilis		Corycella rostrata
Rhizosolenia fragilissima	Oxytoxum spp.		Corycella sp.
Rhizosolenia stolterfothii	Palaeophalacroma		Mimocorycella
Rhizosolenia spp.	unicinctum		Harpacticus sp.
Skeletonema costatum	Peridinium conicum		nauplii
Striatella unipunctata	Peridinium crassipes		copepodids
Synedra sp.	Peridinium depressus		
Thalassionema nitzschioides	Peridinium divergens		
Thalassiosira decipiens	Peridinium jollifei		
Thalassiosira sp.	Peridinium longipes		
Thalassiothrix frauenfeldii	Peridinium mite		
Triceratium sp.	Peridinium oceanicum		
	Peridinium ovum		
	Peridinium quarnerense		
	Peridinium steini		
	Peridinium spp.		
	Podolampas curvatus		
	Podolampas elegans		
	Podolampas palmipes		
	Podolampas spinifer		
	Podolampas sp.		
	Prorocentrum aporum		
	Prorocentrum compressum		
	Prorocentrum micans		
	Prorocentrum triestinum		
	Prorocentrum spp.		
	Protoceratium spp.		
	Pyrocistis obtusa		
	Pyrocistis sp.		
	Pyrophacus horologicum		

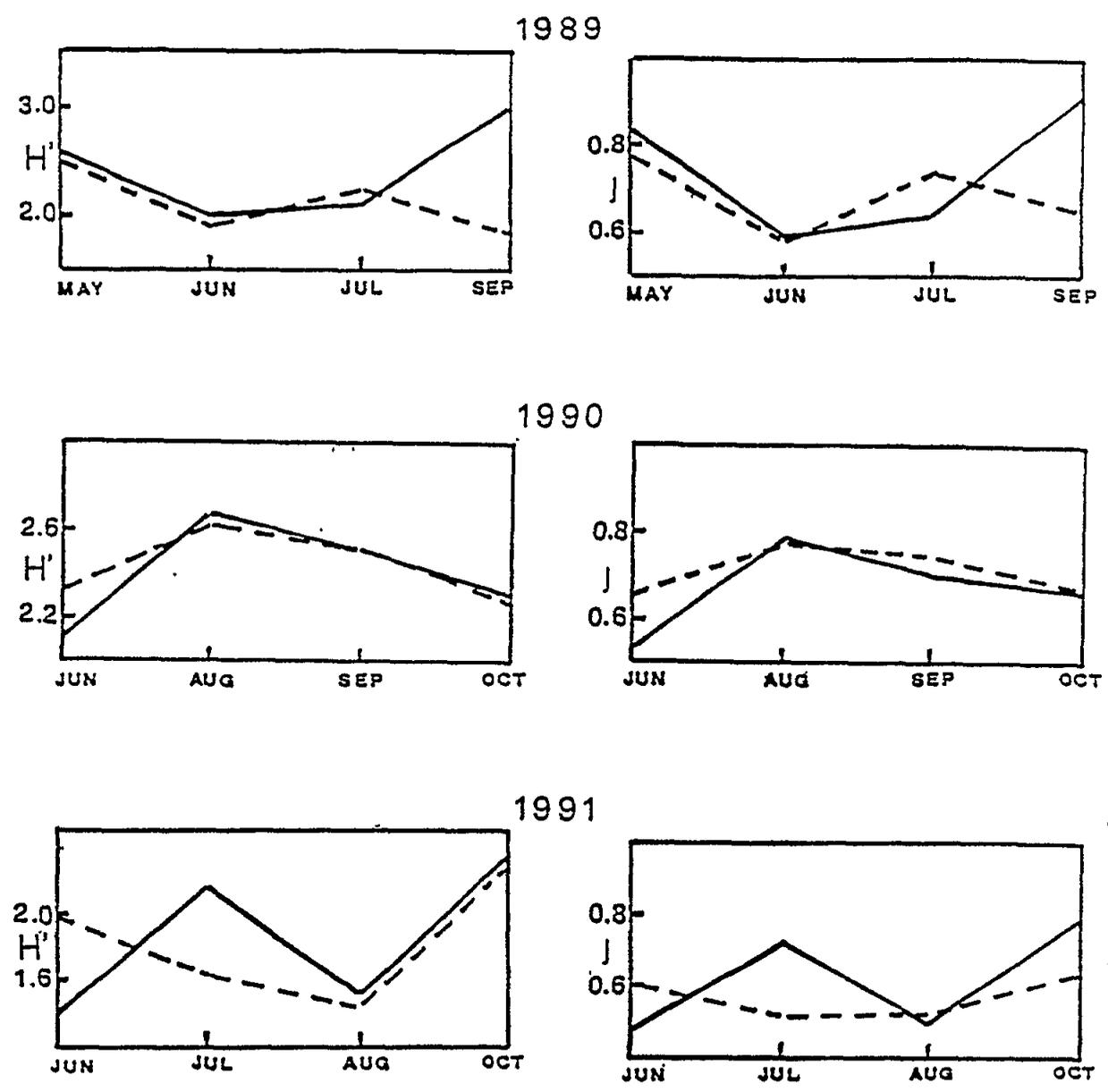


Fig. 2a Temporal variations of diversity (H') and evenness (J) in the phytoplankton community. — ST1 - - - - - ST2

Two different classifications of data were performed: the first one considered all identified species, except for copepods which were maintained at the genus level while the second one used species aggregation to genus level for both phyto- and zooplankton.

The two dendrograms (Figs. 3, 4) showed no appreciable differences between the coastal and the offshore station. High similarity values (about 70%) were observed within the coastal and the offshore station for data of the same month (May and June 1989, August 1990, August 1991).

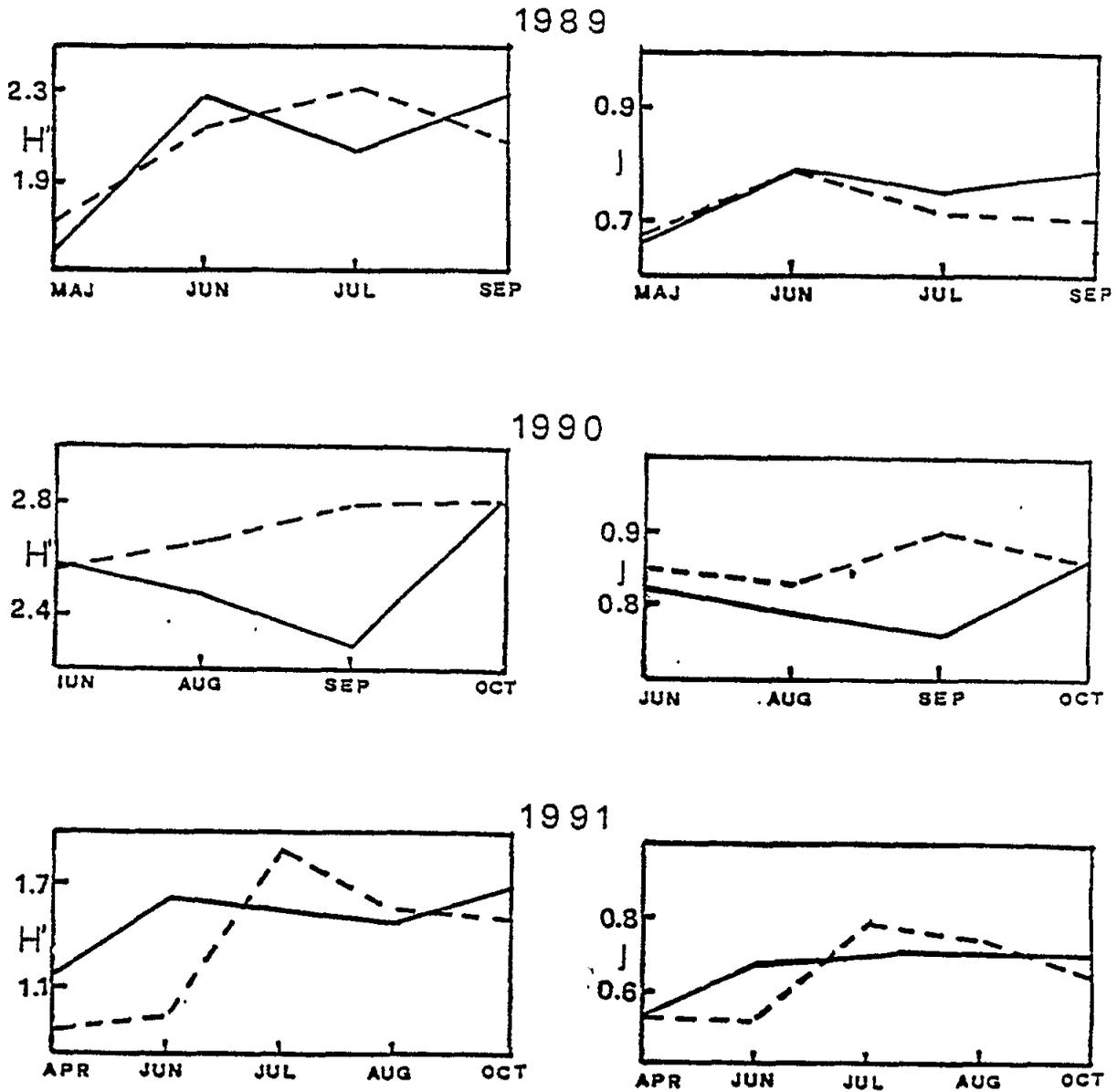


Fig. 2b Temporal variations of diversity (H') and evenness (J) in the zooplankton community. — ST1 - - - - - ST2

A clear separation between the coastal and the offshore station was obtained considering phyto- and zooplankton, aggregated to genus level, together with the bacterial component (Fig. 5). Two subgroups were identified (63% similarity): the first one was represented by all samplings of the offshore station, the other one by all coastal samplings. The only exception was the presence of the May sampling (offshore station) in the coastal subgroup. Moreover, within the dendrogram, months belonging to the same sampling year generally fell in the same subgroup.

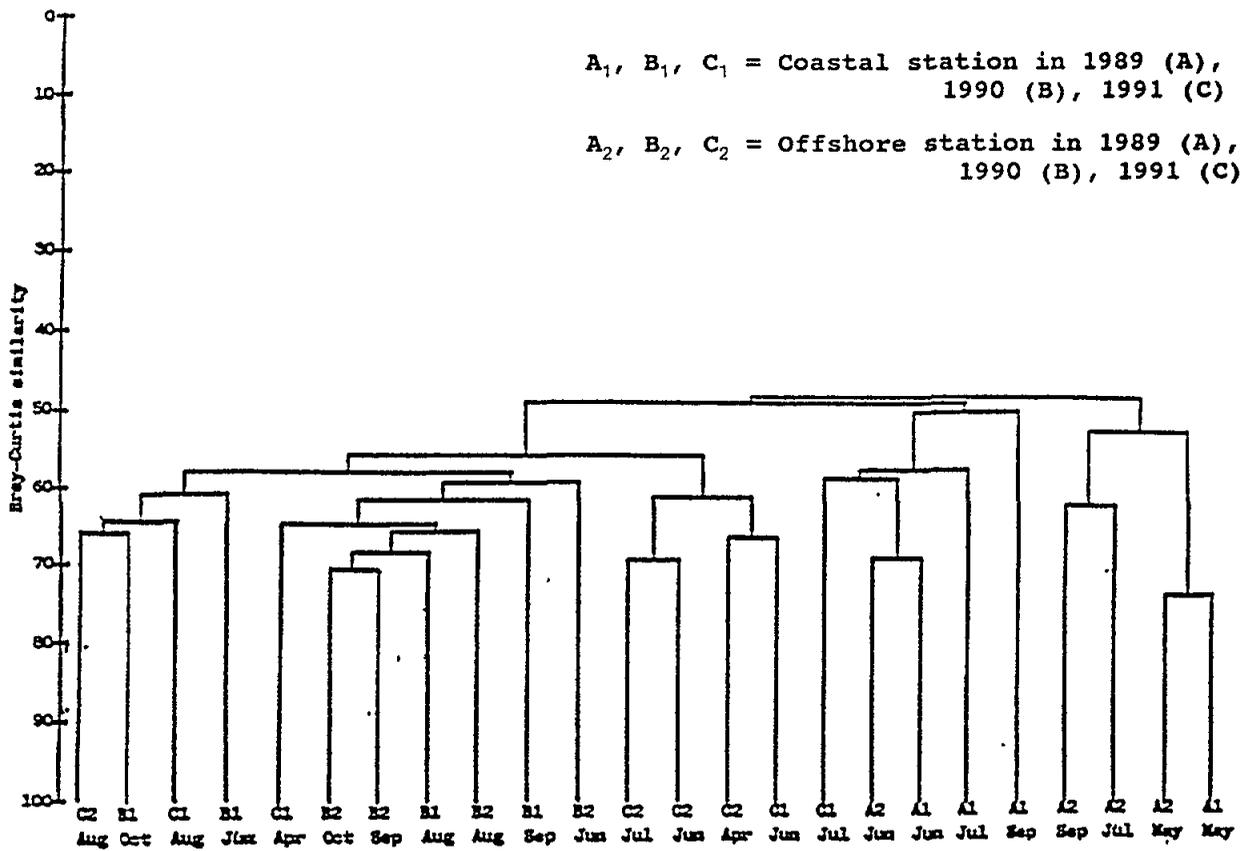


Fig. 3 Dendrogram produced using the Bray-Curtis/Group Average clustering technique on log transformed data. Copepod data aggregated into genera

The areal presentation derived with MDS confirmed the separation between the coastal and the offshore station (two dimensional stress = 0.1) (Fig. 6).

From the principal components analysis (PCA) on the environmental area, the coastal and the offshore station can not be distinguished.

In order to investigate relationships between phytoplankton, zooplankton and environmental parameters, an attempt was made to superimpose temperature, pH, oxygen, salinity, nutrients and chlorophyll-a measurements on the MDS plots derived from the faunistic multivariate analysis. Nutrient and chlorophyll-a distribution seem to be correlated to the plankton with regard to the position of the stations on the plot (Fig. 7a, b, c, d).

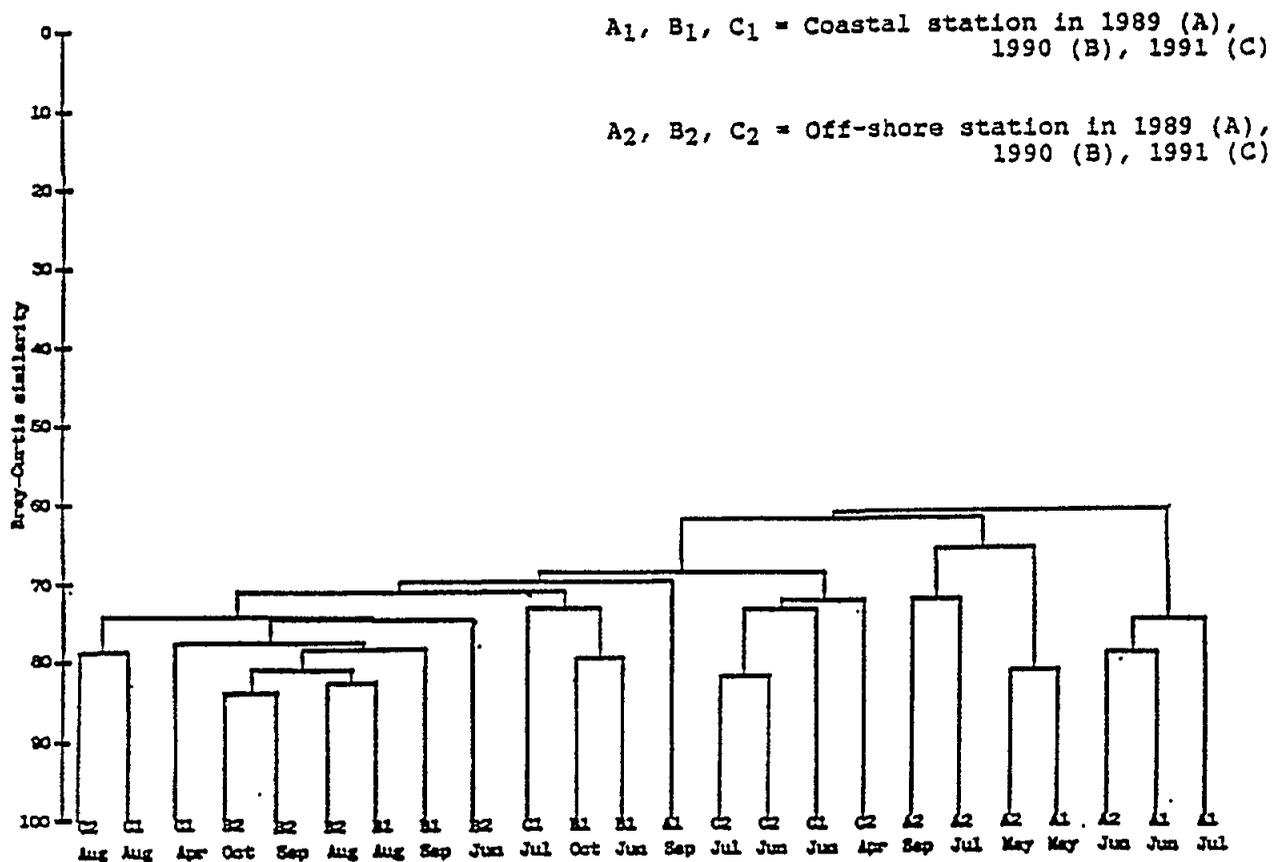


Fig. 4 Dendrogram produced using the Bray-Curtis/Group Average clustering technique on log transformed data. All the species aggregated into genera

4. CONCLUSIONS

Comparing the data of water quality during the three years of investigation, a different trophism in the studied stations can be observed. It was essentially highlighted by chlorophyll-*a* and bacterial concentrations which were generally higher in the coastal than in the offshore station.

In particular, chlorophyll-*a* concentrations approached oligotrophic limits (Marchetti, 1984) and heterotrophic bacteria occasionally exceeded 10,000 CFU ml⁻¹, which is the bacterial concentration found in sea zones affected by waste waters (De Martino *et al.*, 1989). Thus, this zone can occasionally become rich in particulate and organic matter.

The anthropogenic influence on coastal water quality was emphasized by the abundance of total and faecal coliforms that occasionally exceeded the limits determined by Italian Law. Furthermore, a decreasing gradient of bacterial concentration from coastal to offshore waters was observed.

Nevertheless, it was not possible to relate the high recorded coliform concentrations to a low diatom/dinoflagellate ratio that is considered as a change-index of the phytoplankton composition to a pre-eutrophication state (Fruchart, 1986).

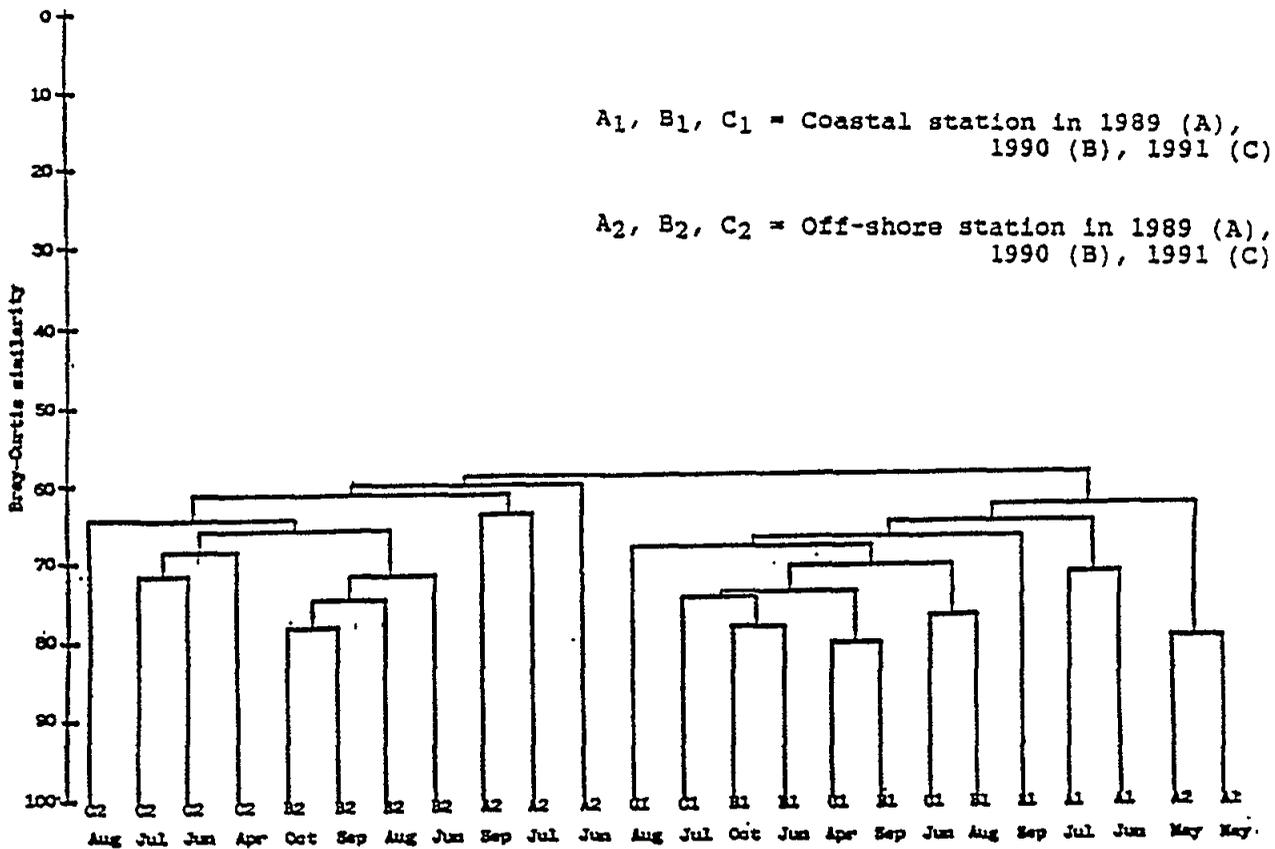


Fig. 5 Dendrogram produced using the Bray-Curtis/Group Average clustering technique on log transformed data. The bacterial component was also considered

As regards phytoplankton and zooplankton, it can be noted that the phytoplankton abundance is prevalingly higher at station ST1 than at station ST2 and is in agreement with the values recorded for the Ligurian Sea by other authors (Bernhard *et al.*, 1969; Innamorati *et al.*, 1987), who reported at different periods sporadic blooms of *Nitzschia seriata* and *Melosira sp.*. The dominance of *Thalassiothrix frauenfeldii* in May was also found by Rampi (1954) in the non-eutrophic coastal waters of the eastern Ligurian Riviera.

As regards zooplankton abundance during the sampling periods, a clear difference between station ST1 and station ST2 was not observed; nevertheless, during the summer months zooplankters were more abundant at station ST1. The data presented in this study agree with values previously reported for the Ligurian Sea (Carli, 1971; Bruzzone *et al.*, 1982). Furthermore, copepods showed a qualitative analogy in line with other studies carried out in the Genova-Sturla area and in the neighbouring Genova-Quarto area (Brian, 1914, 1937; Sertorio, 1956; Della Croce *et al.*, 1972).

The statistical analysis confirms the structural similarity between the two stations. This is particularly evident in the dendrograms, by the contemporary presence, in the same cluster, of the coastal and the offshore

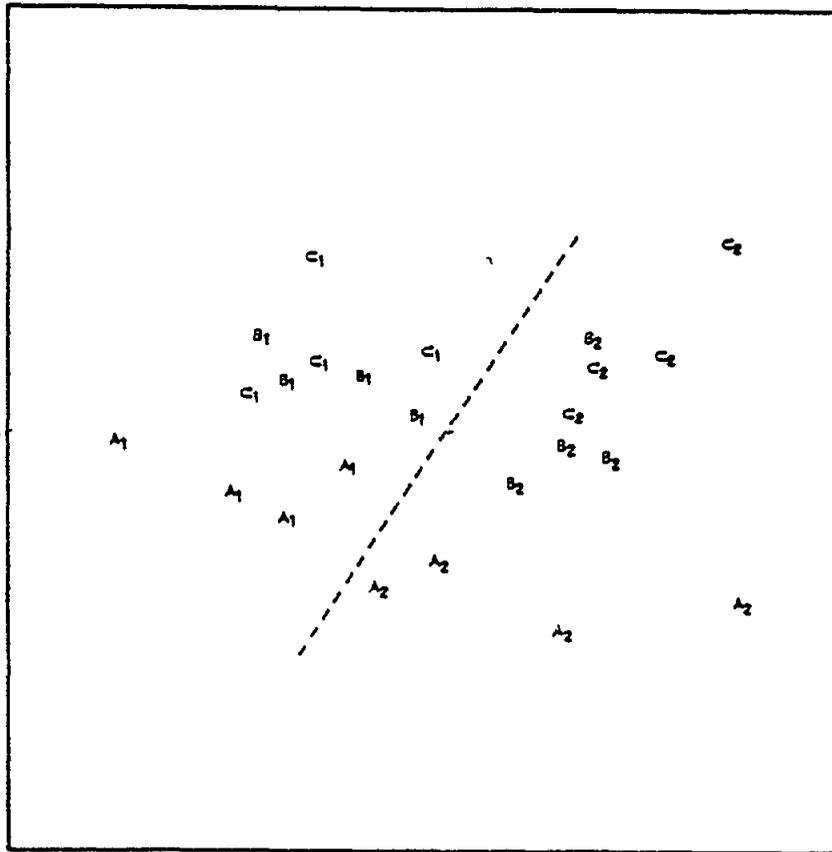


Fig. 6 Non-metric multidimensional scaling (MDS) plot in two dimensions (two dimensional stress = 0.1)
A₁, B₁, C₁ = Coastal station in 1989 (A), 1990 (B), 1991 (C)
A₂, B₂, C₂ = Offshore station in 1989 (A), 1990 (B), 1991 (C)

station data set, deriving from the same seasonal set of samplings. The two stations differed mainly in the bacterial component. At the observed concentration however, bacteria apparently do not severely influence the structural organization of the plankton community.

In conclusion and in agreement with recent studies (Bruzzone et al., 1982; Fabiano, 1983, Fabiano et al., 1984; Innamorati et al., 1987; Carli et al., 1992), oligotrophic water conditions were observed.

5. ACKNOWLEDGEMENTS

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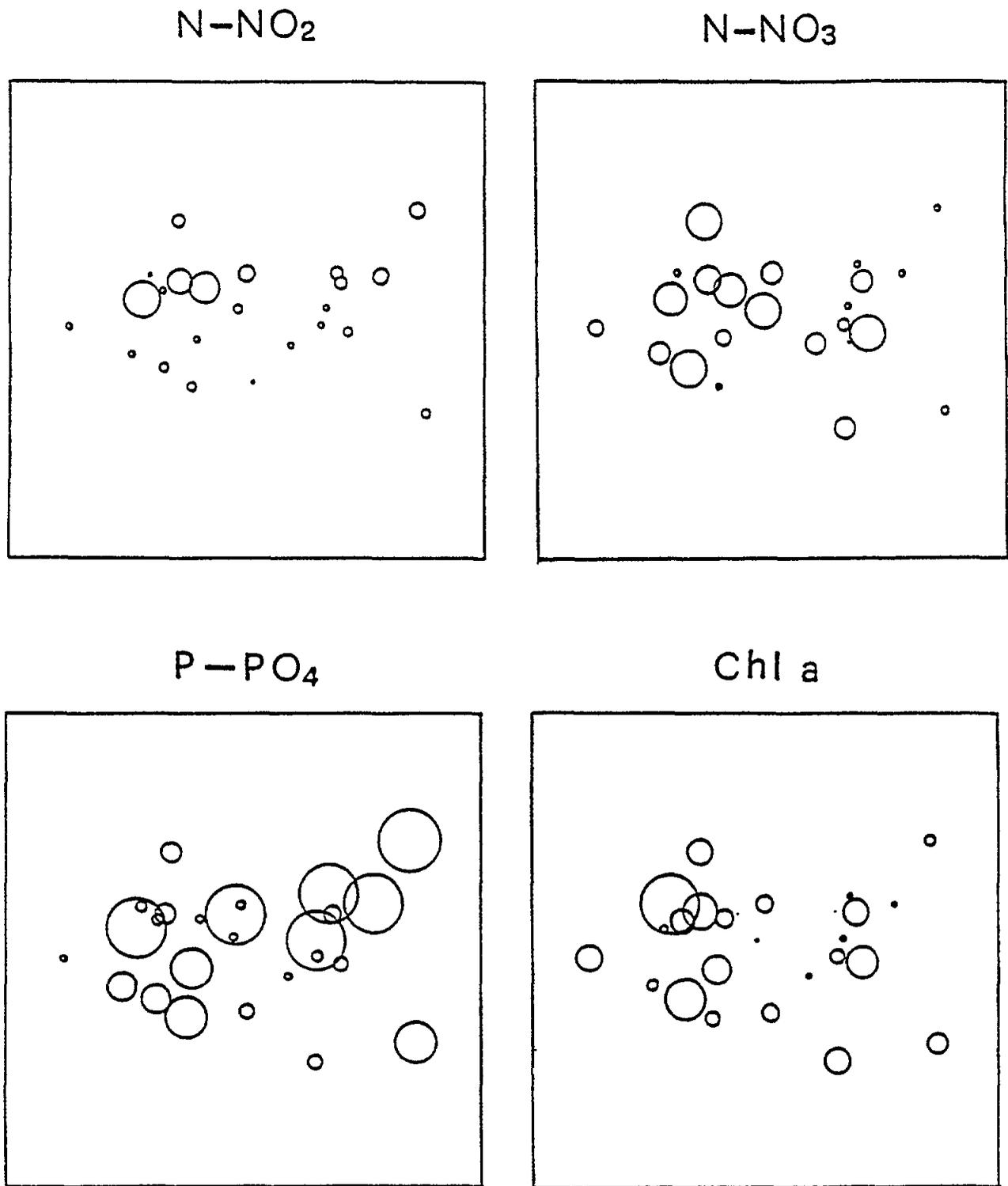


Fig. 7 MDS plot with values of (a) N-NO₂, (b) N-NO₃, (c) P-PO₄, (d) chl a, superimposed on the plankton data

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EUTROPHICATION PROCESSES IN THE KRKA ESTUARY (ADRIATIC SEA)

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ABSTRACT

The exchange of freshwater and marine water in the stratified estuary of the Krka river varies with flux. During winter, the exchange time of freshwater is from 6 to 20 days while during summer it is around 80 days. The exchange time of marine water is about five times longer.

The temperature maximum is located on the lower edge of the halocline where the highest temperature in the Adriatic has been recorded (31EC).

Strong northerly wind induces a tilt of the brackish water layer and hence sudden mortality of marine shellfish culture located close to the halocline.

The halocline is an accumulation interface of living and non-living organic particles and pollutants; a site of physico-chemical transformation of organic matter under the influence of salinity gradient; a site of intensive, mainly marine, primary production with a peak of dissolved oxygen concentration; a site of intensive decomposition processes; a barrier for oxygen transport to the marine layer.

The main source of silica and nitrogen is Krka river. The dominant source of phosphorus in the upper estuary is sinking and decomposition of freshwater phytoplankton while in the lower estuary it is the anthropogenic inflow of the city and port of Šibenik.

Only marine phytoplankton develops blooms in the estuary. In the upper estuary, blooms (such as Gonyaulax polyedra) are located below the halocline. Rarely in Prokljan Lake and regularly in Šibenik area blooms appear above the halocline. Blooms in the upper estuary precede and are a primary cause of benthic hypoxia which induces massive mortality of benthic macrofauna including Pecten jacobaeus. Benthic hypoxia and massive mortality of benthic macrofauna has been observed in two consecutive years.

Growth of phytoplankton in the entire estuary is primarily phosphorus limited with the exception of Šibenik area which is close to nutrient inputs.

1. INTRODUCTION

The project was organized in order to study eutrophication processes in a highly stratified estuary typical of the Mediterranean. The Krka estuary has been selected because these processes may be investigated in their initial stage: until recently the estuary has been one of the most pristine in Europe.

In 1985 the river Krka with the upper part of the estuary and the neighbouring coastal archipelago (Kornati Islands) were declared a national park for their natural beauty, transparent waters and a number of endemic species. In its lower reach, the estuary is exposed to an increasing nutrient load which leads to a gradient between pristine and moderately polluted areas. The estuary is small enough so that it might be viewed as a natural scale model of larger estuarine systems.

Except for their physical scale the small estuaries are as complex as the larger ones. However, their small scale offers the advantage to perform basic and applied research more efficiently. Furthermore, small estuaries of the Mediterranean are important per se being demographically and economically attractive for many centuries, and at present ecologically the most endangered.

Research on eutrophication processes is expected to generate results that are basic to the definition of management steps. Since 1983 the Long-term Pollution Monitoring Programme (MED POL - Phase II) of the estuarine aquatorium combined with multidisciplinary fundamental research has resulted in discoveries of new phenomena on the freshwater/seawater interface.

In this report special attention is devoted to the Prokljan Lake in the middle reach of the estuary, which is situated within the National Park Krka. The area is planned to become a site of intensive aquaculture development (shellfish in particular). Besides its interest per se, this lagoon that is presently not exposed to a significant direct pollution load, represents a very suitable stratified system to study relationships between hydrographic structure, phytoplankton development and dissolved oxygen concentrations near the bottom. As an example, we shall describe the extent and infer the sequence of events which caused hypoxia that resulted in massive mortality of benthic macrofauna in the central part of the Krka estuary during autumn 1988.

2. INVESTIGATED AREA

The river Krka is a karstic river (49 km long until the entrance to the estuary, watershed 2088 km²) entering the Adriatic sea. The Visovac Lake and a series of moss covered tufa barriers and waterfalls precede the estuary and retain much of the already low sediment load. The estuary is relatively narrow, except for two wider parts: Prokljan Lake and the area around Šibenik harbour (Fig. 1). The depth gradually increases from 1 to 2 m below the waterfalls until 43 m near the mouth estuary.

A well defined surface brackish layer is separated from the underlying marine layer by a sharp and hence narrow halocline. The estuary is of a salt wedge type (Žutić and Legović 1987). From daily readings of the water gauge near the waterfalls the flow of Krka varies between 0.17 and 564 m³ s⁻¹ with a mean of about 50 m³ s⁻¹. Depending on the river flow, the thickness of the brackish layer has been found to vary between 0.2 and 6.3 m.

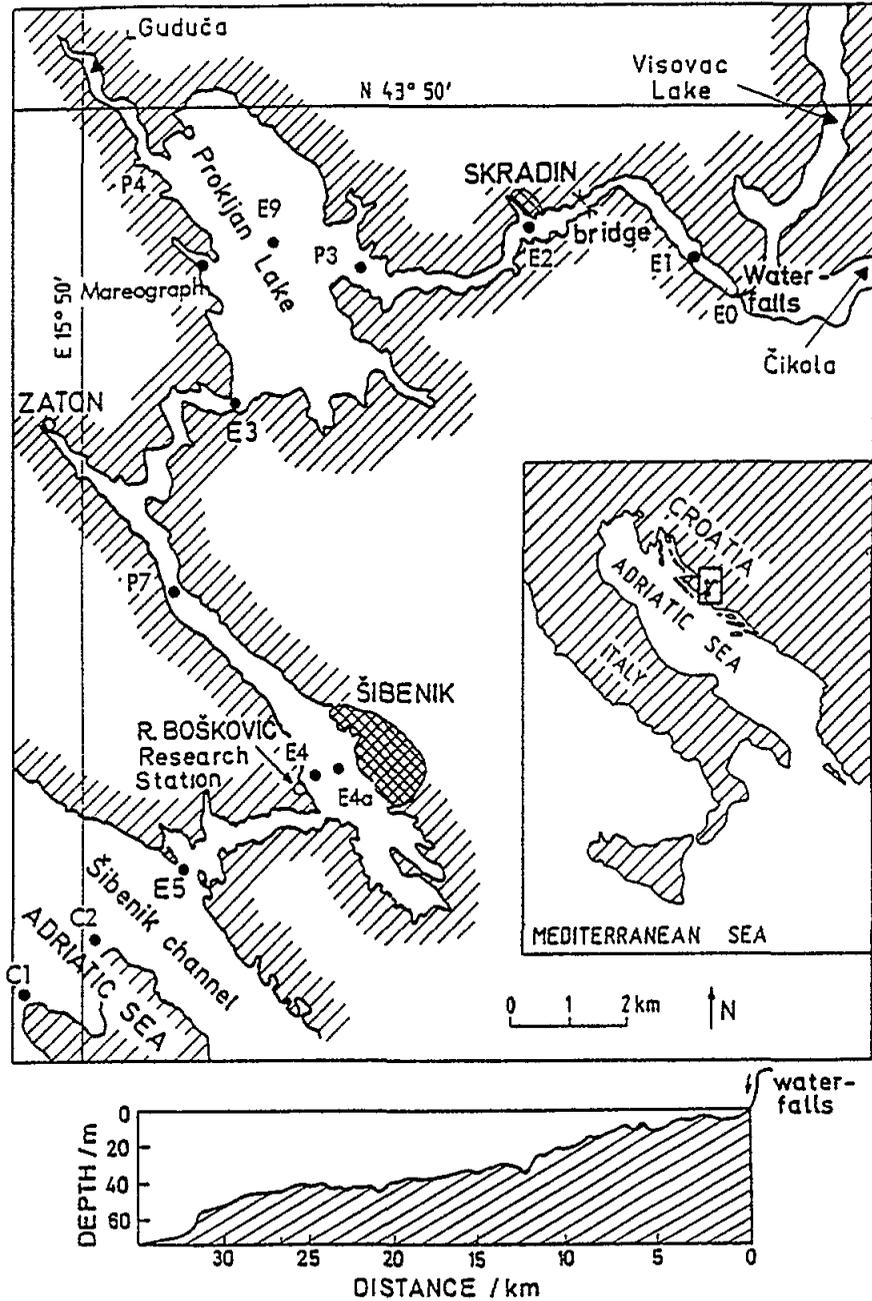


Fig. 1 Krka estuary and position of sampling stations

It has been claimed that Krka river is poor in nutrients (Buljan, 1969; Gržetić and Škrivanić, 1984-1990; Gržetić *et al.*, 1991). The mean concentration of reactive phosphorus is 0.1 mM (PO_4) (range: <0.01-0.4), the mean concentration of nitrogen is 18 mM (NO_3) (range: 4-45), and the mean concentration of silica is 25.8 mM (SiO_4) (range: 2-51). However, when compared to oligotrophic waters of the Adriatic Sea, the concentration of nutrients is an order of magnitude higher.

The halocline is significantly enriched by dissolved and particulate surface-active organic matter of freshwater and marine phytoplankton origin (Žutić and Legović, 1987; Cosović and Vojvodić, 1989; Svetličić *et al.*, 1991).

In the lower part of the estuary, near Šibenik, the main source of nutrients above the natural concentration comes from the outfalls of the town and the transshipment of the phosphate ore (Sekulić, 1986). As a result, in this part of the estuary one finds the highest concentration of marine phytoplankton (Viličić, 1989). An estimate of annual inputs of freshwater and nutrients by Gržetić *et al.* (1991) is reproduced in Fig. 2.

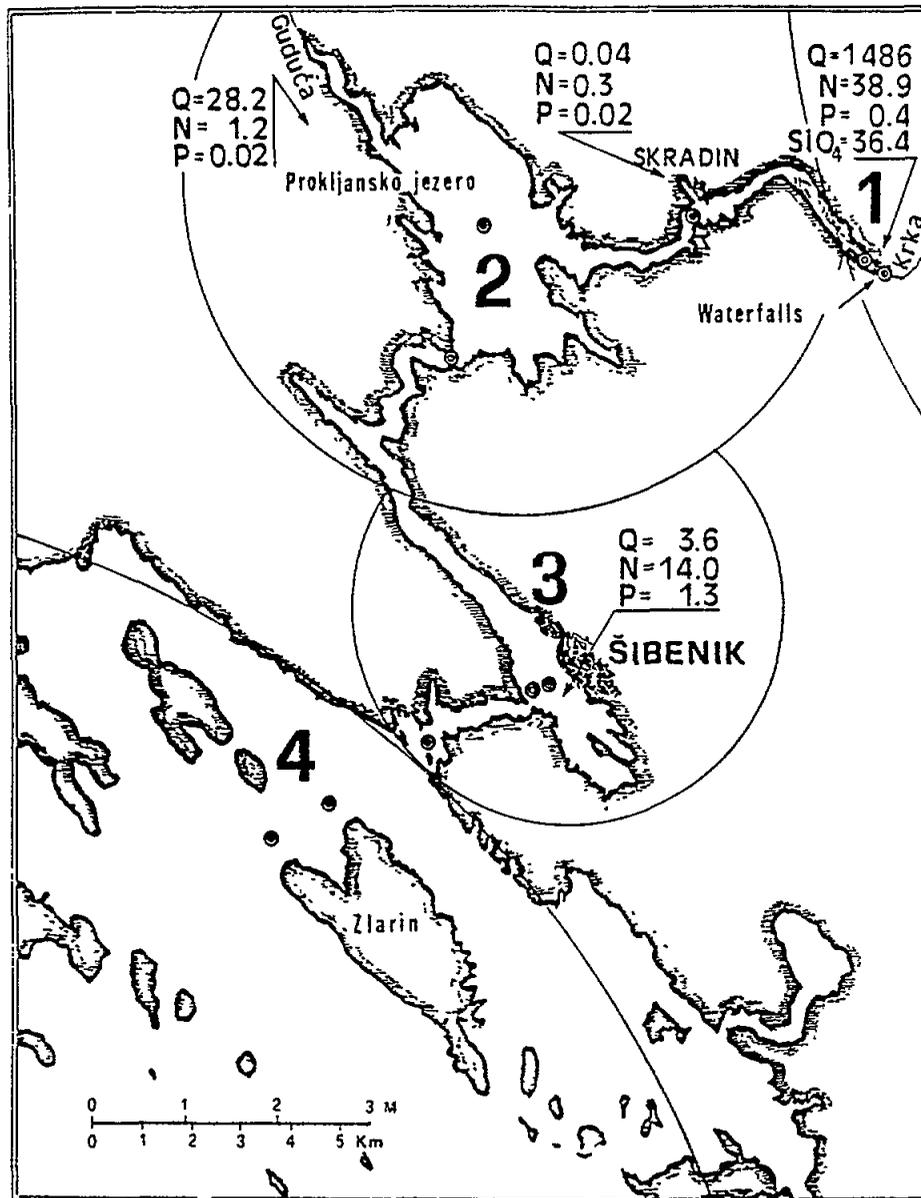


Fig. 2 Estimate of inputs of freshwater ($Q \times 10^6 \text{ m}^3 \text{ year}^{-1}$) and nutrients ($10^6 \text{ mol year}^{-1}$) to different zones of the estuary (from Gržetić *et al.*, 1991)

3. MATERIALS AND METHODS

3.1 Modelling

The development of a simple model for water motion and the model's application to determine residence times in the upper brackish and lower saline layer (Legoviæ 1991) was a step towards rational planning of the field work and interpretation of field data.

3.2 Field work

The field work consisted of:

- a. Seasonal cruises simultaneous and complementary to the MED POL-Phase II Monitoring during which nutrients, pigments, dissolved and particulate organic matter were measured;
- b. More frequent measurements of oxygen content at characteristic depths and on a network of stations in the area of benthic mortality recorded in October 1988 (Fig. 3a);
- c. Underwater observations and sampling of microplankton along the vertical profiles in the water column, and of benthic macrofauna along the bottom transects (Fig. 3a).

Samples for fine vertical distribution of phytoplankton species have been taken regularly at three characteristic stations: station E2 in the upper reach, station E3 in the middle reach and station E4A in the lower reach of the estuary. In contrast to stations E2 and E3, station E4A is under a strong influence of urban and industrial discharge (including the transshipment of phosphate ore) of the city and harbour of Šibenik. The highest phytoplankton density has been recorded in the surface layer at this station. In October 1988 sampling was performed along the vertical profiles in the zone of Prokljan Lake where a subsurface bloom of marine dinoflagellate Gonyaulax polyedra (GP) developed (Fig. 3b).

Underwater observations and sampling of benthic macrofauna were performed by a team of scuba divers along 6 transects in the Prokljan Lake. Among the benthic species two characteristic groups have been selected for a more detailed analysis, with the aim to get an insight into the long-term effects: (1) bivalvia (Pecten jacobaeus, Mytilus galloprovincialis, Chlamus varia) and (2) echinodermata (Psammochinus microtuberculatus, Ophiura texturata, Paracentrotus lividus, Astropecten irregularis).

3.3 Laboratory analysis of phytoplankton

Microscopic analysis of phytoplankton species consisted in extensive identification and counting of microplankton species in sedimented water samples (Uttermoehl method). From March 1988 to March 1989 samples were taken monthly; 166 species of freshwater and marine microplankton have been identified in over 200 samples that were analyzed (Petricioli *et al.*, 1991). The methodology of analysis and interpretation of vertical distributions around the halocline, that represents both freshwater/seawater and density

interface, (Viličić *et al.*, 1989) has been applied. The results enabled us to interpret the event of *Gonyaulax polyedra* (GP) subsurface bloom in October 1988.

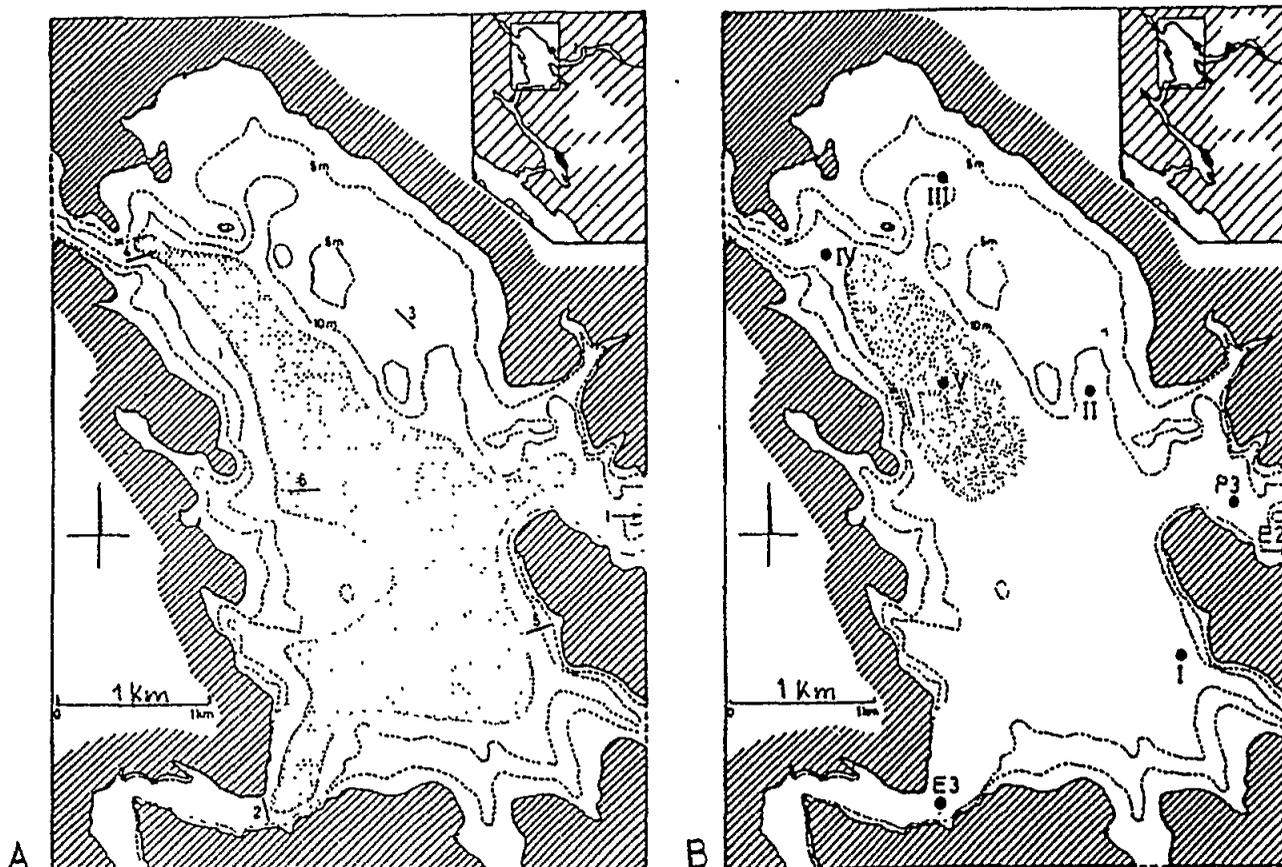


Fig. 3a Middle reach of the estuary (Prokljan Lake) with the zone (dotted area) where benthic mortality was observed in October 1988, and position of transects (1-6) for observation and sampling of benthic macrofauna

Fig. 3b Dotted area indicates the area of subsurface bloom of GP observed by divers on October 19, 1988

4. RESULTS AND DISCUSSION

4.1 Seasonal field measurements

The fine vertical distribution of physico-chemical and organic matter parameters around the halocline are presented in Fig. 4. Parameters of organic matter [dissolved and particulate organic carbon (Cauwet, 1991), surfactant activity and surface active particles, chlorophyll-a and phaeophytin] all show the greatest concentration in the 20-50 cm interface layer. Phytoplankton

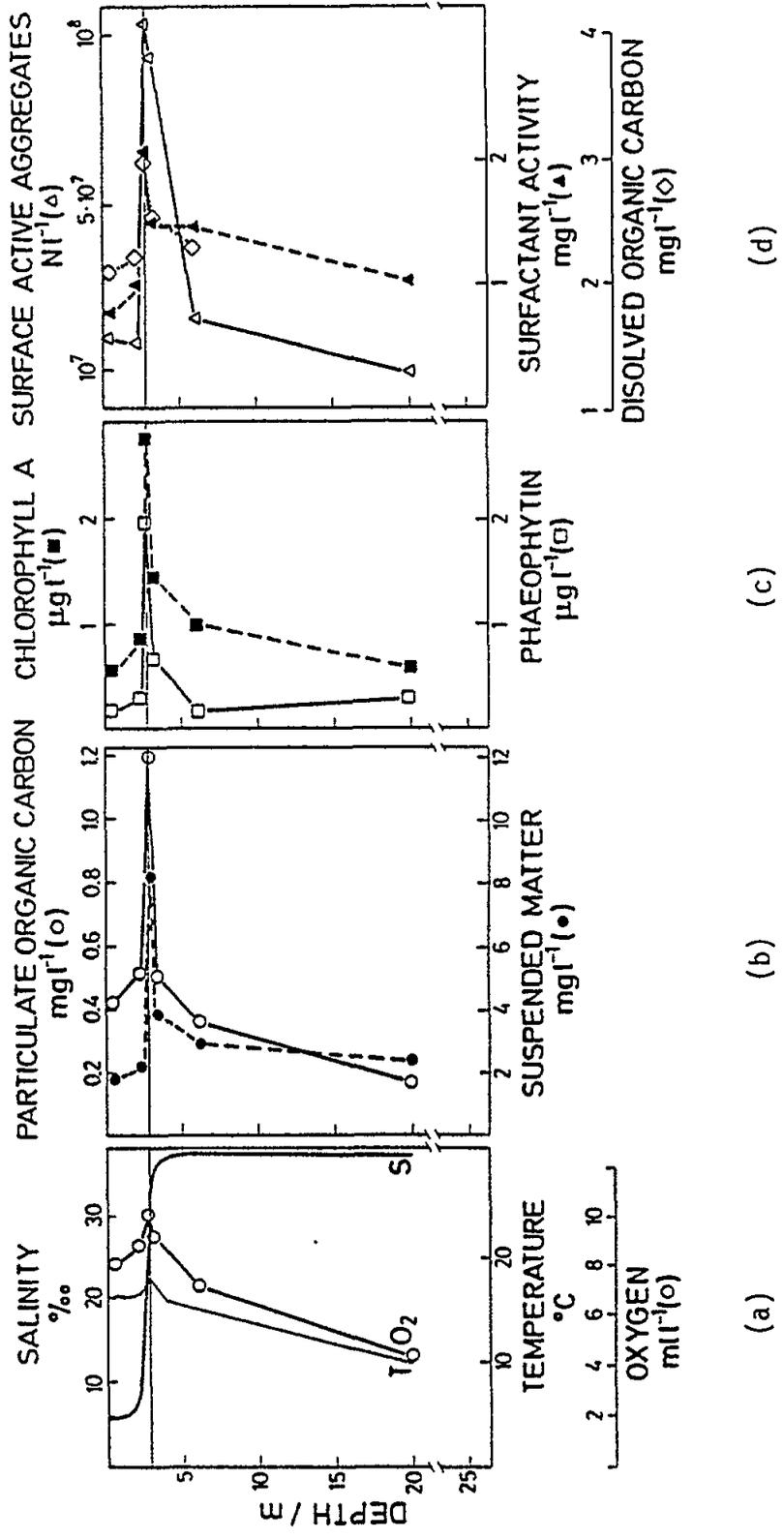


Fig. 4 Typical vertical profiles for (a) salinity, temperature and oxygen concentration; (b) suspended matter and particulate carbon; (c) chlorophyll-a and phaeophytin; (d) surface-active particles, surfactant activity and dissolved organic carbon at station E3, April 22, 1989 (Svetlicic *et al.*, 1991)

accumulates selectively in this layer (Vilièæ et al., 1989); larger size fractions accumulate faster than smaller ones. In particular, nanoplankton accumulates the slowest. The visible interface is also populated by dead phytoplankton cells. Most of the freshwater phytoplankton dies and decomposes in the interface (as revealed by a smaller chlorophyll-*a*/phaeophytin ratio), and it represents the main source of surface-active (dissolved and particulate) organic matter. Marine flagellates migrate and divide in the interface, and some are also found in the upper freshwater layer. Oxygen sag (Morris et al., 1982) is unlikely to develop at the interface, because of the presence of viable marine phytoplankton.

Vertical distributions, as represented in Fig. 4(a)-(d) are typically obtained under stable meteorological conditions but varying biological activity and river flow.

A typical set of results of field investigations is illustrated by a longitudinal distribution of parameters during the seasonal cruises in 1990 shown in Figure 5 (a: spring; b: summer; c: autumn). Plots of parameters along the estuary from the riverine end-member, (station E0) and the head of the estuary (station E1) to the mouth (station E5) and the marine end-member (C1), are presented for the upper freshwater/ brackish layer (sampling depth 0.5 m) and lower marine layer (sampling depths 6.0 m).

The following general characteristics fit well with the behaviour reported in the previous years (Žutiæ 1984-1990):

Salinity in the upper layer increases towards the mouth while concentrations of inorganic nutrients decrease.

In the marine layer, nutrients also decrease towards the mouth. This means that the marine layer is enriched by nutrients at the head of the estuary. Since the salinity at the head of the estuary is the same as at the mouth, nutrients come from biological material that sediments at the head of the estuary via remineralization from the respective organic fractions.

In the surface brackish water, POC (Cauwet, 1991) follows chlorophyll-*a* dynamics and detailed calculations show that most of POC belongs to phytoplankton (Vilièæ et al., 1989). The marine layer at the head of the estuary is generally characterized by the highest values of the suspended matter, chlorophyll-*a* and POC, due to accumulation of the material that sedimented through the halocline and also due to autochthonous production of marine phytoplankton in this water mass of a high residence time.

In the lower part of the estuary (station E4a) a local increase of phytoplankton density and accordingly of pigments, suspended matter and total phosphorus only in the surface brackish layer reflects the influence of the city and harbour of Šibenik with its untreated wastewaters released directly into the estuary, as well as direct enrichment by mineral phosphate of the ore transshipment in the harbour. Most of the constituents accumulate at the halocline, while the underlying marine layer shows little direct influence of the anthropogenic inputs. Thus, even at this location, halocline acts as an efficient barrier to vertical transport of pollutants.

KRKA ESTUARY · 24 - 26 APRIL 1990

○ 0.5 m △ 60 m

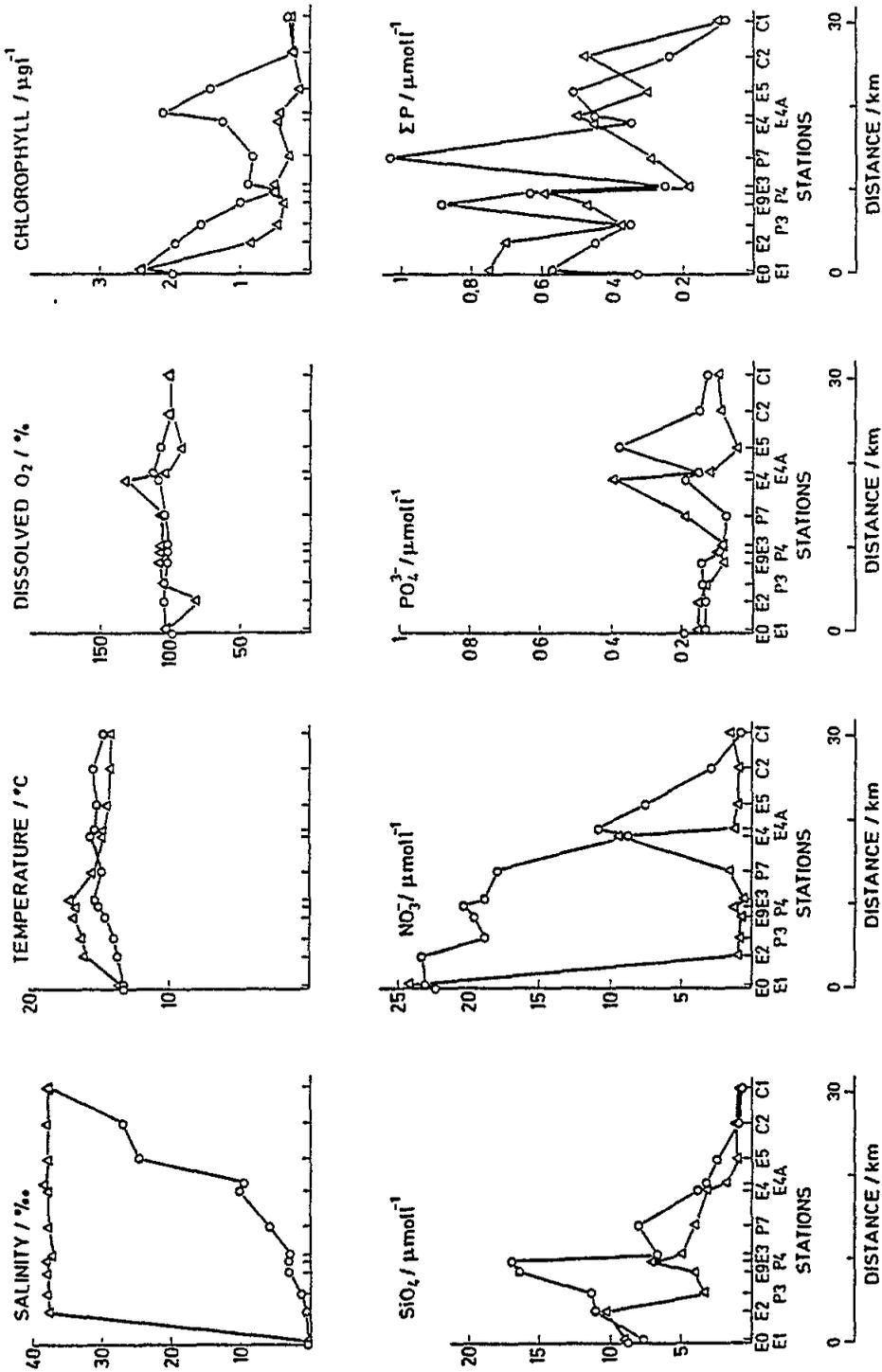


Fig. 5a Longitudinal distribution of salinity, temperature, dissolved oxygen, suspended matter (SM), nutrients and pigments in the surface brackish layer, 0.5 m (○) and in underlying marine layer, 6 m (△) of the estuary for the spring cruise in 1990 (Žutić and Sipos, 1991)

KRKA ESTUARY : 29 - 30 AUGUST 1990

□ 0.05m Δ 60m

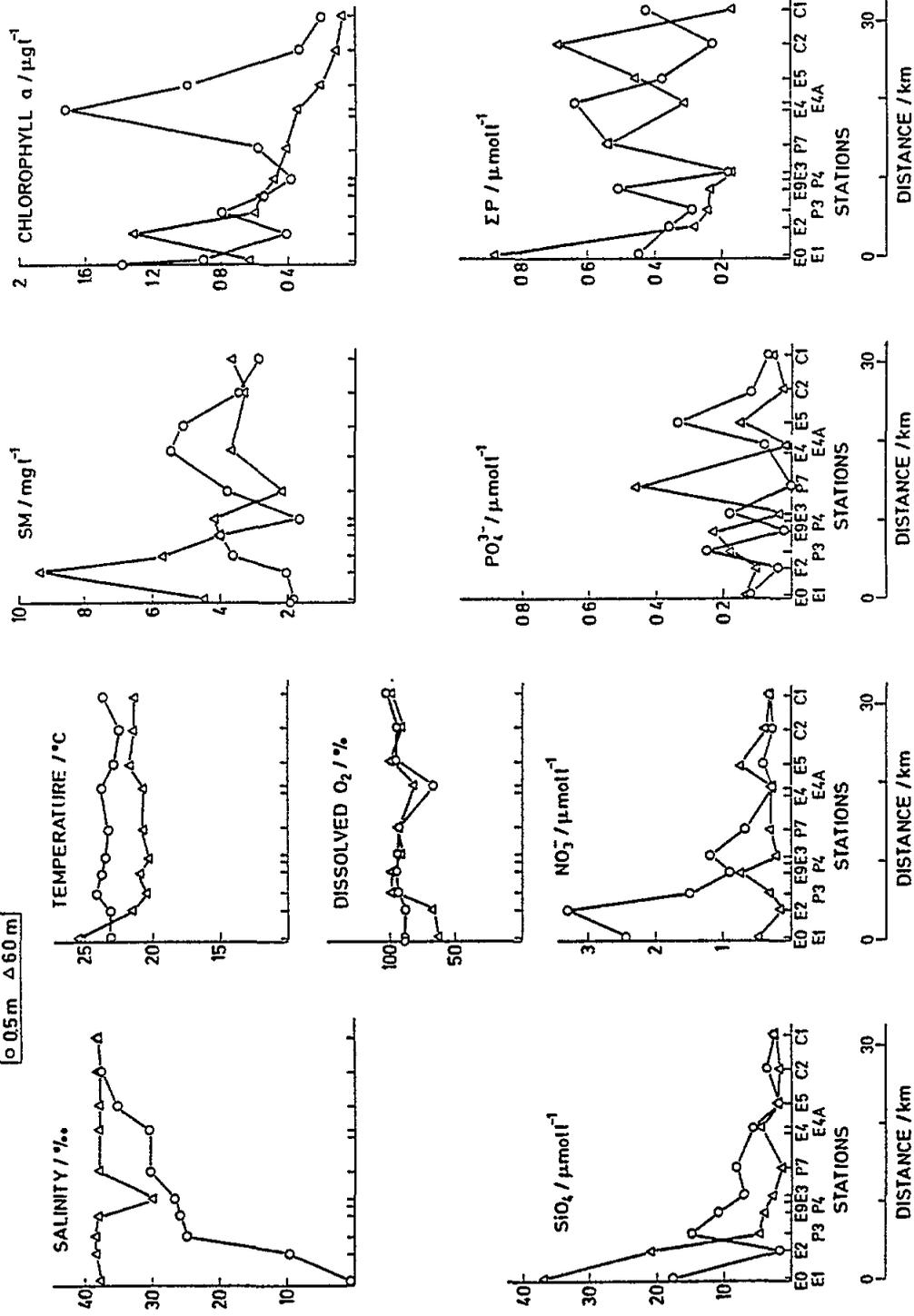


Fig. 5b Longitudinal distribution of the parameters during the summer cruise 1990 (Žutić and Sipos, 1991)

KRKA ESTUARY: 28 SEPTEMBER - 1 OCTOBER 1990

□ 0.5 m △ 60 m

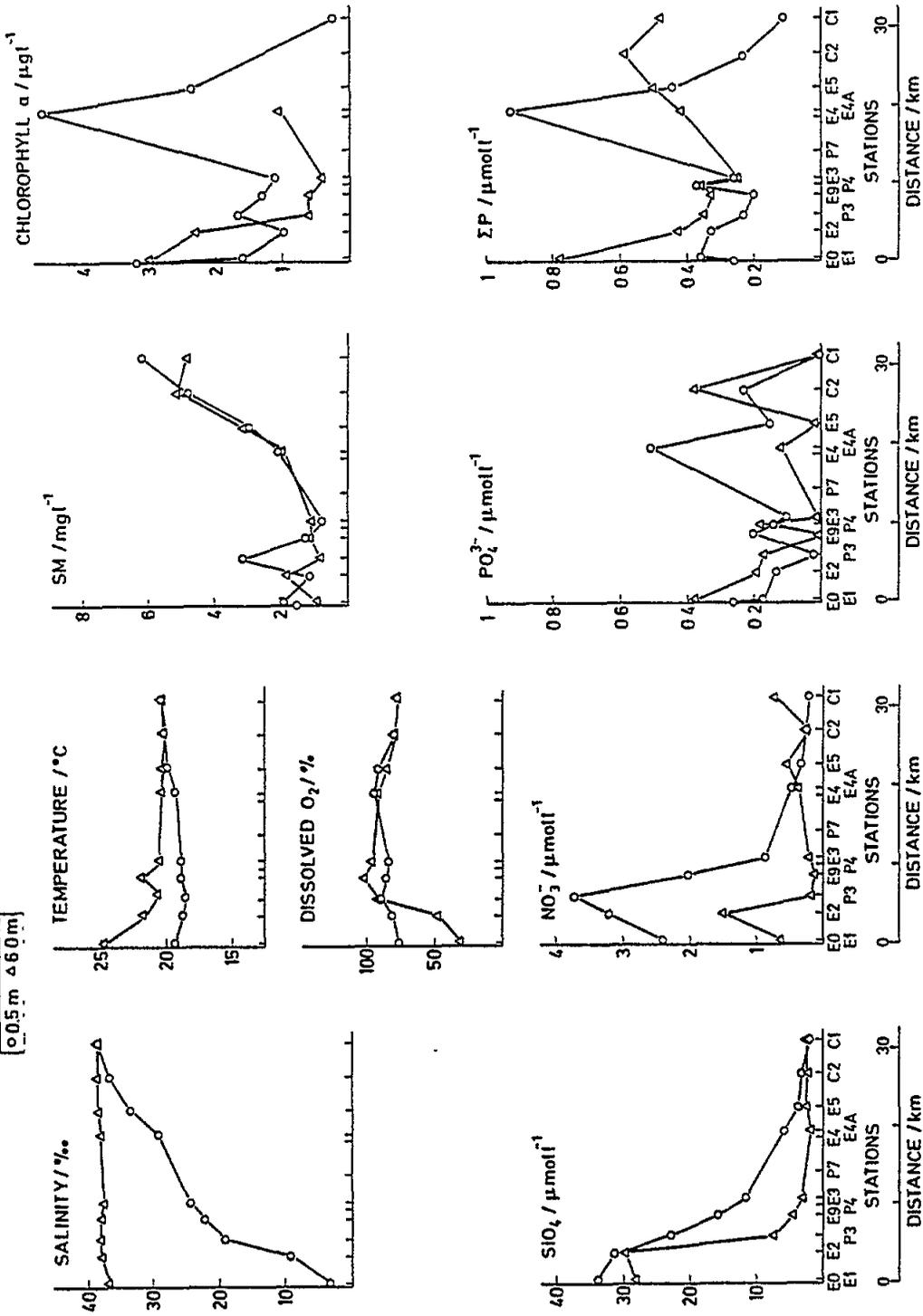


Fig. 5c Longitudinal distribution of the parameters during the autumn cruise 1990 (Žutić and Sipos, 1991)

4.2 Exchange of water in the estuary (Legović, 1991)

A method to calculate the exchange of water in both the upper brackish layer and in the lower marine layer has been formulated. In the upper layer, the exchange of fresh water is calculated from the inflow rate of the river and a change of the volume as a function of the inflow rate. During winter the exchange time is between 6 and 20 days while during summer it is up to 100 days (Fig. 6).

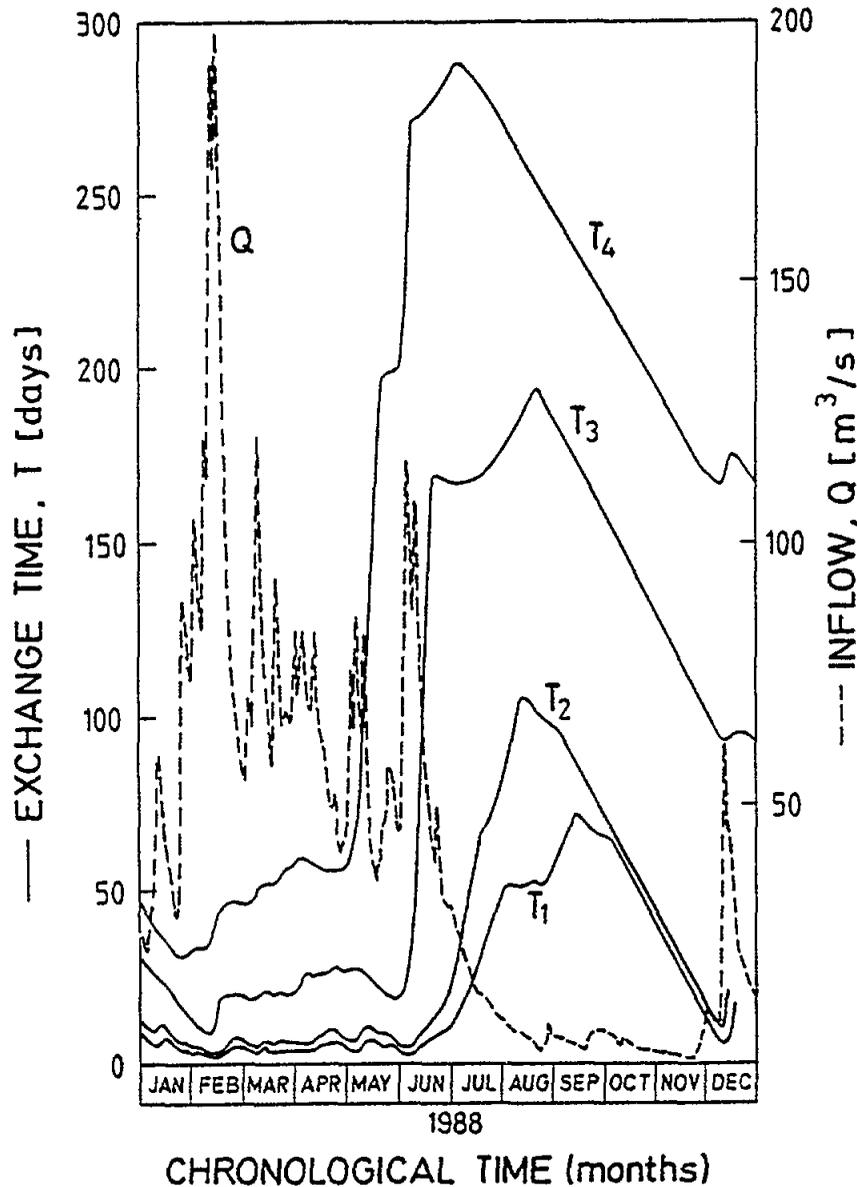


Fig. 6 Daily inflow of river Krka to the estuary during 1988. T_1 - exchange time of freshwater in the Prokljan Lake. T_2 - exchange time of freshwater in the whole estuary. T_3 - exchange time of marine water below the halocline in the Prokljan Lake. T_4 - exchange time of marine water in the layer below the halocline, assuming the entrainment is equal to Q

The exchange of marine water in the lower layer is calculated by taking into account two mechanisms: entrainment into the upper layer and velocity shear below the halocline. The exchange time of marine water during winter is around 50 days. During summer it lengthens up to 280 days.

In cases where the tidal excursion of particles is small in comparison to the length of the estuary, the exchange time may be interpreted as a renewal time. Where a section of the estuary is not narrow, the exchange time may be closer to the half-life than to the renewal time. Renewal time of Krka estuary as a whole may be approximated by the exchange time.

The results of the calculations are in a good agreement with the ^7Be dating experiment performed in May 1988 (Thomas *et al.*, 1989).

The current field has been reconstructed for the period of detailed T, S measurements (Fig. 7) according to the method developed by Legović *et al.*, 1990. From this current field the residence time of water particles in the Prokljan lake has been computed. The results are in good agreement with those for the exchange time computed by the method described earlier. In addition, using this latter method, it is possible to obtain the details of currents in the various locations of the Prokljan lake.

4.3 Effect of wind on the stability of the halocline (Legović *et al.*, 1991b)

Contrary to coastal seas, where wind induced currents efficiently mix waters through the thermocline, in the Krka estuary even the Bora wind is unable to destroy the halocline. On March 4, 1989, before the onset of wind a sharp halocline extended from 2.5 to 4 m below the surface, separating the upper brackish water from the lower marine layer at station E3. Strong wind (20 m s^{-1}) induces a tilt of the halocline so that downwind (5 km wind fetch) the halocline is pushed to 4.6 m below the surface. Wind-driven currents induce a vertical gyre within the upper layer and a gyre in the opposite direction in the lower marine layer. As a consequence, the halocline close to the coast on the downwind side is not only deeper but is also steepened. The entrainment of marine water into the upper brackish layer is intensified on the windward side.

When the water column near the bottom is depleted of oxygen, the induced vertical gyre will replace the water near the bottom with water richer in oxygen. Hence, the induced vertical circulation below the halocline will be beneficial to the benthic organisms affected by hypoxia. However, sudden tilting of the halocline which may persist for a day results in massive mortality of marine shellfish organisms (and cultures) that reside near the halocline on the side of the lake that is opposite to wind blowing.

4.4 Subsurface temperature maximum (Legović *et al.*, 1991c)

The development of a temperature maximum in a stratified estuary, the phenomenon first discovered in the Krka estuary, is a consequence of the presence of a shallow and transparent brackish layer and a well-developed halocline. The maximum is found at the lower edge of the halocline. However, the temperature maximum is continuously eroded by entrainment of warm and saline water into the upper brackish layer. If the entrainment is significant the temperature maximum cannot be formed.

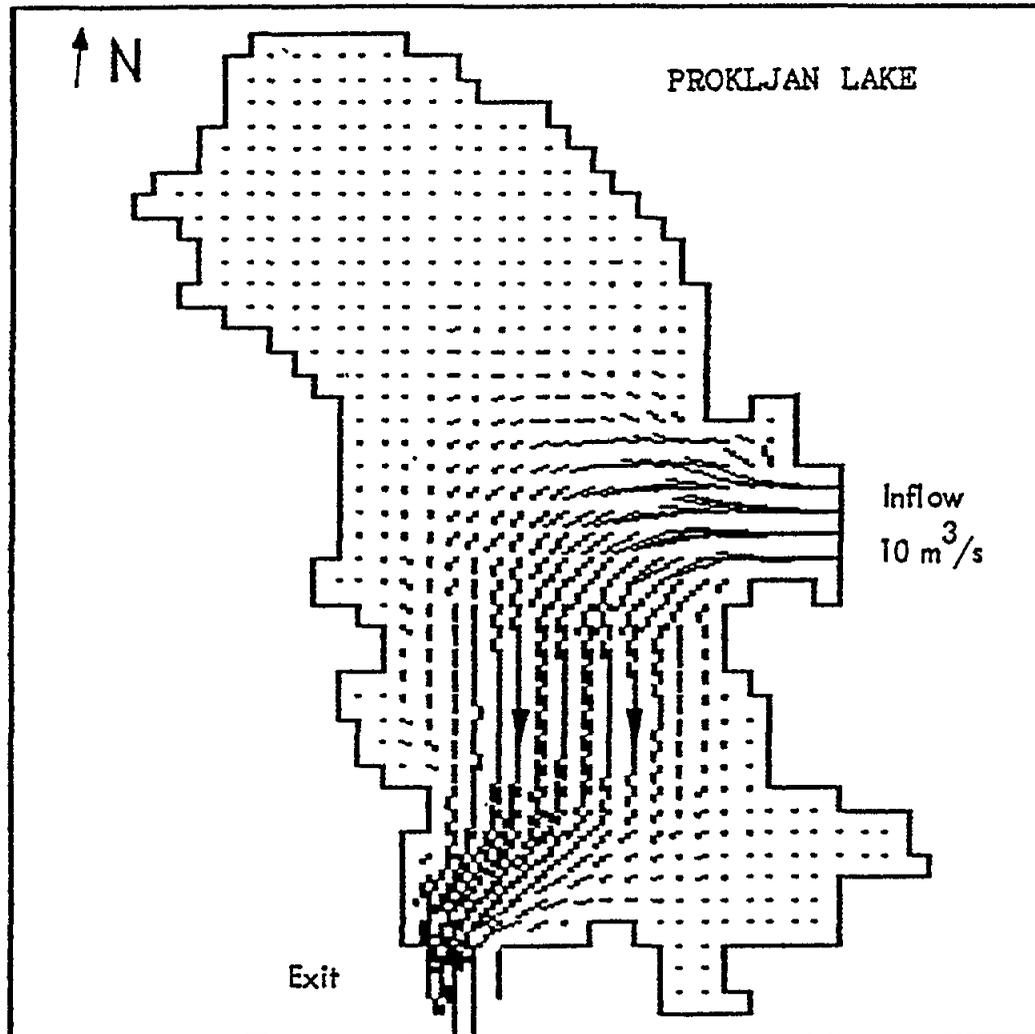


Fig. 7 Residual current field in the upper brackish water layer above the halocline on August 8, 1988. Depth of the halocline is 2.25 m. Maximum current velocity is 1 cm s at station E3

In the Krka estuary, the subsurface maximum can be recorded in the upper and central sections of the estuary (surface salinity <20‰) from mid-April until the end of October. The highest temperature is found in the northern part of the Prokljan Lake, and it may reach 31°C. The maximum in the Prokljan Lake is the highest temperature recorded in the Adriatic sea.

The existence of a temperature maximum contributes to a reduction in the density difference between the upper brackish water and the underlying marine water. As a result, the entrainment is slightly increased.

Obviously, a high temperature gradient in the halocline affects the rate of biochemical reactions, the equilibrium of present chemical species and the rate of precipitation of insoluble substances. The decomposition rate of freshwater phytoplankton that sink to the halocline also increases. This permits nutrients to cycle more efficiently.

4.5 Subsurface bloom of the dinoflagellate *Gonyaulax polyedra* (Legovizæet al., 1991d)

A subsurface bloom of marine dinoflagellate *Gonyaulax polyedra* (GP) was observed on October 19, 1988 in the central part of the estuary (Fig. 3b) as a 6-m-thick red-brownish layer, located below the halocline. We shall discuss here a possible explanation for its occurrence. To our knowledge, a GP bloom in a stratified estuary has not been reported before.

Coloured water observed on October 19, 1988 (Figs. 3b, 8a) is due to GP cells which developed during a period of stable weather and low freshwater inflow (thin brackish layer). The GP developmental cycle in the Prokljan Lake probably started from resting cysts. According to findings from Kaštela Bay (Marasoviæ 1990), the critical excystment seawater temperature is 20EC.

On August 4, a temperature of 20EC was found near the bottom only in the upper reach of the estuary. Thus, it is not surprising that the first record of GP was obtained near the bottom at station E2. At the same time, a few GP cells were also found at station E3, at the surface, during increased surface salinity (>15‰). In contrast, slightly lower temperature was recorded at seaward stations at corresponding depths, and even lower temperature was found at greater depths near the bottom. At these stations, it would be expected that if present, GP cysts could begin excystment at a later date.

The above supports the hypothesis that the subsurface GP bloom started in the upper reach of the estuary. According to underwater observations, the initial GP bloom appeared northwest of station 5 on September 27. The observed GP bloom probably started by excystment near station E2 and was followed by excystment along the northeastern, northern and northwestern sides of the lake as the temperatures near the bottom in these areas increased.

In October 1988 Prokljan Lake stabilized by a strong halocline, and the exchange of seawater was slow. The exchange rate of seawater in the Prokljan Lake is at its lowest in October, because the river discharge is then at its minimum (Fig. 6). In the surface layer, the dominant currents are tidal and wind induced. The average surface residual current at station E3 is nearly 1 m s^{-1} (Fig. 7). The current is much smaller in the marine layer, and especially in the central and northern Prokljan Lake. Here, the dominant currents are tidally induced. As the residual horizontal transport of particles in the estuary is very small, we suppose that the GP population cannot be significantly transported horizontally. Observation of the GP concentration at station E3 seem to support this hypothesis.

If a strong wind occurs over the estuary, the dispersion of cells participating in the bloom would increase. However, the marine layer below the halocline is protected from moderate winds over the estuary (Legovizæet al., 1991b).

During their growth cycle, GP cells consume nutrients and because of weak circulation impoverish the environment, as observed in the northeastern and northern part of the Prokljan Lake (at stations 2 and 3) in October 1988 GP and many other dinoflagellates migrate vertically during daily changes of light intensity. The GP swimming speed varies from 2 to 20 m day^{-1} (Thronsen, 1973). At station 5, GP was limited to the marine layer below the halocline. The upper boundary of the coloured water layer at station 5 during the

afternoon sampling (at 14.00 h) was limited to 2 m below the halocline; this indicates that the bloom had begun to sink towards the bottom, where the cells would try to supply their nutrient needs during the forthcoming night. Given that favorable conditions for growth prevail, the supply of nutrients in a readily available form determines the highest concentration that the cells may attain. In the Prokljan Lake, the supply of nutrients comes mainly from the sinking and decomposition of freshwater phytoplankton. Most of the decomposition seems to take place at the halocline but some of the phytoplankton may sink to the bottom and decompose there.

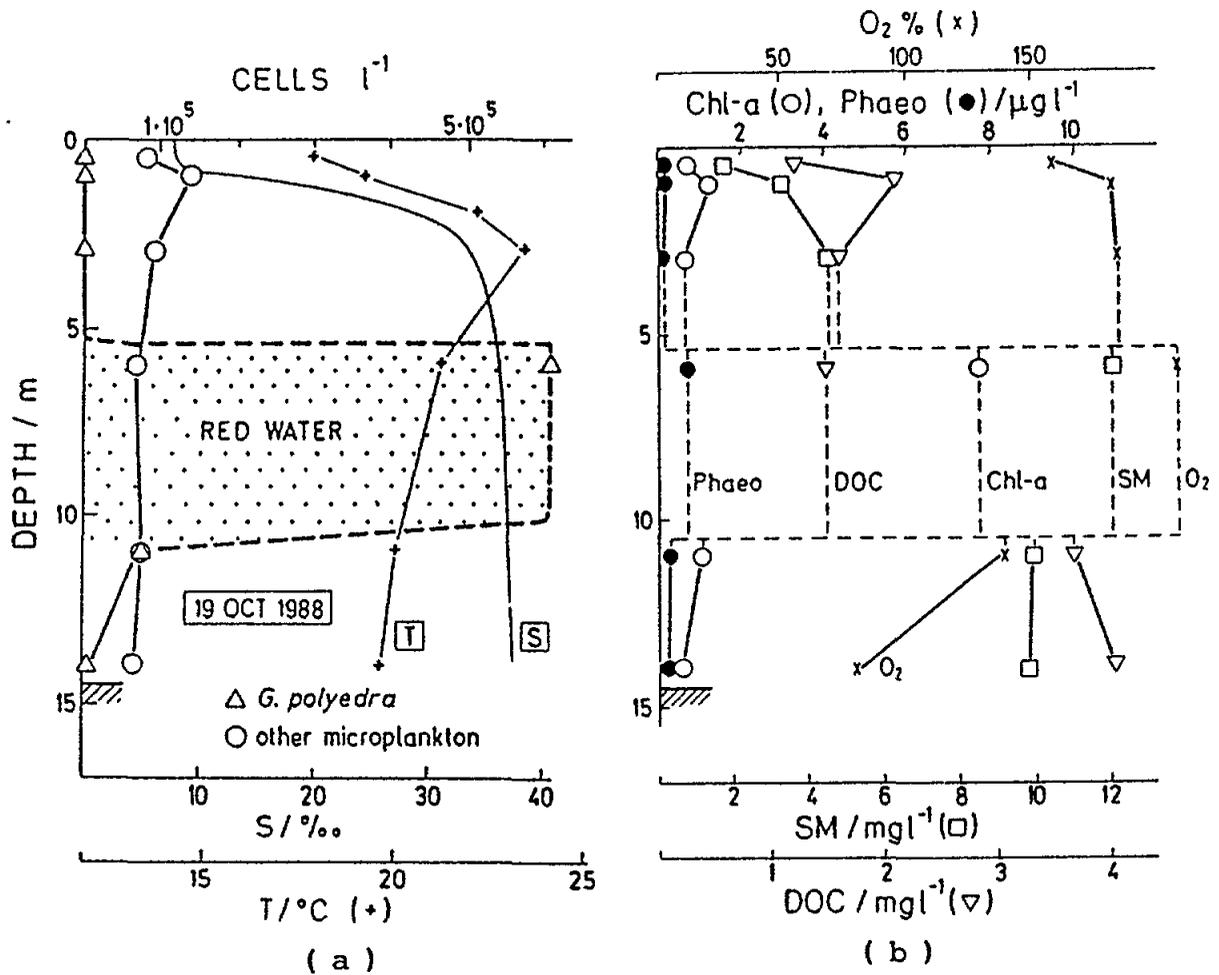


Fig. 8a Vertical distribution of temperature (T), salinity (S) and population density (cells l⁻¹) of *G. polyedra* and of all other microplankton at station V (Fig. 3b). Time: 15.00 h, October 19, 1988 (Legović et al., 1991d)

Fig. 8b Vertical distribution of dissolved oxygen, chlorophyll-a (Chl-a), phaeophytin (phaeo), suspended matter (SM) and dissolved organic carbon (DOC)

As the freshwater that enters the estuary carries little allochthonous organic matter, most of the dissolved organic matter supply also comes from the release and decomposition of freshwater phytoplankton.

Analyzed coloured water contained GP population which was still growing. When the nutrient supply becomes scarce, the bloom dissipates rapidly due to loss of motility and sinking (Holmes *et al.*, 1967). Metabolic activity, degradation of GP near the bottom and products of encystment consume dissolved oxygen and produce toxins, resulting in mass mortality of benthic organisms. This indeed occurred in the Prokljan Lake. The higher concentration of DOC near the bottom probably resulted from extracellular production by the senescent GP cells and cells in the encystment process.

It is unlikely that GP could develop a bloom in the lower part of the estuary and in front of Šibenik, for the following reasons: (a) excystment from presumably existing cysts cannot occur as the temperature near the bottom is too low; (b) a bloom cannot be transported sufficiently fast from the Prokljan Lake; (c) successful transport of the bloom from the coastal sea is unlikely because the cells would have to endure lower temperatures and a lower light intensity for at least 2 months.

4.6 Hypoxia and benthic mortality (Legović *et al.*, 1991a)

The first report on the dissolved oxygen (DO) concentration in the Krka estuary was published by Buljan (1969). The data taken on vertical profiles at ten stations in March, June and November 1949 and December 1961 cruises were considered. The maximum oxygen concentration was found at the surface near the waterfalls in March and the smallest value of 2.11 mg O₂ l⁻¹ was found during the December cruise close to the bottom in Prokljan Lake. Buljan (1969) stated that in late autumn "old" water appeared in Prokljan lake and extended up the estuary to Skradin bridge and down the estuary until Zaton.

In autumn 1988 hypoxia in the central part of the Krka estuary resulted in massive mortality of benthic macrofauna (Fig. 3a) of proportions not recorded yet. This does not seem to be a regular yearly phenomenon as: (1) the maximum age of dead scallops in the Prokljan Lake was over 4 years, and (2) during the subsequent year, the density of scallops was drastically smaller than during the five preceding years.

4.6.1 Origin of hypoxia

Generally, the concentration of organic matter is lower in Prokljan Lake than in the upper reach near Skradin. The temperature near the bottom is also lower since Prokljan Lake is deeper. As a result, the O₂ concentration near the bottom decreases to values which are on the average slightly higher than in the upper reach. Further down in the Šibenik area, the temperature near the bottom is even lower (15.5EC at the depth of 40 m) and O₂ concentrations are similar to those in Prokljan or higher.

There exist situations which may result in lower O₂ concentrations near the bottom in Prokljan Lake than in the upper reach. During longer periods of sunny and dry weather, phytoplankton blooms may develop in the Visovac lake, which is located upstream from the waterfalls (Fig. 1). This brings larger quantities of freshwater phytoplankton through the

waterfalls. The phytoplankton sinks to the halocline. Most of the sinking is completed from Skradin to the entrance of Prokljan Lake. Since the temperature is rather high at the lower edge of the halocline (up to 31EC), the decomposition is fast. Marine phytoplankton takes the advantage of the released nutrients and develops a bloom in Prokljan Lake. Rapid sinking and decomposition of such a bloom may cause severe hypoxia on the bottom. One of such blooms was present at the NW side of Prokljan Lake during the second interval of measurements (Legoviæ *et al.*, 1991d). The decomposition of algae originating from this bloom increased hypoxia on the bottom of the Prokljan Lake. When O₂ concentration drops below 1 mg O₂ l⁻¹ at the temperature of 22EC it is followed by mortality of most macrozoobenthic organisms which are either buried in the sediment or are too slow to escape. The organisms most sensitive to low O₂ concentration belong to bivalves, brittle stars and sea-cucumbers (Theede *et al.*, 1969). In nearly anoxic conditions, even organisms which are more resistant to oxygen insufficiency but can not move fast die (*Sipunculoidea*, *Enteropneusta*, *Polycheta*). When these organisms die all at once, a larger quantity of organic matter is subject to mineralization which further decreases O₂ concentration and hence severe hypoxia may persist longer. How long will it persist depends on the appearance of the first intensive rains which increase the discharge of river Krka. This in turn increases the exchange rate of seawater in Prokljan Lake through the compensatory flow (Legoviæ 1991). As a consequence, the layer near the bottom is partially renewed with marine water that is colder and has a higher oxygen content.

Episodes of strong bura wind will also cause more intensive horizontal and vertical transport within the marine layer (Legoviæ *et al.*, 1991b). This will result in O₂ enrichment near the bottom.

Why does the most intensive benthic hypoxia occur in the autumn? Particulate organic matter which comes through the river or is generated in the water column sinks to the bottom. It is well known that the decomposition rate increases exponentially with temperature (Rudnick and Oviatt, 1986). It appears that the temperature near the bottom is the highest in the autumn (20EC). In addition, during summer and autumn the marine layer is vertically stratified by temperature which means that vertical mixing is slower than during the rest of the year.

What is so special about hypoxia in the autumn of 1988, i.e. why such an extent of hypoxia does not appear every year? Here we shall not enter into long-term arguments (Justiæ *et al.*, 1987) since our data reach back only five years. Hence, our discussion will focus only on year to year differences.

In comparison to several previous years, the autumn of 1988 was very dry. As a consequence the river flow was small and the brackish layer was thin. Due to the thin brackish layer and sunny weather, higher light intensity was available to phytoplankton in the marine layer. Hence, if given enough nutrients, marine plankton is able to develop denser blooms. Although the Krka discharge is smaller, the inflow of phytoplankton from the freshwater Visovac Lake is higher since it developed denser blooms due to stagnant water.

When the concentration of marine phytoplankton is larger than usual in Prokljan Lake, its sinking and decomposition cause higher oxygen demand near the bottom. Since the residence time of marine water in Prokljan Lake is longer than average, the renewal with the richer and colder water from the sea is slower, hence hypoxia is more intensive and persists longer.

5. CONCLUSIONS

Nutrients in Krka estuary originate from freshwater inflow, seawater incoming from the Adriatic, atmospheric precipitation and anthropogenic load. According to the longitudinal distribution of nutrients (Fig. 5), the main source of silicate and nitrate is Krka river. The dominant source of phosphorus in the upper estuary is Krka river. According to estimates by Gržetiæ et al. (1991), the dominant source in the lower estuary (Šibenik area) is anthropogenic.

We have presented evidence of autochthonous development of *G. polyedra* bloom in the upper part of the estuary. The bloom was triggered by the onset of high temperatures in late summer. It preceded benthic hypoxia and massive mortality of benthic macrofauna.

In general we expect the lowest O₂ concentration near the bottom in the salt wedge towards the waterfalls rather than in the Prokljan Lake. To a smaller extent the hypoxia also appears in front of Šibenik. A severe hypoxia may develop in Prokljan Lake during autumn following a marine phytoplankton bloom. Its decomposition may drive the O₂ concentration values below 1 mg l⁻¹ at depths greater than 10-15 m causing massive mortality of benthic macrofauna. The hypoxia may persist until Krka flow increases and water on the bottom is renewed by compensatory flow with colder and oxygen richer water.

Although the estuary receives the highest anthropogenic load in its lower reach where the highest phytoplankton densities were recorded in the surface brackish water layer, phytoplankton blooms have much more serious consequences in the upper reach of the estuary.

An increase in anthropogenic nutrient load to the river or the upper part of the estuary would increase the primary production. This would intensify the phytoplankton blooms and their spatial extent. As a consequence more intensive hypoxia would result over a larger portion of the estuary. The benthic and other marine communities of the upper and middle reach of the estuary are in greatest danger.

Since we found that subsurface blooms of marine phytoplankton may cause benthic hypoxia in the upper part of the estuary, the major research question to be answered in the future is: What is a precise relationship between organic load (inflow and sinking of phytoplankton) > decomposition below the halocline > marine phytoplankton bloom > sinking to the bottom and bottom hypoxia in different parts of the estuary?

6. ACKNOWLEDGEMENTS

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IMPACT OF EUTROPHICATION ON SEA-URCHIN POPULATIONS
OF THE AMVRAKIKOS GULF (IONIAN SEA, GREECE)

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ABSTRACT

Quantitative estimations of some populations of the edible sea urchin Paracentrotus lividus (Lamarck) have been made in the semi-enclosed Amvrakikos Gulf (Ionian Sea), submitted to high organic enrichment. Investigations in situ all around the Gulf showed that P. lividus populations occupy almost the totality of the shallow rocky bottoms, with extremely high density of very small individuals. In order to ascertain relationships between eutrophication and Paracentrotus population, three sites were sampled within the Gulf and one reference station was chosen in an oligotrophic area outside the Gulf.

In the Gulf, population densities reached 76 ind. m⁻², while in the Ionian Sea they fell to 3.3 ind. m⁻² (summer sampling). A striking difference in size was also noticed among the populations, those situated in the Gulf having a significantly smaller size compared to those found in the oligotrophic area (diameter average 2.19 cm and 4.59 cm respectively).

The small body size, coupled with the disappearance of macrophyto-benthos in the localities occupied by the sea urchin within the Gulf, lead us to consider the hypothesis of changes in feeding habits. Thus, P. lividus populations living in the Gulf appear to be adapted to eutrophication, by retaining the microphagous feeding habit. As a result, while survival is possible, a lot of energy is consumed in feeding, with a negative effect in body growth.

1. INTRODUCTION

Sea urchins are undoubtedly one of the most important elements of the hard bottom benthos, often acting as a factor determining the abundance and distribution of coastal phytobenthos. Phenomena of sea urchin overpopulation, with consequent destructive grazing on seaweeds, have been observed throughout the world (Shepherd, 1973; Breen and Mann, 1976; Mann, 1977; Foreman, 1977). Many authors have also investigated the trophic relationships between sea urchins and phytobenthos (Lawrence, 1975; Lawrence and Sammarco, 1982; Verlaque and Nedelec, 1983; Verlaque, 1984), as well as theories related to overpopulation (Elner and Vadas, 1990).

In the Mediterranean sea, Paracentrotus lividus (Lamarck) is one of the most abundant and widely distributed echinoderm species. Although its embryology, anatomy and physiology have been well studied, less is known on its ecology and feeding habits. The occurrence of P. lividus overpopulation has been observed and extensively studied in the coastal area of

Marseille-Cortiou, which is mainly affected by domestic pollution (Regis, 1981; Harmelin et al., 1981; Verlaque and Nedelec, 1983; Delmas and Regis, 1984; Delmas, 1988). The present study examines a similar extensive phenomenon of Paracentrotus overpopulation observed along the rocky coasts of the Amvrakikos Gulf, one of the major Gulfs in Western Greece.

2. STUDY AREA

The semi-enclosed Gulf of Amvrakikos (Fig. 1) forms an important embayment of the Ionian sea on the western coast of Greece. The northern part is occupied by the delta of the rivers Louros and Arachthos, and by a complex system of lagoons. Extensive agricultural activities in the nearby region result in a high discharge of nutrients. Recent data (Frigos and Balopoulos, 1988) show that the concentration of silicates is about 13 times above background levels, while the concentration of phosphates and nitrates is 4 and 2 times above background levels, respectively. Moreover, intensive phytoplankton blooms (Gotsis and Panayotidis, 1988) as well as very high zooplankton abundance values (Pancucci et al., 1988) have been reported, comparable to those of the most eutrophic gulfs in the Mediterranean. All around the gulf, except for the lagoons or in the immediate vicinity of the rivers, where the salinity is a prohibitive factor for echinoderm survival, the rocky coasts present bare rocks covered by small sea urchins, which seem to belong to the same size group. The echinoderm overpopulation is also reflected in the zooplankton, where echinoid larvae were extremely abundant (up to 61% of the total zooplankton population) during May, 1987 (Pancucci et al., 1988).

A further significant observation is the absence of other common echinoids, e.g. Arbacia lixula, from all the sites visited, coupled with the absolute dominance of Paracentrotus lividus.

Based on the above data, four stations were chosen: Stations 1, 2 and 3, having similar eutrophic conditions, situated in the Amvrakikos Gulf and Station 4, a reference station, outside the Gulf, in the oligotrophic environment of the Ionian sea.

At Station 1, large stones and a cement pier, constructed at the site several years ago, serve as an ideal substrate for Paracentrotus lividus. At Station 2, near the town of Preveza, Paracentrotus lividus cover the cement pier at the fish farm of Margarona.

Station 3, was chosen due to the recent (1989) construction of a pier which has created a new substrate for the macrophytobenthos. Fewer and larger individuals of Paracentrotus lividus than at stations 1 and 2 were observed on rocks, which were also occupied by Cystoseira sp.. This environment enabled us to observe any potential overpopulation event from its early stages. Station 4 was situated near a Posidonia oceanica bed. The substrate was rocky, covered with Laurencia, Acetabularia, and Dyctiota species among others.

Following the analysis of material collected during the first sampling trip, Station 2 was eliminated, having exactly the same characteristics as Station 1.

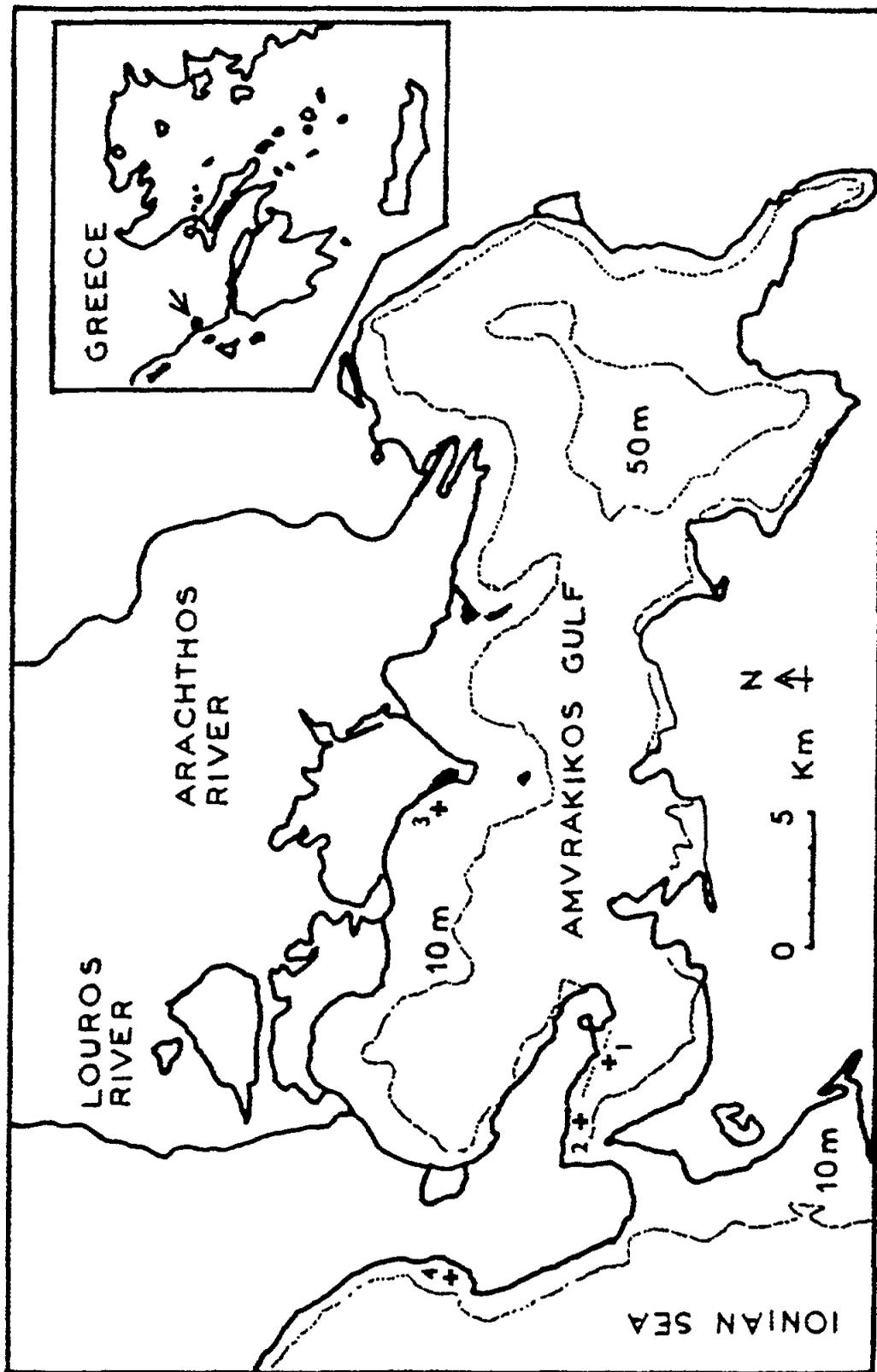


Fig. 1 Location of sampling stations

3. MATERIALS AND METHODS

During 1991, three sampling cruises took place in the Amvrakikos Gulf (April, June and July). In the present study the results of the spring (April) and summer (July) cruises will be discussed, as representative of the effect of seasonal changes.

Sampling was performed by scuba diving at the same depth (0-1 m) for each station, with the aid of a 1 m² frame. In situ measurements were carried out over an area of at least 10 m²; small-size specimens under stones were not included.

In total, 1240 specimens were collected. The diameter (D), height (H) and spine-length (SL) of the test were measured for each individual. Specimens were grouped into several size classes (with a 0.5cm gradation) according to their diameter. After dissection, specimens were subdivided, according to the sexual maturity of their gonads, into Juveniles (J), Males (M) and Females (F). The gut content of several specimens from each station was examined under microscope. Descriptive statistics, including Average (Avg.), Standard deviation (Std.), Variance (Var.), Minimum (Min.) and Maximum (Max.), were estimated for each parameter as well as for the ratios SL/D and H/D. Regression analysis was also applied on the ratio H/D. In addition, One-way and Two-way ANOVA were applied to data subdivided into size classes.

4. RESULTS AND DISCUSSION

4.1 Biometry

The abundance (N) of P. lividus at each station and the results of descriptive statistics for the spring and summer sampling are shown in Tables 1 and 2 respectively.

It is clear that the abundance decreases significantly from Station 1 to Station 4, while body size increases in the same order. Station 3, as already mentioned, represents an intermediate site, with larger specimens than those of the other Amvrakikos stations and, at the same time, higher abundance values in relation to the reference station. One-way ANOVA applied on the diameters of the sea urchin tests revealed statistically significant differences among stations ($F=405.232$ in spring and 999.999 in summer respectively for $P<0.001$). It was noted that, while at stations 1 and 2 the majority of the specimens had diameters between 2 and 3 cm, at the other two stations these size classes were almost absent in spring and in summer (Figs 2 and 3). On the other hand, measurements of spine length showed a clear lengthening in smaller individuals. Thus, the average of the ratio SL/D ranged between 0.41 (Station 3) and 0.56 (Station 1) during spring and between 0.42 (Stations 3 and 4) and 0.55 (Station 1) in summer. When this ratio is considered in relation to the distribution of specimens into size classes, a decrease of this ratio with increasing body size is observed for all stations (Figs 4 and 5).

These results are only partly in agreement with those of Delmas and Regis (1984) as the average ratio values estimated in the entire study area were higher than those observed by the authors mentioned. These variations could probably be attributed to geographical

differentiation. However, both studies show that SL/D is inversely proportional to body size. It is noted that specimens belonging to the size class 2.51 - 3.00 cm were adults at the Amvrakikos Gulf stations but sexually immature at the reference station. Thus, the nanism of the Amvrakikos population results in the retention in the adult stage of a character (lengthening of the spines), which is typical of the juvenile stage. This phenomenon appears to be related to the sea urchin feeding habits (Regis, 1981; Verlaque, 1984).

Table 1

Results of descriptive statistics (Spring).
(SL= spine-length, H= height, D= diameter).

	SL	D	H	SL/D	H/D
St.1 (N/m²=52.7)					
Avg	1.17	2.12	1.07	0.56	0.51
Std	0.15	0.44	0.22	0.09	0.03
Var	0.02	0.19	0.05	0.01	0.00
Min	0.70	1.00	0.48	0.31	0.43
Max	1.80	3.68	1.80	0.81	0.79
St.2 (N/m²=46)					
Avg	1.20	2.23	1.16	0.55	0.52
Std	0.20	0.49	0.28	0.09	0.03
Var	0.04	0.24	0.08	0.01	0.00
Min	0.60	0.80	0.42	0.34	0.45
Max	1.70	3.22	2.00	0.75	0.68
St.3 (N/m²=7.6)					
Avg	1.57	3.90	2.07	0.41	0.53
Std	0.17	0.58	0.31	0.08	0.05
Var	0.03	0.34	0.10	0.01	0.00
Min	1.22	2.40	1.18	0.29	0.44
Max	2.00	5.05	2.90	0.61	0.88
St.4 (N/m²=2)					
Avg	1.86	4.54	2.37	0.42	0.52
Std	0.18	0.65	0.38	0.06	0.02
Var	0.03	0.42	0.15	0.00	0.00
Min	1.40	2.70	1.25	0.34	0.46
Max	2.20	5.40	2.90	0.53	0.56

In agreement with Delmas and Regis (1984), the ratio H/D does not differ significantly, for all stations, showing that the general morphology of the species does not change (Figs 6 and 7). The somewhat high values at station 3 were considered as a possible indication of stress. In addition, one "very tall" juvenile specimen was found at Station 4 during summer sampling. However, these small differences were not significant, as shown by the regression analysis applied on the data (Figs 8 and 9).

Table 2

Results of descriptive statistics (Summer).
(SL= spine-length, H= height, D= diameter).

	SL	D	H	SL/D	H/D
St.1 (N/m ² =76)					
Avg	1.18	2.19	1.12	0.55	0.51
Std	0.14	0.43	0.23	0.08	0.03
Var	0.02	0.18	0.05	0.01	0.00
Min	0.55	1.00	0.50	0.33	0.45
Max	1.58	4.20	2.15	0.83	0.63
St.3 (N/m ² =13)					
Avg	1.65	3.99	2.10	0.42	0.53
Std	0.12	0.55	0.29	0.07	0.05
Var	0.01	0.31	0.08	0.01	0.00
Min	1.35	1.82	1.25	0.31	0.37
Max	1.95	5.30	2.75	0.77	0.85
St.4 (N/m ² =3.3)					
Avg	1.89	4.59	2.51	0.42	0.55
Std	0.15	0.68	0.37	0.05	0.05
Var	0.02	0.46	0.14	0.00	0.00
Min	1.40	3.00	1.60	0.31	0.48
Max	2.25	5.90	3.10	0.53	0.81

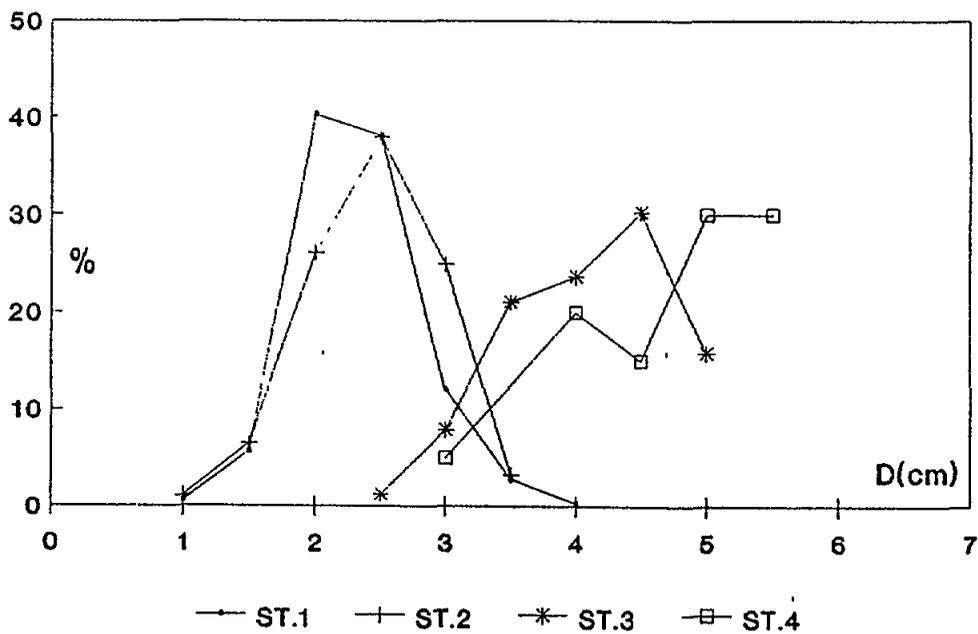


Fig. 2 Distribution of specimens into size classes (Spring sampling)
D = diameter

4.2 Size-sex relation

Tables 3 and 4 show the distribution of P. lividus specimens into size classes according to their sexual maturity. That is, samples were divided according to the maturity of their gonads and not on the basis of their diameter, which would group almost all the examined specimens into adults (Azzolina et al., 1985).

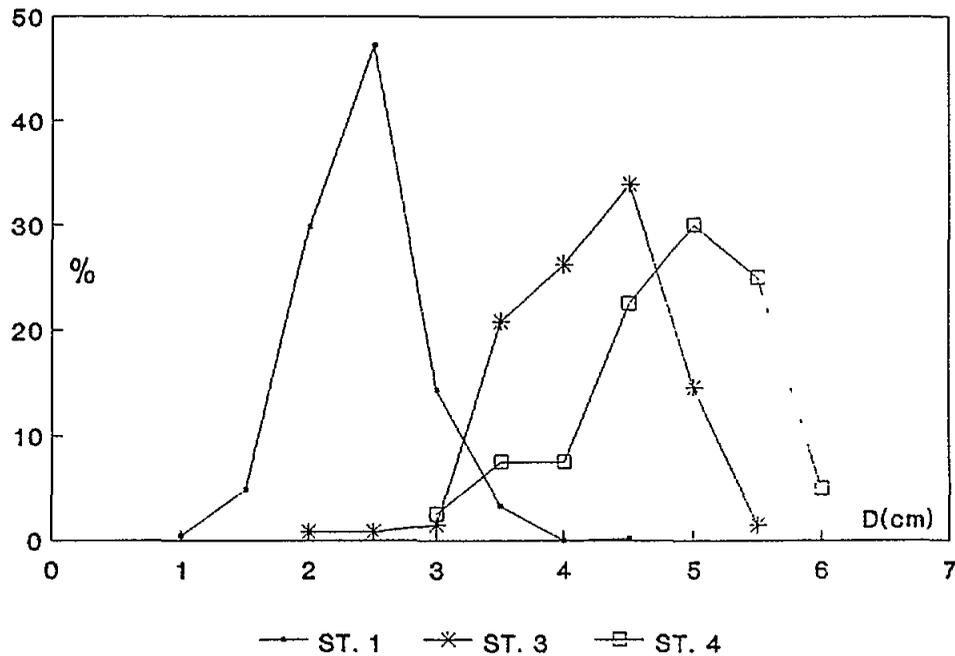


Fig. 3 Distribution of specimens into size classes (Summer sampling)
D = diameter

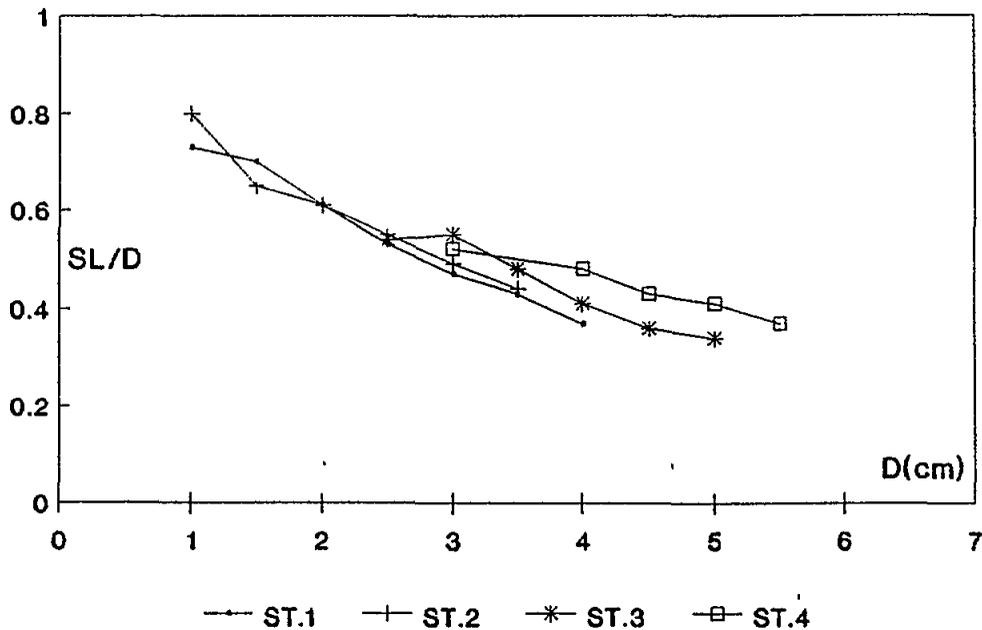


Fig. 4 Variation of the ratio SL/D as a function of the test diameter at each station (Spring sampling). SL = spine length; D = diameter

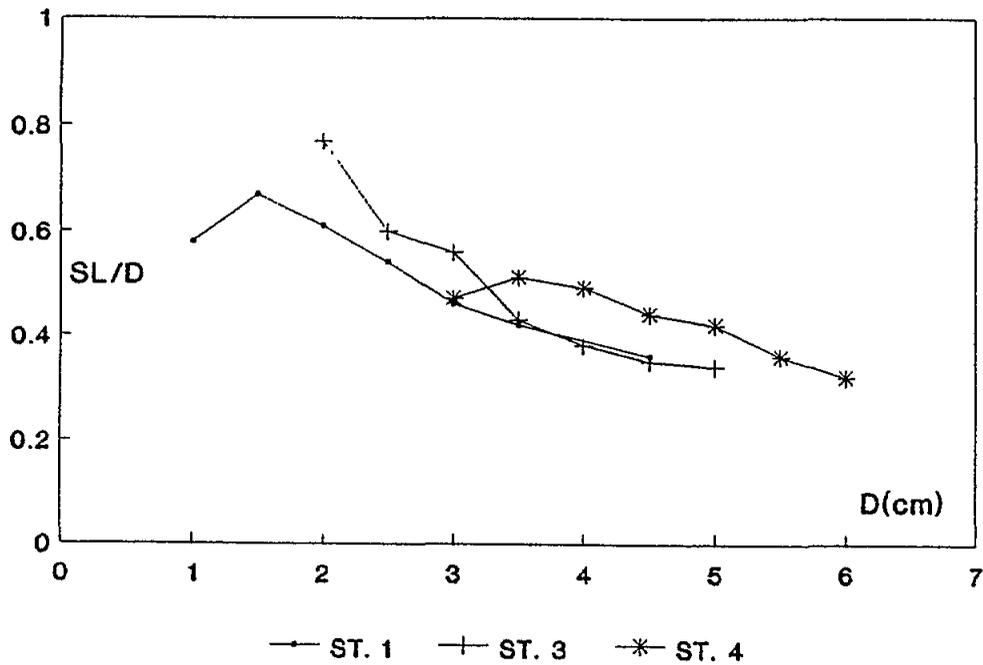


Fig. 5 Variation of the ratio SL/D as a function of the test diameter at each station (Summer sampling). SL = spine length; D = diameter

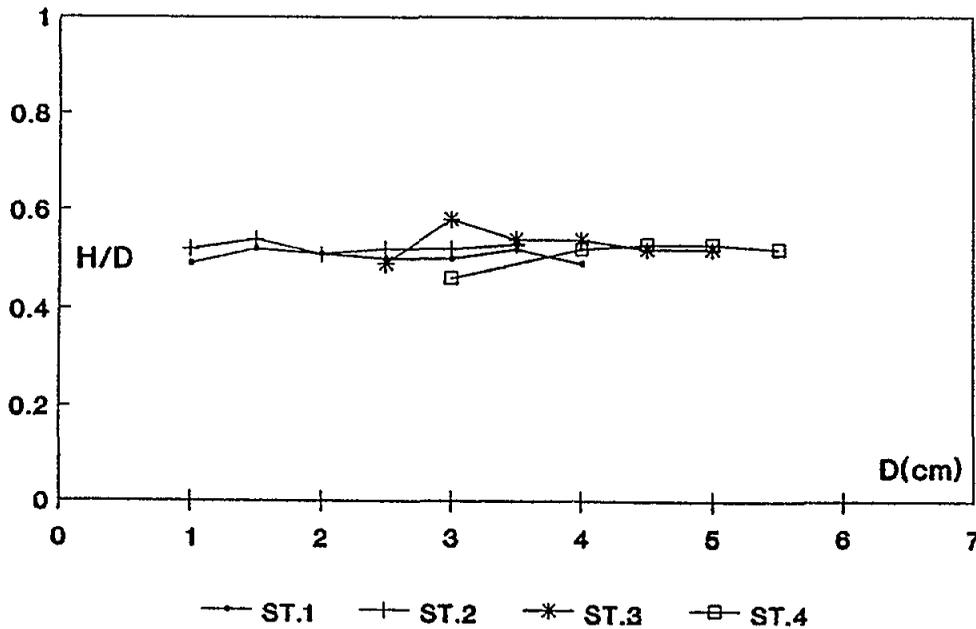


Fig. 6 Variation of the ratio H/D as a function of the test diameter at each station (Spring sampling). H = height; D = diameter

Figures 10 and 11 show the distribution of sea urchins as percentages of juveniles (immature species) and adults for each size class. Station 3, with 100% adult specimens, has not been included in Fig. 11.

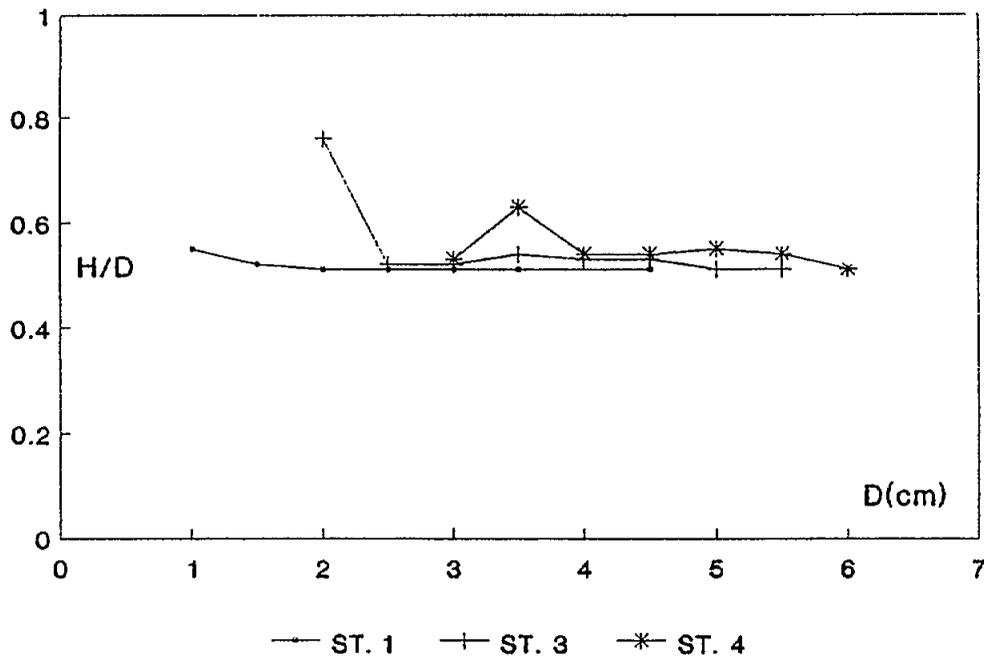


Fig. 7 Variation of the ratio H/D as a function of the test diameter at each station (Summer sampling). H = height; D = diameter

It can be seen that at Stations 1 and 2, sexual maturity is reached earlier, compared to the reference station, with 100% adults in Amvrakikos Gulf and 100% "juveniles" in the Ionian sea for the same size class. In addition, females prevail over males at all stations (Tables 3 and 4), while the two-way ANOVA applied on the parameter "sex" in relation to the diameter showed that females are the larger individuals at all stations.

4.3 Seasonal variations

From the above, it can be concluded that an increase in abundance, as well as a slight increase in size (0.07, 0.09 and 0.05 cm for Stations 1, 3 and 4 respectively) is observed with time, for all stations (Tables 1 and 2). No significant changes, however, were observed in the distribution of specimens into size classes (Figs 2 and 3). Thus, at Station 1, the growth of specimens can be detected from the size class 1.51-2.00 to the size class 2.01-2.50 cm, without substantial variations (1 sole specimen was found to belong to the size class 4.01-4.50 cm, with negligible consequences on the overall results). Stations 3 and 4 during summer present a larger number of size classes, with the addition of larger specimens, even though at a low percentage.

As far as sexual maturity is concerned (Tables 3 and 4, Figs 10 and 11), Stations 1 and 4 presented the same picture in spring and summer, while some changes were observed at Station 3; in this case, spring sampling included some immature specimens but in the summer all individuals were adults.

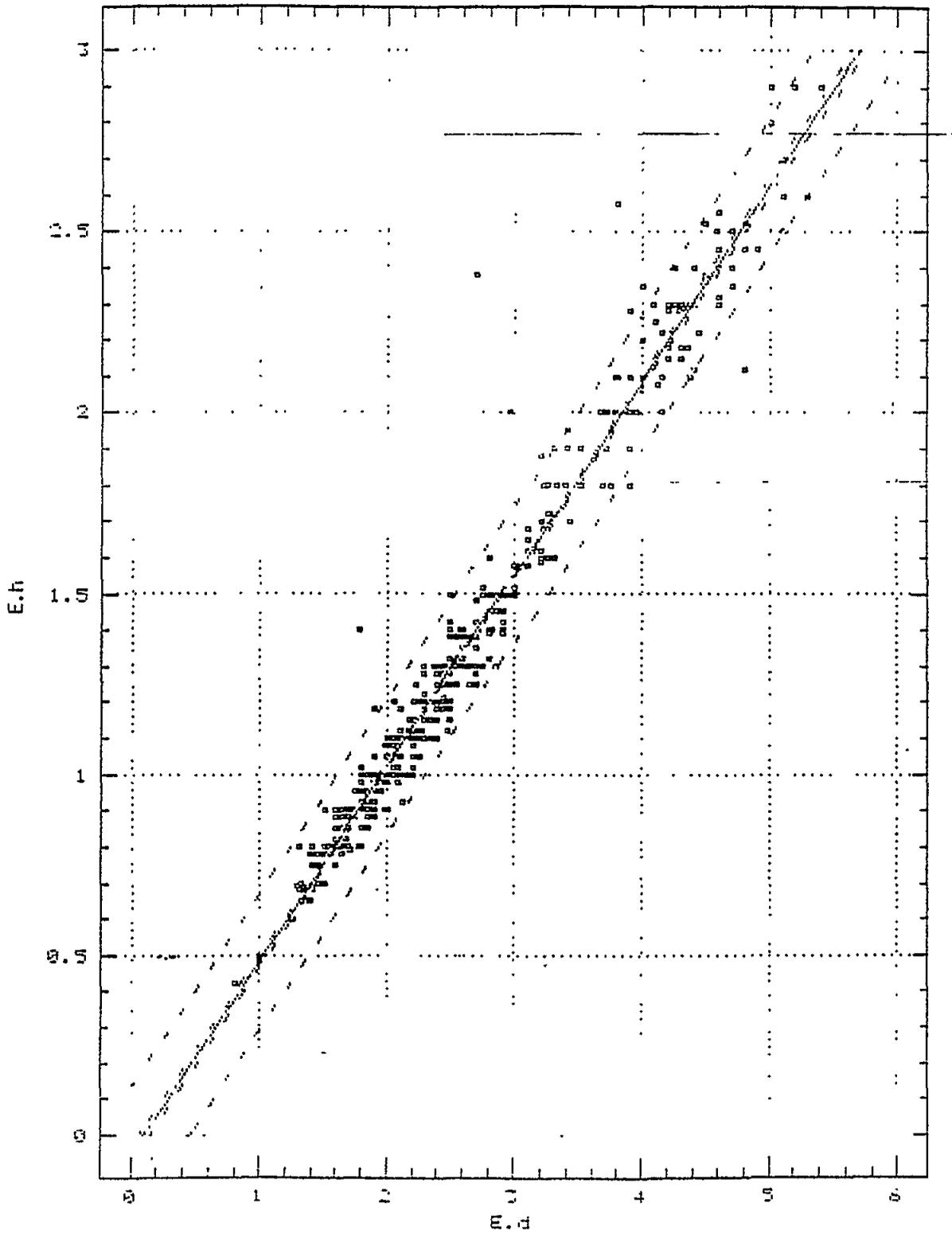


Fig. 8 Regression analysis between test height and diameter applied to the total of sampled specimens (Spring sampling)

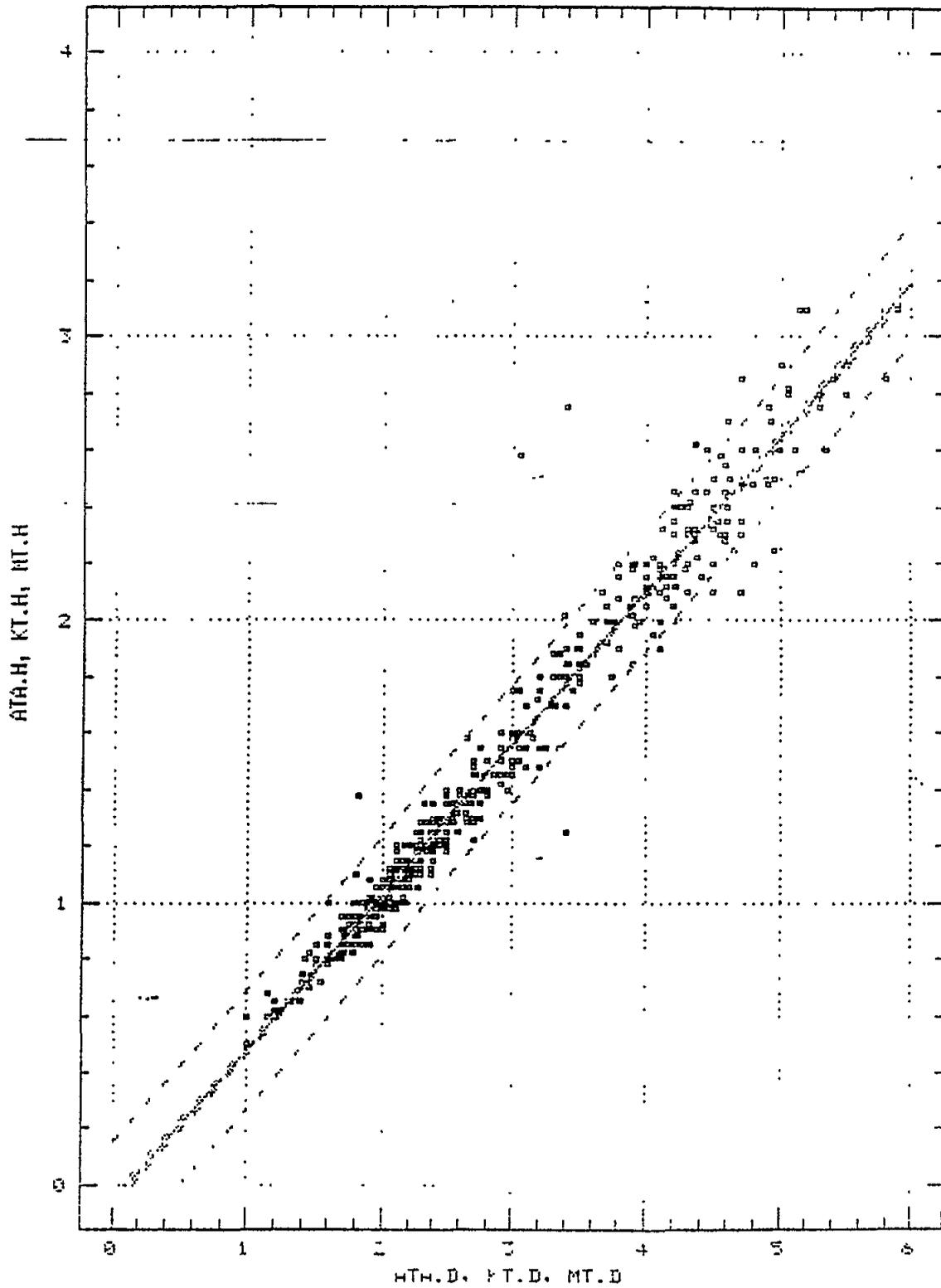


Fig. 9 Regression analysis between test height and diameter applied to the total of sampled specimens (Summer sampling)

Table 3

Distribution of specimens according to sex (Spring).

	Juvenile %	Male %	Female %
St. 1			
Class (cm)			
0.51 - 1.00	100.0	-	-
1.01 - 1.50	100.0	-	-
1.51 - 2.00	74.0	11.1	14.9
2.01 - 2.50	11.6	30.0	58.3
2.51 - 3.00	2.6	18.4	78.9
3.01 - 3.50	-	11.1	88.9
3.51 - 4.00	-	100.0	-
St. 2			
Class (cm)			
0.51 - 1.00	100.0	-	-
1.01 - 1.50	100.0	-	-
1.51 - 2.00	66.6	12.5	20.8
2.01 - 2.50	22.8	22.8	54.2
2.51 - 3.00	-	43.5	56.5
3.01 - 3.50	-	66.6	33.3
St. 3			
Class (cm)			
2.51 - 3.00	50.0	33.3	16.7
3.01 - 3.50	31.2	18.8	50.0
3.51 - 4.00	-	33.3	66.7
4.01 - 4.50	-	39.5	60.5
4.51 - 5.00	-	33.3	66.7
St. 4			
Class (cm)			
2.51 - 3.00	100.0	-	-
3.01 - 3.50	-	-	-
3.51 - 4.00	25.0	-	75.0
4.01 - 4.50	-	-	100.0
4.51 - 5.00	-	33.3	66.7

4.4 Feeding habits

Based on the preliminary results of gut contents obtained from several specimens at each station, Amvrakikos Gulf specimens can be clearly distinguished from those of the Ionian sea. Gut contents of sea urchins collected at Stations 1, 2 and 3 consisted of white homogeneous pellets, small mussels and gastropods. The gut contents of sea urchins collected at Station 4 in the Ionian Sea consisted of heterogeneous brown pellets without animal residues. The analysis of gut contents under microscope gave the following results.

Table 4

Specimen distribution according to sex (Summer).

	Juvenile %	Male %	Female %
St. 1			
Class (cm)			
0.51 - 1.00	100.00	-	-
1.01 - 1.50	86.40	-	13.60
1.51 - 2.00	44.90	17.60	37.50
2.01 - 2.50	6.00	32.60	61.40
2.51 - 3.00	1.50	35.40	63.10
3.01 - 3.50	-	40.00	60.00
3.51 - 4.00	-	-	-
4.01 - 5.00	-	-	100.00
St. 3			
Class (cm)			
1.51 - 2.00	-	-	100.00
2.01 - 2.50	-	-	100.00
2.51 - 3.00	-	-	100.00
3.01 - 3.50	-	29.60	70.40
3.51 - 4.00	-	8.80	91.20
4.01 - 4.50	-	18.20	81.80
4.51 - 5.00	-	10.50	89.50
5.01 - 5.50	-	-	100.00
St. 4			
Class (cm)			
3.01 - 3.50	100.00	-	-
3.51 - 4.00	66.60	-	33.30
4.01 - 4.50	11.10	44.40	44.40
4.51 - 5.00	-	16.70	83.30
5.01 - 5.50	-	10.00	90.00
5.51 - 6.00	-	-	100.00

Gut contents of samples collected at station 1: principally inorganic calcareous material, together with unicellular algae and diatoms. No pluricellular erect algae were observed, while the encrusting algae (Erythrocladia sp. and Myrionema sp.) were rare.

Gut contents of samples collected at station 2: generally the same as for station 1, however in the centre of each white pellet a piece of Cladophora sp. was observed. Chaetomorpha sp. was also observed.

Gut contents of samples collected at station 3: the same for station 2 for several specimens, while small mussels were plentiful in the majority of specimens.

Gut contents of samples collected at station 4: no presence of white inorganic pellets. The predominant element was Stypocaulon scoparion (Phaeophyceae), while Posidonia oceanica leaves, Jania elongata (Rhodophyceae), epiphytic algae (Ectocarpales) and encrusting algae were also observed.

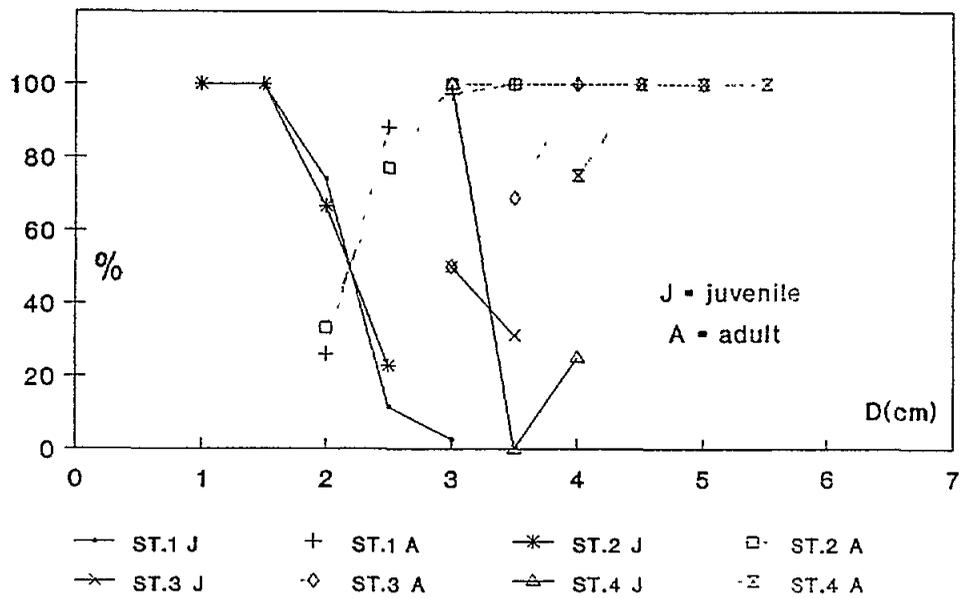


Fig. 10 Distribution of juvenile and adult specimens into size classes (Spring sampling)

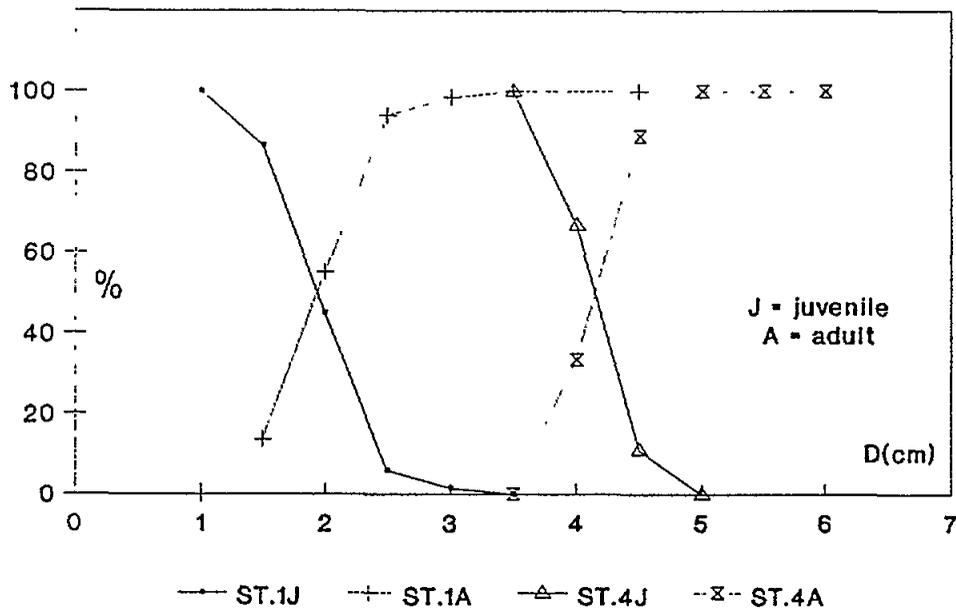


Fig. 11 Distribution of juvenile and adult specimens into size classes (Summer sampling)

It seems that *Paracentrotus lividus* at Stations 1 and 2 although in the adult stage, have not effected the transition from a microphagous, plankton-feeding habit to a macrophagous habit, feeding mainly on multicellular algae (Verlaque, 1984). This phenomenon is considered to be directly related to overpopulation due to the fact that intensive grazing during the last years has almost completely destroyed the macrophytobenthos

of the Amvrakikos Gulf. Station 3 may require a more accurate and long-term study, particularly since the massive presence of mussels in a habitat rich in phytobenthos cannot be explained at present.

5. CONCLUSIONS

The results of this study show that P. lividus in the Amvrakikos Gulf appear to be adapted to eutrophication, derived mainly from agricultural effluents. It is possible that the high levels of organic matter initially led to a rapid development of P. lividus, with high reproductive rates, and a consequent overpopulation and disappearance of other species less tolerant or more selective in their trophic habits.

This phenomenon has a feedback effect on the body size, which is related to trophic requirements: in such a eutrophic environment, P. lividus seem to adapt trophic habits, by retaining the microphagous trophic mode. As a result, while survival is possible, a lot of energy is expended in feeding, with a negative effect on body growth.

The hypothesis of precocious mortality (Delmas and Regis, 1984) does not seem to be valid in this study as no dead specimens were found.

Moreover, the lengthening of spines may be considered as a morphofunctional adaptation to a more active and efficient uptake of the plentiful organic material, dissolved or suspended, existing in the water column. It is considered that through this adaptive strategy, the sea urchins not only manage to survive in a highly eutrophicated environment, but also flourish therein.

At present, it is not possible to interpret the complex situation observed at station 3. This site differs significantly from the remaining stations of the Amvrakikos Gulf; human activity has created a new uncolonised substrate, where overpopulation conditions have not yet been established. It is considered that in a few years the P. lividus population at station 3 may show the same characteristics as those of the overpopulated stations. Further monitoring of the area is therefore necessary.

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PHYTOPLANKTON BLOOM CONSEQUENCES ON BENTHIC ORGANISMS

by

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ABSTRACT

In the shallow North Adriatic, the 1989 autumn offshore phytoplankton bloom was followed by a lack of oxygen in the bottom layers and a wide scale mortality of sediment living meio- and macrofauna. The course of event and the recovery of populations were monitored at three offshore stations. SCUBA diving as well as grab and core sampling methods were applied.

At both the macro- and meiofaunal levels, the infaunal response to oxygen depletion and the recovery strategies of species, populations and assemblages were similar and comparable. In meiofauna an initial mortality of 80-95% was established: nematode populations were less affected than copepods and other taxa. The recovery "latent" period lasted about six months and afterwards a sharp increase in abundance occurred. From the macrofauna, some sponges, polychaetes, echinoderms and tunicates were almost totally exterminated but most of the actinians survived. The recovery of macrofaunal populations occurred stepwise but the process was faster in infauna than in sessile epifaunal assemblages. Some bivalve and nematode species took advantage of the "free space" phenomenon observed at all stations surveyed. After two years of recovery the monitoring showed that at the macro- and meiofaunal levels, the communities studied were not yet stabilized.

1. INTRODUCTION

In the Adriatic Sea, appearances of floating mucous aggregations and their deposition on the sea bottom were first noticed some centuries ago, usually hampering fishermen's activities. The biogenic origin of mucous aggregations was first studied by Hauck (1872) who in the material sampled in the Gulf of Trieste and in the Quarner area had established the dominance of a pelagic diatom Nitzschia closterium. Subsequent studies proved that mucous aggregates could be produced both by pelagic and/or benthic species of several microphytes (Pucher-Petkoviæ and Marasoviæ 1984; Fanuko *et al.*, 1989). In the area, the phenomenon coincided with spatial and temporal blooms of some diatom and peridinean species (Hauck, 1872; Piccinetti and Manfrin, 1969; Fanuko, 1989).

In the past, surface floating mucous aggregates were mostly noted in the shallow north Adriatic (Fonda Umani *et al.*, 1989; Najdek *et al.*, 1989) and more rarely in the deeper east Adriatic insular region (Pucher-Petkoviæ and Marasoviæ 1984). The mechanisms of phytoplankton blooms and the ensuing mucous aggregate appearances (Herndl and Peduzzi, 1988) were investigated in the natural geomorphologic, sedimentologic and hydrographic features of the area (Stachowitsch and Avèin, 1988; Degobbis *et al.*, 1991). The anthropogenic pollution sources were also considered (Pèrès and Bellan, 1970; Zarkanellas, 1979). The synergistic effects of all these phenomena were reflected in a gradual intensification of

eutrophication characteristics in the ecosystems concerned (Degobbis *et al.*, 1979; Stachowitsch and Avèin, 1988; Degobbis, 1989; Gilmartin *et al.*, 1990; Jorissen *et al.*, 1992) which led to a final phenomenon - a lack in oxygen which usually proved to be fatal to marine organisms and benthic communities (Stefanon and Boldrin, 1982; Montanari *et al.*, 1984; Faganeli *et al.*, 1985; Orel *et al.*, 1986; Justiaet *et al.*, 1987; Degobbis *et al.*, 1990; Jaklin and Zahtila, 1990; Travizi, 1990; Hrs-Brenko, 1992).

The oxygen depletion in bottom layers has usually followed the appearances of sea snow, and the deposition of mucous material on the bottom (Herndl, 1988). The physical effects of the mucus deposited on the macroflora and macrofauna were also considered (Zavodnik, 1977; Stachowitsch, 1984; Zavodnik *et al.*, 1989). The effects of the above phenomena on the benthic meiofauna, especially sediment dwellers have only recently attracted attention (Gray *et al.*, 1988; Aleffi *et al.*, 1992; Vrišer and Malaèiè, 1992).

At the beginning of November 1989, fishermen noted an unusual displacement of benthic fish stocks along the coast and offshore west Istria, while sediment living organisms unfamiliar to them appeared in bottom trawl catches. About one week later SCUBA divers detected the first moribund and/or dead shellfish and heart-urchins laying on the bottom. The phenomenon was concrete evidence of abnormal conditions in the ecosystem, calling for immediate action. Therefore, the aim of this project was to identify the reasons for the noted phenomena, to localize and estimate the area influenced, and to assess the responses of macro- and meiofauna to the disturbed environmental conditions. Subsequent studies on the generation and effects of flocculated sea snow and mucous string appearances seemed to be necessary. Finally, a long term monitoring of the recovery of benthic populations and communities at macrofaunal and meiofaunal levels was requested.

2. MATERIALS AND METHODS

2.1 Area investigated

In situ observations of flocculated sea snow and strings in the water column, and the mucous material deposited on the bottom were performed by SCUBA divers at all stations in the northern Adriatic (Fig. 1). Detailed benthic surveys were also undertaken at many stations located in the west Istrian coastal area. Subsequent SCUBA observations, sampling and measurements were performed at three permanent stations (005, 007, 107) located in the area most affected by anoxic conditions (Table 1). Occasionally, the state of benthic communities and occurrences of mucous aggregates were inspected at numerous additional offshore and coastal stations scattered all over the northern Adriatic.

For offshore surveys the RV "Vila Velebita", and for coastal work the MB "Burin" of the Center for Marine Research Rovinj were used.

2.2 Study period

Basic hydrographic conditions were monitored by the Center for Marine Research (CMR) Rovinj at the permanent station 107 from the beginning of 1989. Intensive field research began after the establishment of benthos mortality, i.e. in the autumn of the same year. Monitoring surveys of sediment living

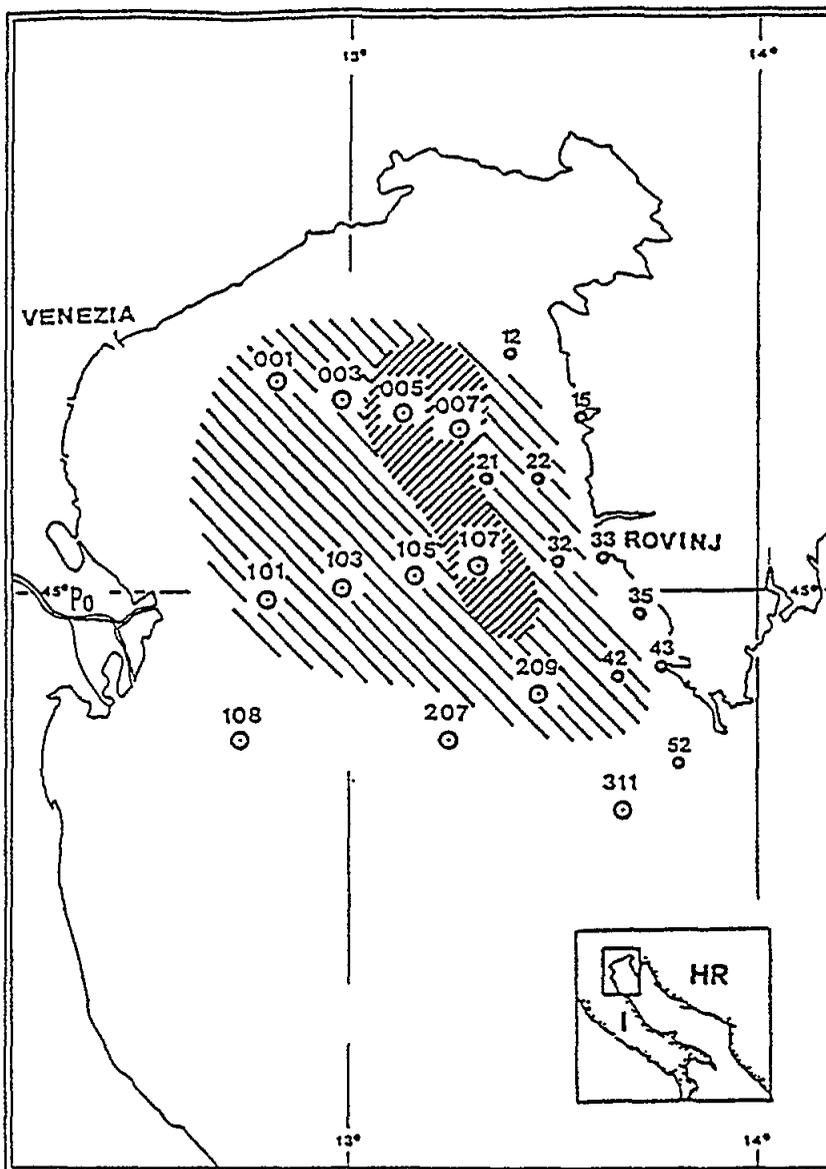


Fig. 1 Research stations. Mucous aggregations distribution and area affected by the 1989 bottom anoxia are indicated (from: Jaklin and Zahtila, 1990)

meiofauna were initiated at the same time as the first survey in November 1989, while the quantitative monitoring of macrofauna began in December after the permanent offshore study stations had been defined.

Monitoring surveys in 1990 were initially performed at about monthly intervals but after an apparent community stabilization the study stations were surveyed only once or twice per season. Thus, sediment sampling and simultaneous in situ SCUBA observations of mucous aggregates and macrofauna

were performed in December 1989, each month in 1990 (except in May), and in January, February, April, June, September or October (station 107), and December 1991. Field work was finished by 17 December 1991. Consequently, during the field research period, i.e. from 1989 to 1991, each permanent monitoring station was surveyed 18 times for macrofauna and 19 times for sediment living meiofauna.

Table 1

Position, depth, bottom and community characteristics at investigated stations.

Station	Geographical coordinates	Depth (m)	Sediment	Community
005	45E18.4' N 13E08.0' E	30	Sandy silt	Community of coastal detritic bottom mixed with ooze characterized by <u>Schizaster canaliferus</u> , and accompanied by <u>Pinna pectinata</u> , <u>Corbula gibba</u> , <u>Chione ovata</u> , <u>Nephtys hystricis</u> , <u>Eunice vittata</u> and <u>Owenia fusiformis</u>
007	45E17.0' N 13E16.0' E	30	Silty sand	Transitional community of detritic bottom enriched by silty elements, rich in <u>Schizaster canaliferus</u> , <u>Corbula gibba</u> and <u>Atrina pectinata</u> , accompanied by <u>Leiostraca subulata</u> , <u>Sphaerocardium paucicostatum</u> , <u>Maldane glebifex</u> and <u>Owenia fusiformis</u>
107	45E02.8' N 13E19.0' E	36	Silty sand	Community of coastal detritic bottom characterized by tubicole polychaetes, <u>Pitaria rude</u> accompanied by <u>Corbula gibba</u> , <u>Myrtea spinifera</u> , <u>Leanira yhleni</u> , <u>Amphiura filiformis</u> and <u>Schizaster canaliferus</u>

2.3 Working techniques

Parameters were studied using standard sampling, processing and preparation methods adopted for the coordinated Italian-Yugoslav (Croatian) monitoring of the northern Adriatic Sea (Zavodnik, 1982).

Sea water samples for physical and chemical analyses were taken using Niskin bottle samplers at standard hydrographic depths and two meters above the bottom, respectively. For quantitative sampling of sediment inhabiting fauna a van Veen grab 0.1 m² was used; four grab

subsamples totalling 0.4 m² per survey were taken at each station. Subsamples for sediment living meiofauna (three per survey) were taken by SCUBA divers using 3.5 cm inner diameter hand corers (Vidakoviæ 1984). During in situ observations, for documentation purposes, SCUBA divers used an underwater Nikonos V photcamera, and the SB 102 flash unit.

Laboratory processing and analyses as well as interpretation of results were carried out at the Center for Marine Research, Rovinj. Several specimens were included in the CMR study collections. All results were computer stored.

The water temperature was measured using Richter and Wiese reversing thermometers mounted on Niskin water bottles while salinity was determined with a high precision Kahlsico laboratory salinometer. Dissolved oxygen values were obtained using the modified Winkler's titration method.

Macrofauna processing. The grab sediment aliquots were sieved through a 2 mm sieve, and the remainder was preserved in neutralized 4% formol or 60% alcohol. Subsequent processing, identification and counting of macrofauna took place in the laboratory. Macrofauna weighing included wet, dry and ash weights, from which the organic matter content was calculated.

Meiofauna processing included sediment fixation in neutralized 4% formol and staining with Rose Bengal, and elutriation and sieving through 100 µm and 50 µm sieves. The examination and counting of meiofauna components were carried out under a Wild dissecting microscope. The identification of slided nematodes mounted in glycerol was carried out under Zeiss and Opton microscopes.

SCUBA observations consisted of in situ counting and measurement of macrofauna and macroflora, notes on behavior and condition, and pencil sketching and underwater photography of mucous aggregates and benthic organisms and populations, respectively.

2.4 Presentation of results

Only some selected and synthesized results of parameters most characteristic and important for the interpretation of the events studied are presented in tables and graphs due to the very large amount of data collected.

3. RESULTS

3.1 Hydrographic parameters

In the survey period, surface and bottom temperature variations were largely within the long-term average values, although the maximum sea surface temperature in July 1989 reached 26.25EC. At a depth of 35 meters, i.e. near the bottom, temperature fluctuated from about 8.50EC in February to nearly 20EC in mid-October 1991. It is noteworthy that in the same year, a bottom temperature of 11-12EC persisted for an unusually long period of four months, i.e. from April to the end of July.

From the beginning of 1989 to the end of 1991 bottom salinity was continuously rather high, i.e. about 38‰. Only slight variations, not exceeding the span of $1 \cdot 10^{-3}$, were measured occasionally in the summer-autumn season.

In contrast, oxygen saturation fluctuations were highly characteristic. By the end of April and throughout May 1989, oxygen saturation in the layer about two meters above the bottom tended to diminish gradually until October-November, when an abrupt drop in oxygen concentration led to an almost complete anoxia near the bottom (Fig. 2). A strong vertical mixing of the water column, caused by storm conditions a few days later, contributed to an immediate rise of the oxygen content to a seasonally "normal" level of about 0.9. Fairly normal conditions were restored in the subsequent months until the end of 1990. From January until May 1991 the oxygen saturation was about 1.00 but subsequently dropped to only about half of this value, and fell below the biological level of anoxia in mid-September (0.25) and by the end of October (0.30). Normal oxygen conditions were restored within a few days of strong vertical mixing of the water column.

3.2 Mucous aggregation appearances

In 1989 during most of the surveys at the northern Adriatic coastal and offshore stations, SCUBA divers noted the appearances of "harmless" sea snow floccules distributed mostly uniformly in the water column, except when their distribution was discontinued at the thermocline layers, and near the bottom. By the end of spring and in the summer, large floating mucous aggregates appeared (Jaklin, in: Kaltenböck and Herndl, 1992). Many, apparently newly formed, had a delicate and whitish coloured cobweb appearance. Older aggregates were more compact and resembled several meters long strings and "clouds" of a green-yellow to a brownish colour. Surface aggregations were distributed discontinuously, mostly in the central and western parts of the north Adriatic, although by the end of summer and at the beginning of autumn, due to changes in water mass distribution (Degobbis *et al.*, 1989), the water column aggregations displaced eastward settled to the bottom forming wide strings, or discontinuous carpets 5 to 10 cm thick. At all stations which were heavily attacked by old mucous aggregates, about 80-90% of the bottom surface was dark gray, brown or blackish coloured. At some sites, large cylindrically shaped aggregations more than 10 meters long and reaching nearly half a meter in diameter were noted. Large clumps of sessile animals, fan shells and sea grass and also rocky outcrops and gently rising coastal slopes were covered by a brownish carpet of mucous or cob-web structure. One month later, sea snow was still present throughout the water column although more rarely, but only a few floating string-like structures were noted. From large portions of the sea bottom the mucous carpet has disappeared, or only a very thin dark brown layer remained.

In 1991, the sea snow appeared in the north Adriatic offshore areas in early spring. In coastal waters, the flocculated sea snow appeared slightly later but was not transformed to strings before summer. Bottom mucous aggregations ("carpets") in the monitored area were occasionally noted by SCUBA divers on the sedimentary bottom but in notably lower quantities than in 1989/1990. In general, coastal rocky slopes were void of mucous deposits.

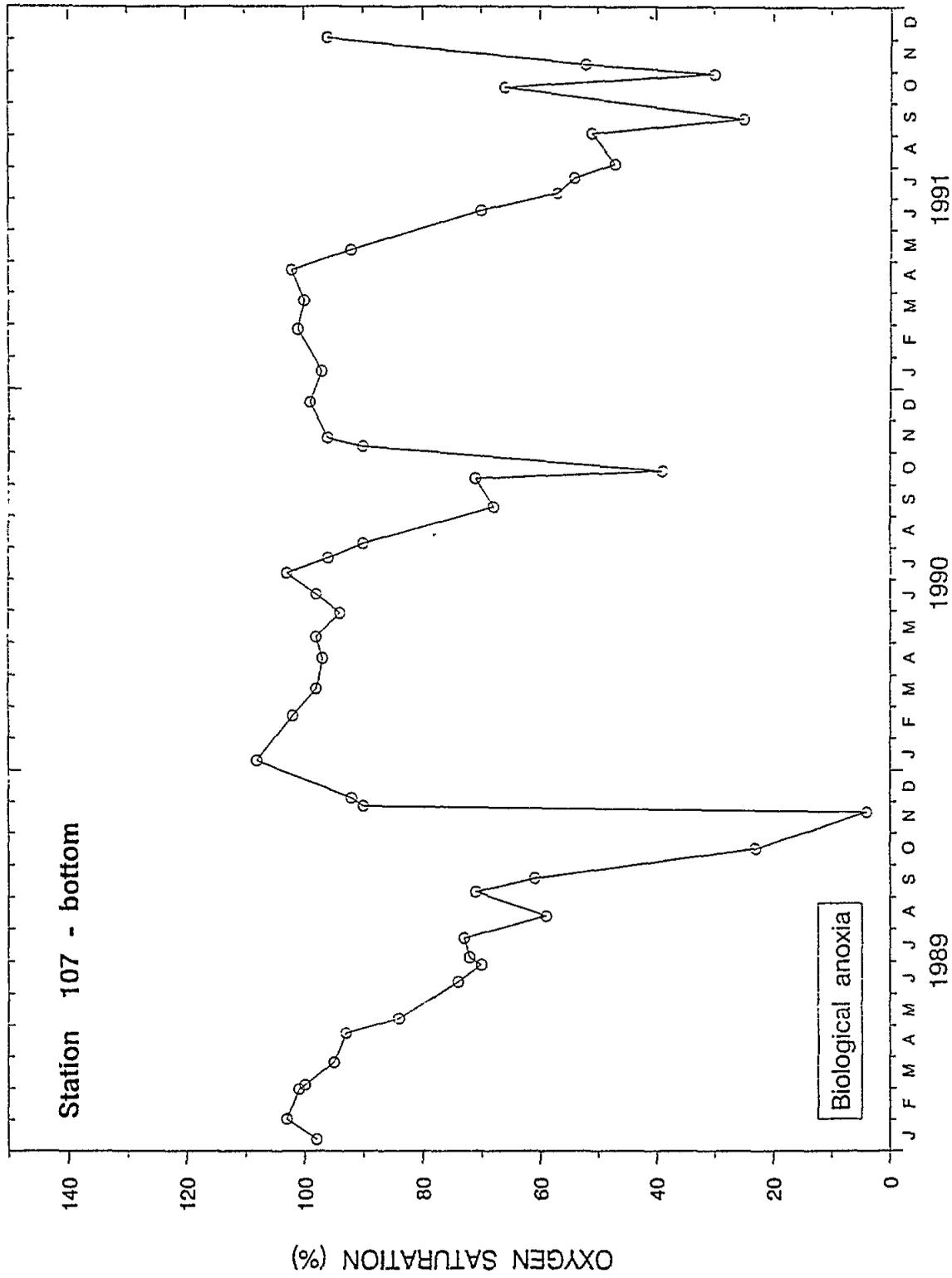


Fig. 2 Oxygen saturation fluctuations in the bottom layer of station 107 in 1989-1991

3.3 Organisms response to oxygen depletion

In late autumn 1989, the first indications of an ecosystem disturbance were unusual displacements of benthic fish and mass occurrences of sediment living organisms in trawl and dredge catches. During the period of bottom anoxia, and shortly after the restoration of normal oxygen saturation conditions, SCUBA divers reported great quantities of dead organisms and decaying remains laying on the bottom, many apparently covered by a whitish mould. The emergence of macroinfauna, and the death of most organisms coincided with the onset of biological anoxic conditions, confirmed in the area by hydrographic research. The immediate visible reaction of the macrofauna was a local displacement in an effort to reach the upper, i.e. better oxygenated layers within the sediment and/or in the water column. For this reason, some brittle-stars were observed lifting their disks above the sea bed surface, infauna emerged from the sediment and sedentary organisms clustered in large multispecies clumps, on projected outcrops, on large shellfish shells, etc.

Another visible response of the macrofauna was a specific behaviour of particular individuals: sea anemones and ceriantharians were observed having outstretched cylinder-like bodies and widely opened tentacular crowns; many moribund shellfish were observed with an extended foot and their valves open; aspidochirotan sea-cucumbers eviscerated; astropectinid sea-stars had a highly swollen aboral surface; moribund heart-urchins and sea-urchins dropped, and began to lose erect spines.

The final effect of intolerable oxygen depletion was the organisms' death. However, large differences in species tolerance were noted by SCUBA divers, and established while processing sediment grab samples. Among the macrofauna, the most susceptible to environmental disturbance appeared to be the heart-urchin Schizaster canaliferus; the population was completely exterminated soon after the establishment of anoxic conditions. A large-scale mortality also occurred in Psammechinus microtuberculatus, Ophiothrix fragilis (= O. quinquemaculata) and Labidoplax digitata.

The polychaete worms Aphrodite aculeata, Pectinaria belgica and many molluscs were also found to be very sensitive to oxygen depletion. The population of Chlamys sp. decreased by more than 50%, and the fan shell Atrina fragilis nearly completely disappeared - more than 90% of specimens were found dead. It seemed that most gastropod molluscs had survived. A low mortality rate was also observed in more agile animals, such as crabs and fish, of which only a few dead specimens (Liocarcinus depurator, Gobius sp.) were noted at the stations surveyed. SCUBA divers noted that some cnidarians had completely survived.

The sediment living meiofauna were also decimated. Unfortunately, a comparison with the previous ("original") state was possible only at station 107. It became evident that in the course of the 1989 autumn anoxic conditions, possibly 85-90% of the individuals had perished; nematodes survived better than copepods.

According to extensive SCUBA diving surveys just after the 1989 bottom anoxia had been established in the north Adriatic, a mass mortality of benthic macrofauna occurred in the

offshore area of about 1.200 km² (Fig. 1). In the neighboring areas of about 3.500 km², the bottom fauna were less affected and only isolated dead and/or moribund specimens were noted (Jaklin and Zahtila, 1990).

3.4 Population recovery

Grab monitoring and SCUBA observations, at about monthly intervals, indicated that the population recovery process in some macrofauna species was established soon after the cessation of anoxic conditions. The most indicative case was probably Corbula gibba, a minute shellfish: to adult survivors (specimens 10-12 mm long) were, in the subsequent months, added many juveniles 2-4 mm long, thus exhibiting a fair and constant growth curve (Hrs-Brenko et al., 1992). By spring 1990, Corbula was a dominant species at all stations monitored but later its numerical and relative abundances decreased (Fig. 3). A similar trend of population structure was also noted in Musculus marmoratus which by autumn 1990 was decisively depressed. In some other bivalves, such as Chione ovata, Acanthocardia echinata and Hiatella arctica, the "normal" population density was reached in about one year. The first juveniles of Atrina fragilis, the largest shellfish species in the area, were collected in February and March 1990. Their shells were only 9-15 mm long but later on a fair growth of the settled population was noted: one year old specimens attained about 120 mm length, while in autumn and winter 1991, specimens of about 200 mm length were collected.

Similar phenomena probably also occurred at the meiofaunal level. For example, according to analysis of the sediment living nematofauna at station 005 just after the 1989 anoxic event, Ptycholaimellus ponticus was the dominant species (40-48%) of the total nematode specimens (Fig. 4). In the following months, this species was suppressed by other species, but became a dominant species again in the winter of 1990/1991. Later in 1991, the structure of the nematofauna population appeared to alter with regard to the preceding year and stabilized with an Axonolaimus setosus, Dorylaimopsis mediterranea and Sabatieria spp. complex. In order to comprehend these changes, a structural population analysis of species encountered, with respect to juvenile male, female and ovigerous female composition was very useful.

3.5 Macrofaunal community recovery

Grab monitoring at stations 005, 007 and 107 indicated that the recovery of infaunal assemblages was established soon after the anoxic conditions had ceased. In a period of 2 to 4 months, species diversity had doubled for communities at certain stations, while an overall increase in diversity was observed within a year (Table 2). In the course of the second year of recovery, community diversity tended to stabilize at a level which approximated the prior to anoxia level, although minor (seasonal?) fluctuations in space and time were noted. In the early recovery period, at all three stations surveyed, a characteristic feature was the dominance of newly settled shellfish, in particular Corbula gibba (Fig. 3), which was also reflected in their weight contribution to the community standing crop structure (Figs 5, 6).

With time, the polychaete annelids steadily grew in importance with respect to diversity and abundance, although with regard to biomass the molluscs occupied the first rank until the end of 1991. In the second year after mass mortality, the echinoderms also increased in importance,

particularly at station 107. However, by December 1991, the abundance of the brittle-star *Amphiura filiformis*, characteristic of station 107, was still far below the abundance noted in the years prior to anoxia.

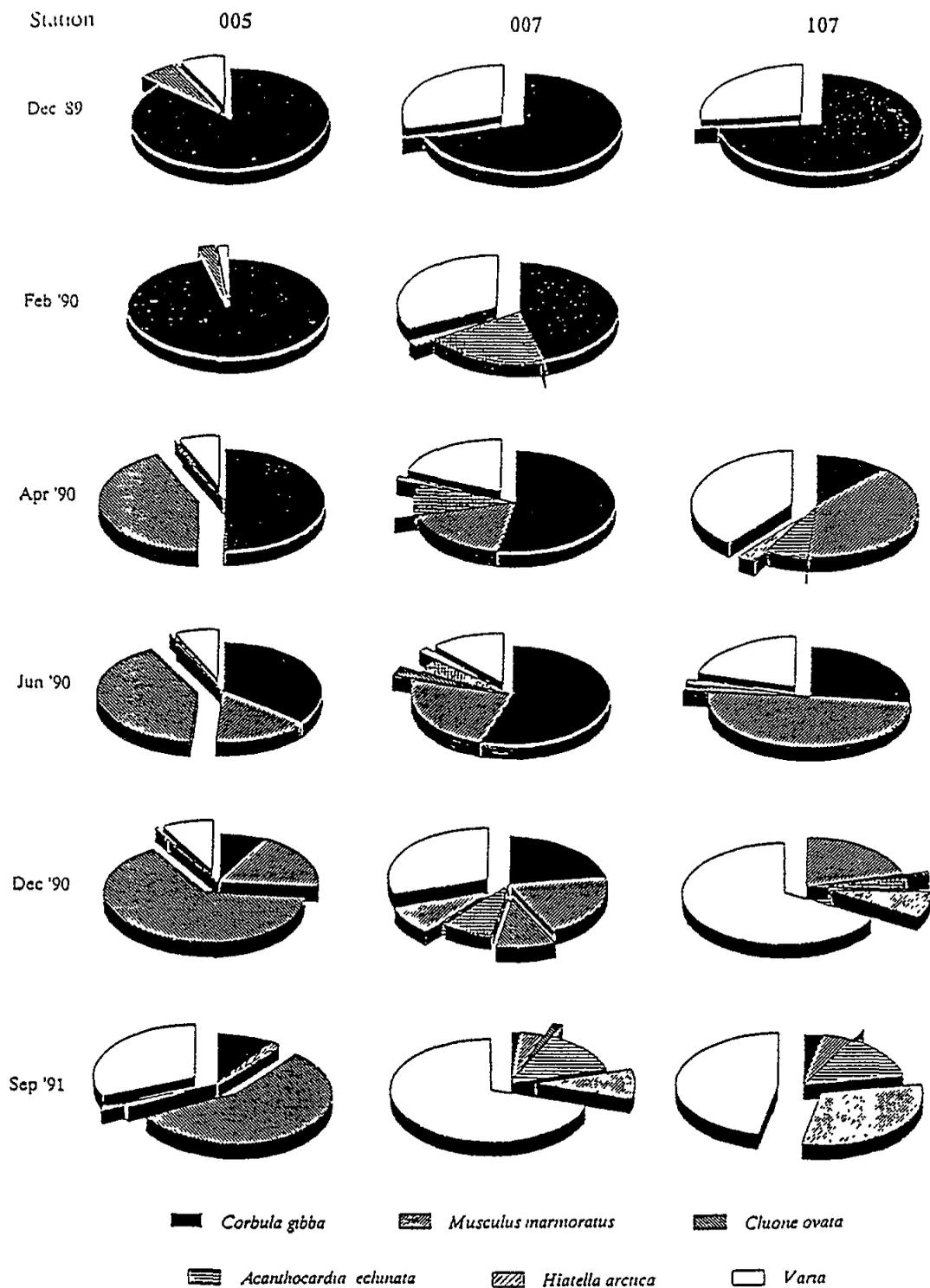


Fig. 3 Percentage abundances of bivalve molluscs in the recovery period 1989-1991

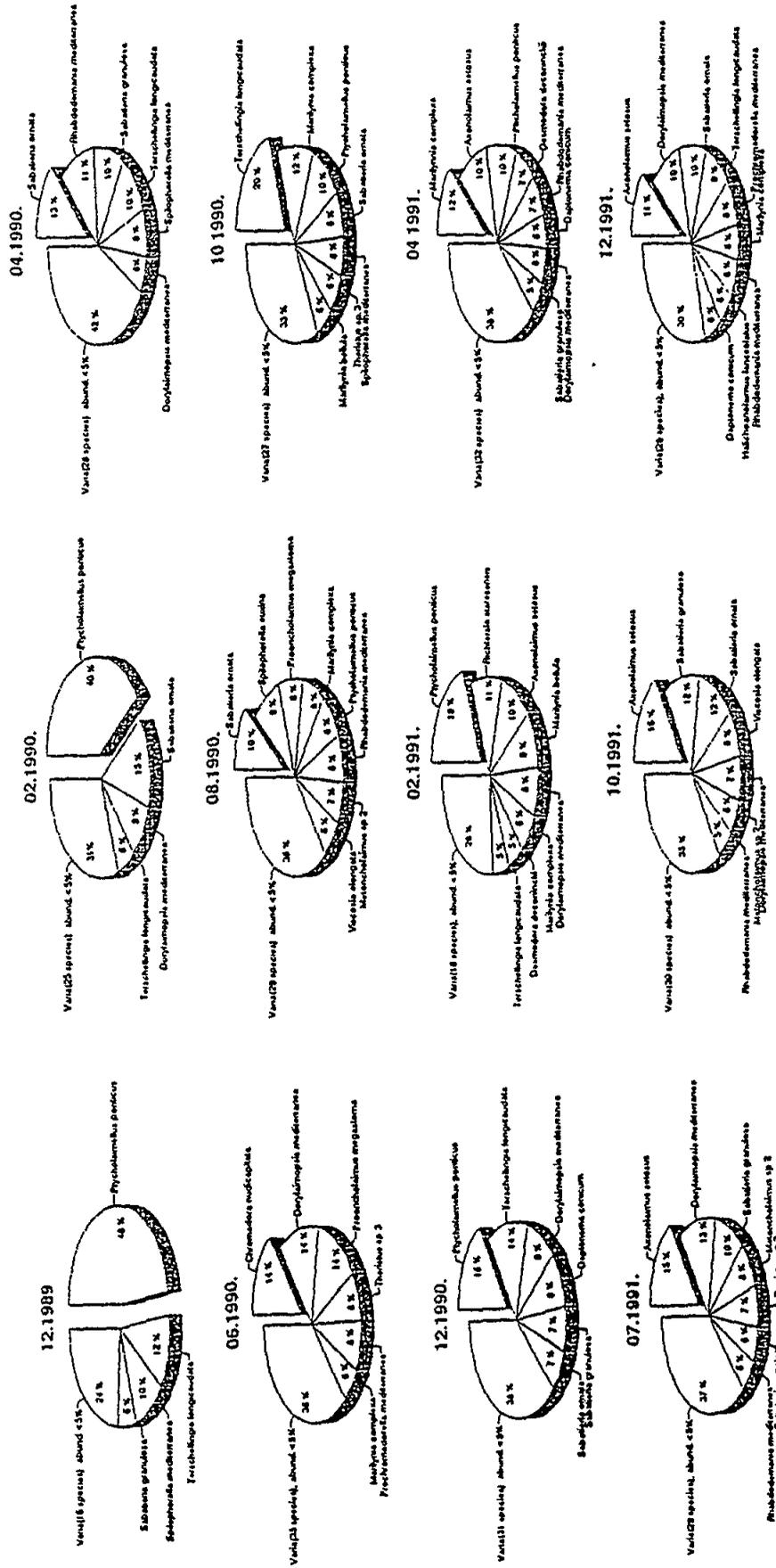


Fig. 4 Sediment living nematodes population variations at station 005 in the recovery period 1989-1991

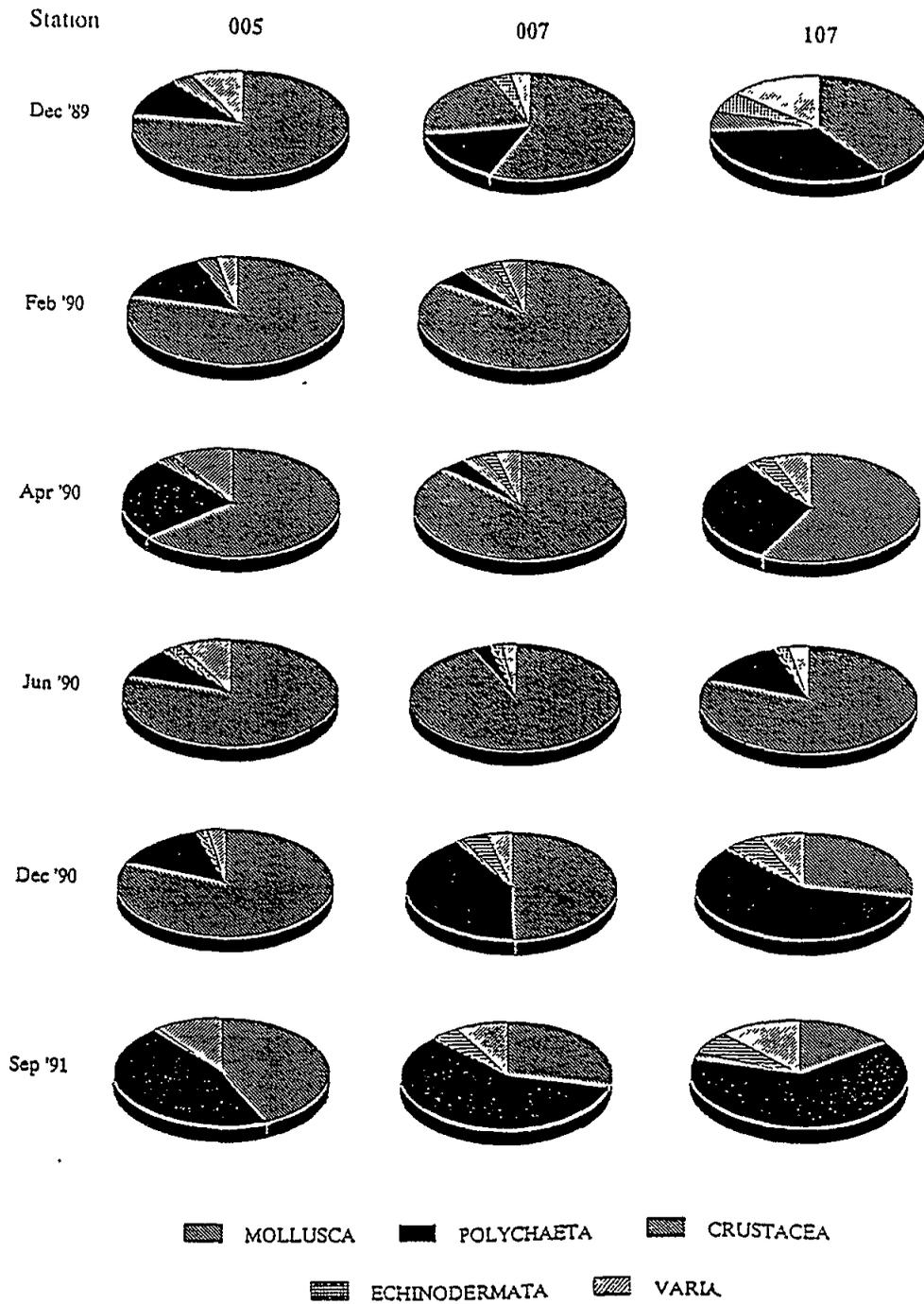


Fig. 5 Macrofauna percentage abundance variations in the recovery period 1989-1991

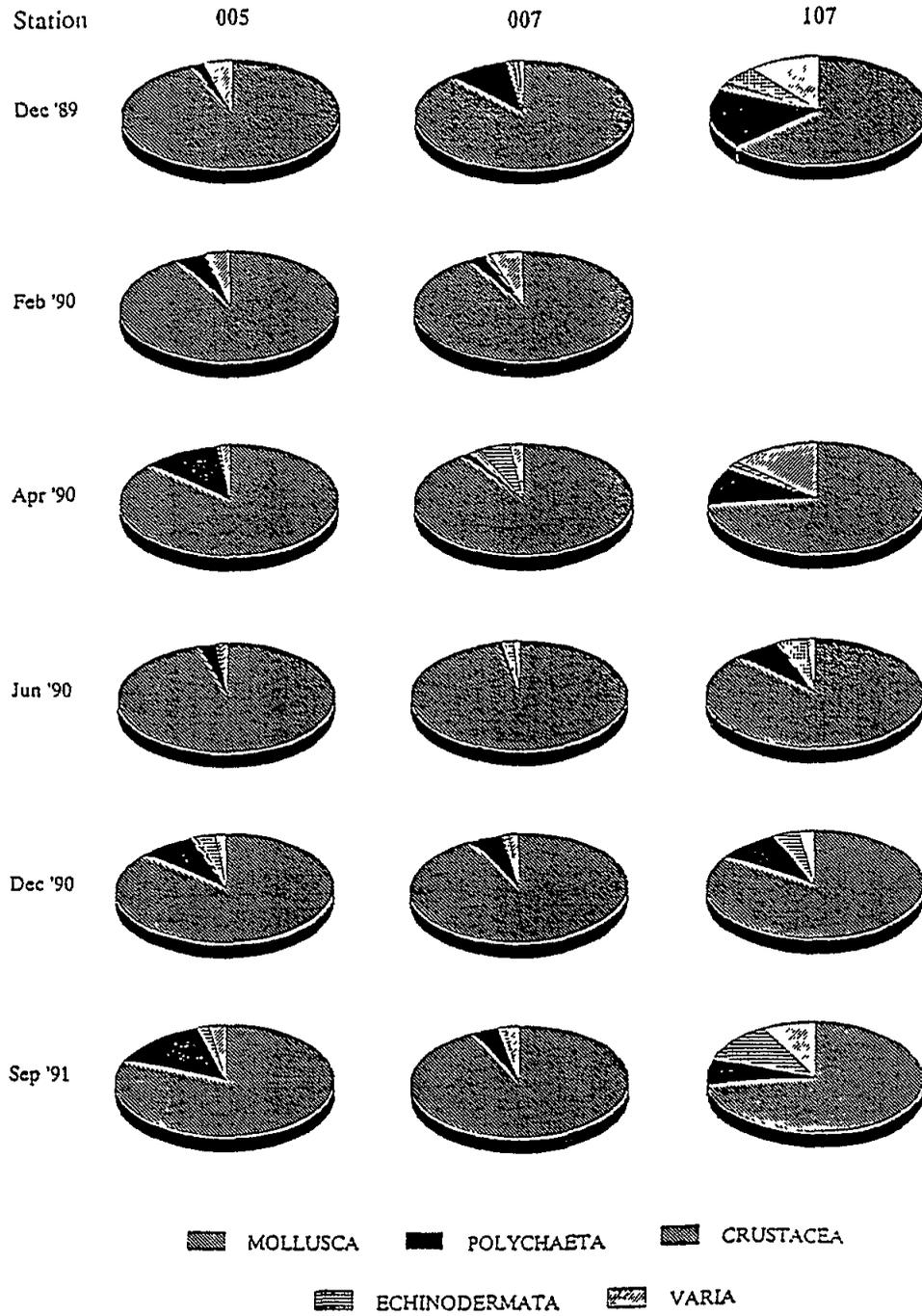


Fig. 6 Macrofauna percentage biomass (w.wt.) variations in the recovery period 1989-1991

At the stations monitored, the macrofaunal biomass variations can not be obviously correlated. For example, at station 005 the "initial" biomass (wet weight) of survivals measured just after the 1989 anoxic event was roughly 100 g 0.4 m⁻². While slightly fluctuating in the course of the community recovery period, by the end of the second year the biomass had increased to only about half of its initial value (Table 2). In contrast, at stations 007 and 107 a very low initial biomass (only about 6 g m⁻²) in the first year of recovery, subsequently increased 18 and 16 times respectively.

Table 2

Diversity, abundance and biomass progressive changes at stations monitored in the recovery period 1989-1991.
(Biomass in g 0.4 m⁻² w.wt.)

Date	Station 005			Station 007			Station 107		
Duration	Species No	Specimens No	Biomass	Species No	Specimens No	Biomass	Species No	Specimens No	Biomass
December 89 (0 months)	18	402	104.90	12	32	6.04	26	65	6.50
February 90 (2 months)	20	424	98.26	35	198	15.90			
March 90 (3 months)	34	334	53.38	50	418	20.33	38	264	42.58
April 90 (4 months)	28	448	83.68	37	359	35.38	44	239	9.79
June 90 (6 months)	47	675	112.11	41	785	93.60	62	934	50.67
December 90 (12 months)	54	1485	180.68	70	521	109.07	71	741	105.24
September 91 (21 months)	57	617	167.29	81	778	284.14			
October 91 (22 months)							72	555	152.84

Approaching the end of the second year, the biomass increase at station 007 was 47 times, and at station 107, 23 times greater than the initial value. These values were mostly due to the abundance of bivalve molluscs. For example, the species Acanthocardia echinata, Laevicardium oblongum and Musculus marmoratus accounted for 49.1 and 55.8% of the total community wet weight at stations 007 and 107 respectively.

The analysis of faunistic data according to ABC curves (Warwick et al., 1987) shows that in the two-year period after the anoxic stress, the communities surveyed had not yet reached a mature state, particularly those at station 107. K-dominance curves for species biomass were below the abundance curves, which is a certain indicator of a transitional stage and instability of the communities concerned (Fig. 7).

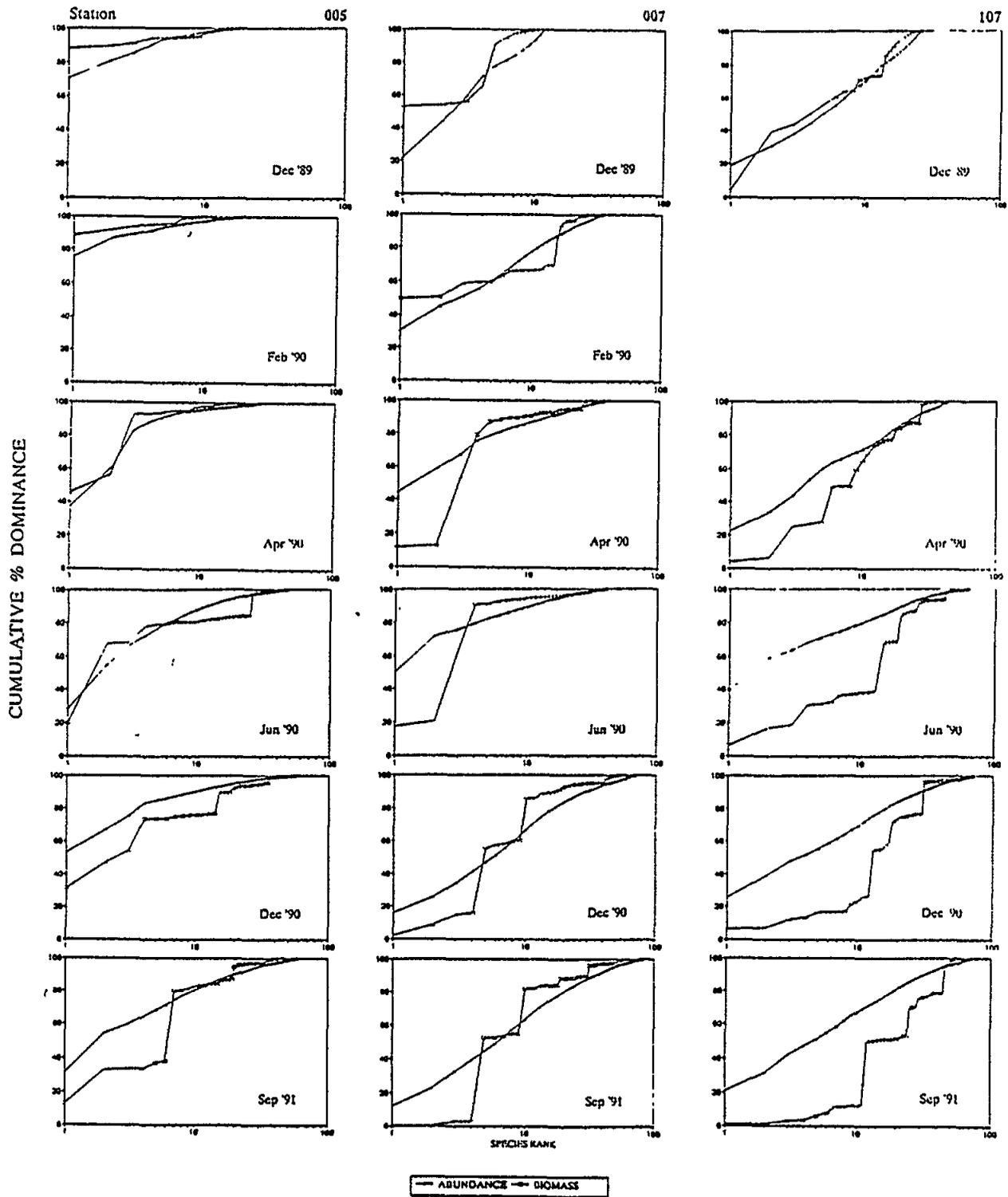


Fig. 7 State of macrobenthic communities at stations monitored in the period 1989-1991

3.6 Meiofaunal community recovery

In contrast to the macrofauna, the recovery of sediment living meiofauna had a shorter duration and occurred very swiftly. However, about six months after the anoxic stress, the meiofaunal community structure showed insignificant signs of improvement. Abundance values of the main groups remained fairly stable, and showed only a very slow increase until June 1990 (Fig. 8) when the total density increased to nearly two (stations 005 and 007) or six (station 107) times that of the preceding month. The Ne/Co ratio was still distinguished by a very high value. In July, signs of an intensive abundance increase were noted in all main groups, although the nematode percentage participation in the total meiofaunal abundance decreased. At station 005 the Ne/Co ratio declined from 226 to 38, while at the other two stations monitored this ratio remained relatively high until August (station 107) and September (station 007). Nevertheless, in August a phase of apparent stabilization was reached, i.e. a phase of normal density oscillations, shortly intensified in October, when hydrographical data suggested the appearance of hypoxia (Fig. 2). In December 1990 oxygen depletion was not recorded by field measurements but according to structural changes in the meiofaunal community it seemed that hypoxia had occurred again, although it was obviously less expressed, and perhaps shorter in duration than a year ago.

In 1991 rather irregular seasonal fluctuations occurred in sediment living meiofauna abundances, and a decreasing trend in autumn-winter was noted (Fig. 8). The absolute dominance of nematofauna was determined, however the "normal" distribution of total meiofauna within the sediment core, in comparison to the features of the previous two years was obviously not disturbed (Fig. 9, Table 3).

The process of nematofauna recovery showed an evolutionary strategy similar to that of the total meiofauna. After an initial period of recovery, the species number suddenly increased by more than 100%. Species dominance declined (Fig. 10), and all diversity indices, increased and stabilized, suggested the re-establishment of ecological balance.

4. DISCUSSION

In the coastal and offshore north Adriatic areas, floating and deposited slimy aggregations ("mare sporco") were first reported some centuries ago (Pucher-Petković and Marasović 1984; Fonda Umani *et al.*, 1989). Consequently, the basic reasons and trigger mechanisms of this phenomenon in no way should be attributed exclusively to anthropogenic pollution of the sea, as expressed by general public opinion. In fact, fishermen and tourists in particular are much more susceptible to visual effects of the phenomenon (i.e. appearances of mucous aggregates and mortalities of economically important organisms), than they are interested in the real fundamental and trigger reasons of the events. The shallow north Adriatic, however, is in no way a special case in the world oceans: its fate is shared also by Tokyo Bay, Chesapeake Bay and the New York Bight, Elefsis Bay, the German Bight, the Bornholm Basin and many other areas world wide (Stachowitsch and Avèin, 1988). Environmental features common to all the areas mentioned are: a shallow depth not exceeding 30-50 meters, a fine-grained sedimentary bottom, a specific hydrography manifested in current systems and seasonal stratification of the water column, sensitivity of the water body to meteorological conditions and

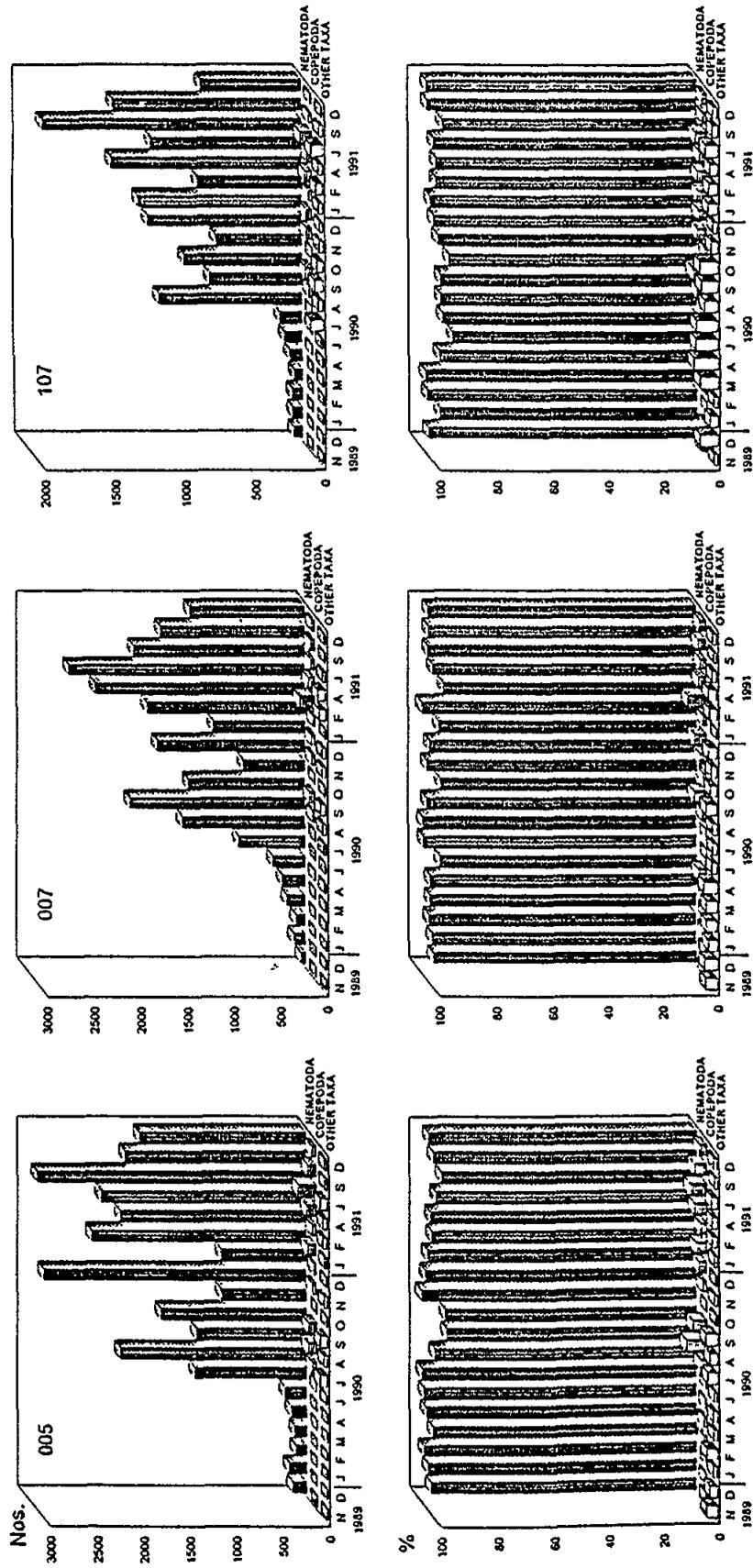


Fig. 8 Numerical (above) and percentage (below) abundance variations of sediment living meiofauna at stations monitored in the period 1989-1991

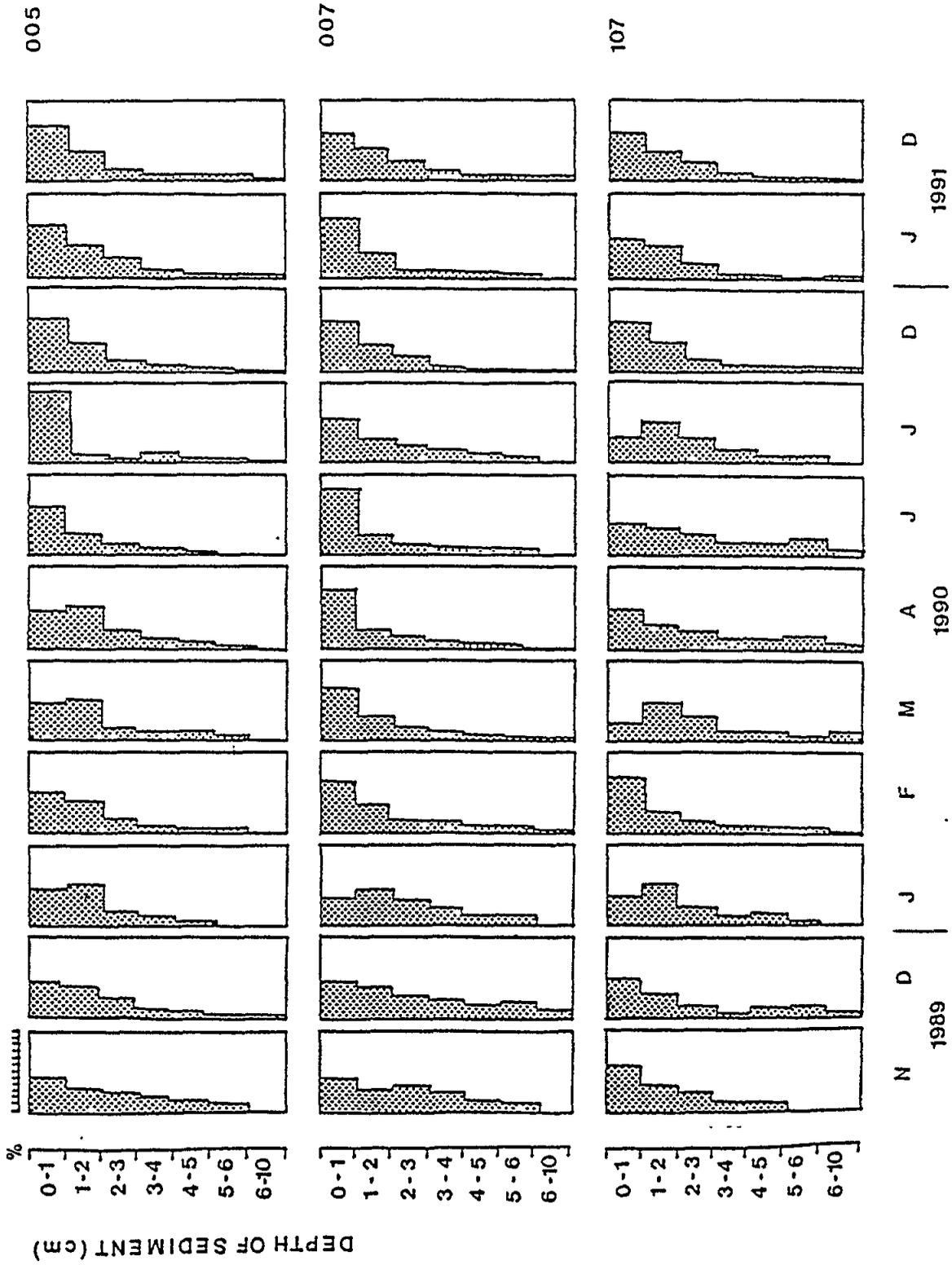


Fig. 9 Percentage abundance distribution of total meiofauna within the sediment core in the recovery period 1989-1991

Table 3

Input matrix data presented in Figure 9. An example is station 005.

DENSITY (Nos)

Dat./Sli.	0-1 cm	1-2 cm	2-3 cm	3-4 cm	4-5 cm	5-6 cm	6-10 cm	TOTAL
11.'89	62.00	39.00	34.00	18.00	8.00	2.00	0.00	163.00
12.'89	85.00	73.66	31.00	4.33	3.00	0.33	0.66	197.98
01.'90	52.00	57.33	9.00	2.33	1.00	0.33	0.33	122.32
02.'90	64.00	58.00	13.33	2.33	1.00	0.66	0.33	139.65
03.'90	71.67	74.00	18.00	2.33	1.33	0.67	0.33	168.33
04.'90	98.66	104.66	28.66	3.00	1.66	1.00	0.00	237.64
06.'90	1125.00	40.66	11.00	30.00	8.00	6.00	1.00	1221.66
07.'90	1279.66	483.66	187.33	116.33	39.33	20.33	4.00	2130.64
08.'90	1064.67	107.33	99.00	17.67	25.00	5.33	5.00	1324.00
09.'90	1230.00	338.67	94.67	36.67	10.33	6.67	21.33	1738.34
10.'90	621.00	148.33	111.33	29.00	12.66	2.33	2.00	926.65
11.'90	1531.67	928.00	200.00	156.33	44.66	25.66	4.66	2890.98
12.'90	592.33	257.33	70.00	18.33	8.00	3.33	2.00	951.32
01.'91	1529.00	390.67	317.33	122.33	37.00	22.33	5.67	2424.33
02.'91	1323.33	473.33	232.33	40.66	17.00	6.33	2.00	2094.98
04.'91	1445.00	608.67	204.00	57.66	24.67	10.67	4.00	2354.67
07.'91	1806.00	936.33	331.00	47.00	17.00	7.67	3.00	3148.00
09.'91	1272.00	419.67	212.33	103.00	39.00	12.33	6.67	2065.00
12.'91	1140.33	521.00	119.33	59.33	19.67	9.33	4.00	1872.99
TOTAL	16393.32	6060.30	2323.64	866.63	318.31	143.30	66.98	26172.48
AVG	862.81	318.96	122.30	45.61	16.75	7.54	3.53	1377.50
MAX	1806.00	936.33	331.00	156.33	44.66	25.66	21.33	3148.00
MIN	52.00	39.00	9.00	2.33	1.00	0.33	0.00	122.32
STD	601.65	279.06	101.51	45.20	14.09	7.51	4.66	988.19

ABUNDANCE (%)

Dat./sli.	0-1 cm	1-2 cm	2-3 cm	3-4 cm	4-5 cm	5-6 cm	6-10 cm	TOTAL
11.'89	38.04	23.93	20.86	11.04	4.91	1.23	0.00	100.00
12.'89	42.93	37.21	15.66	2.19	1.52	0.17	0.33	100.00
01.'90	42.51	46.87	7.36	1.90	0.82	0.27	0.27	100.00
02.'90	45.83	41.53	9.55	1.67	0.72	0.47	0.24	100.00
03.'90	42.58	43.96	10.69	1.38	0.79	0.40	0.20	100.00
04.'90	41.52	44.04	12.06	1.26	0.70	0.42	0.00	100.00
06.'90	92.09	3.33	0.90	2.46	0.65	0.49	0.08	100.00
07.'90	60.06	22.70	8.79	5.46	1.85	0.95	0.19	100.00
08.'90	80.41	8.11	7.48	1.33	1.89	0.40	0.38	100.00
09.'90	70.76	19.48	5.45	2.11	0.59	0.38	1.23	100.00
10.'90	67.02	16.01	12.01	3.13	1.37	0.25	0.22	100.00
11.'90	52.98	32.10	6.92	5.41	1.54	0.89	0.16	100.00
12.'90	62.26	27.05	7.36	1.93	0.84	0.35	0.21	100.00
01.'91	63.07	16.11	13.09	5.05	1.53	0.92	0.23	100.00
02.'91	63.17	22.59	11.09	1.94	0.81	0.30	0.10	100.00
04.'91	61.37	25.85	8.66	2.45	1.05	0.45	0.17	100.00
07.'91	57.37	29.74	10.51	1.49	0.54	0.24	0.10	100.00
09.'91	61.60	20.32	10.28	4.99	1.89	0.60	0.32	100.00
12.'91	60.88	27.82	6.37	3.17	1.05	0.50	0.21	100.00
AVG	58.23	26.78	9.74	3.18	1.32	0.51	0.24	100.00
MAX	92.09	46.87	20.86	11.04	4.91	1.23	1.23	100.00
MIN	38.04	3.33	0.90	1.26	0.54	0.17	0.00	100.00
STD	13.69	11.76	4.09	2.32	0.96	0.28	0.25	0.00

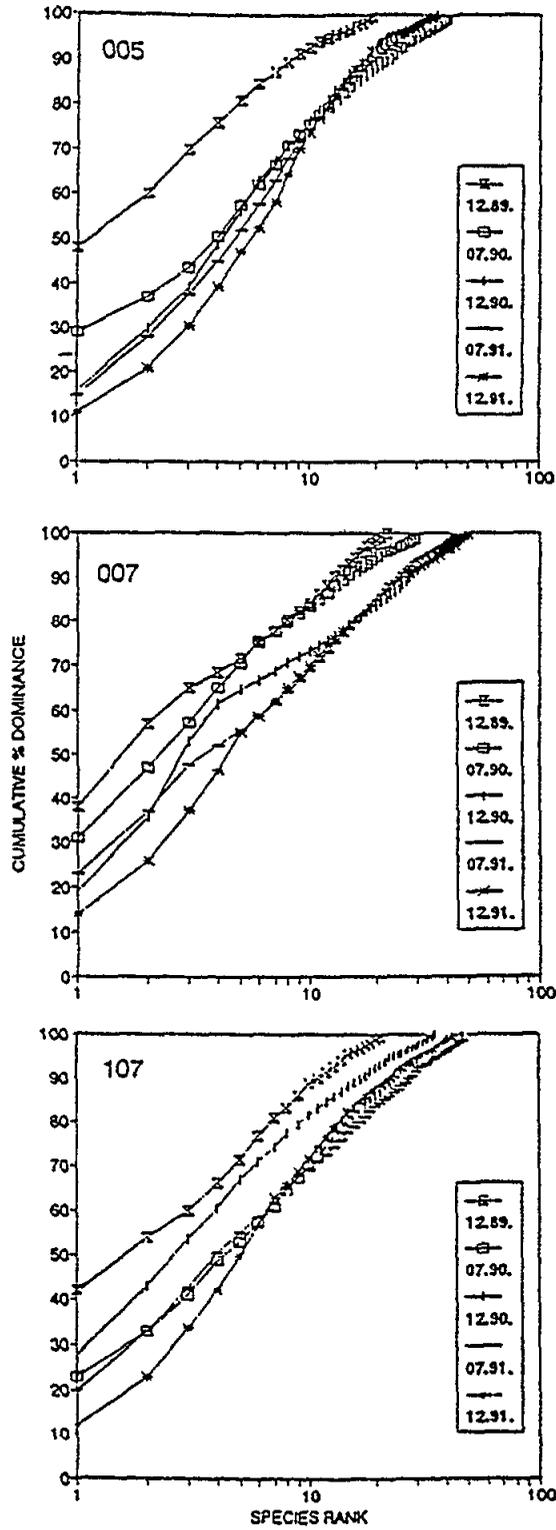


Fig. 10 Recovery stages of sediment living nematode populations

a high pelagic and benthic biomass. A high input of nutrients, riverborne or pollution originated, in interaction with the above factors can trigger phytoplankton and/or phyto-benthos blooms which in unstable ecosystems are inevitably followed by a high input of organic matter, its decay, and a resulting oxygen depletion under stable environmental conditions. The floating mucous aggregates, and sedimented strings and carpets, are only visible agents to which unusual behavior and mortalities of benthic organisms are attributed.

Occurrences of these phenomena have recently led to wide-scaled interdisciplinary research, due above all to their decisive influence on national economies. In general, fundamental mechanisms of eutrophication and related phenomena have been elucidated (Stachowitsch and Avèin, 1988), particularly for the north Adriatic Sea (Stachowitsch, 1984; Herndl, 1988; Smolaka and Degobbis, 1987; Degobbis, 1989; Degobbis *et al.*, 1989, 1990, 1991; Malej *et al.*, 1989; Najdek *et al.*, 1989; Gilmartin *et al.*, 1990). Soon however it became evident that the conclusions could not apply generally and unconditionally from a relatively small area such as the shallow north Adriatic. Namely, neither the phenomena (i.e. phytoplankton blooms, oxygen depletion, mass mortalities) in the area concerned are triggered and supported by the same decisive agents, nor are they strictly determined with regard to place and time, nor could the final result, and the time of ecosystem recovery be accurately foreseen, due to the specific local features of the marine environment. In the north Adriatic, at present the appearances and manifestations of sea snow and other mucous aggregations have already been excellently explained (Stachowitsch *et al.*, 1990; Degobbis *et al.*, 1991) including a prediction of a biological anoxia event (Stachowitsch, 1991) and subsequent short-term effects of oxygen depletion on benthic organisms have become possible (Stachowitsch, 1984).

Unfortunately, little is known on the long-term effects of anoxic conditions on benthic ecosystems (Stachowitsch and Avèin, 1988). Following the extermination of most species, or the total macrofauna, an increasing trend of species diversity and abundance in subsequent time intervals is an expected process noted world wide in marine, freshwater and land ecosystems. The speed of community recovery, however, depends on many abiotic factors, the reproductive and settlement strategies of autochthonous surviving species and the actual settlement and growth of new, perhaps casual, invaders. The recovery of an injured benthic ecosystem, and the particular communities and assemblages within it, is a lengthy process in no way determined by spatial concurrence and longevity of the settlers. On a sedimentary bottom, recolonization of the epigrowth is facilitated by old and new biogenic structures (i.e. shells and tests) which may become available after a large scale mortality of benthic organisms (Stachowitsch, 1991). According to previous research, a recovery of soft bottom macrofaunal assemblages in the New York Bight could not be expected before several years (Steimle and Radosh, 1979), and in the Saltkallefjord the recovery time established was eight years (Rosenberg, 1976). In the Gulf of Trieste, the re-establishment of an Ophiotrix-Reniera-Microcosmus epifaunal community was projected to require more than five years if no new stress event intervened (Stachowitsch, 1991).

The results of the present research are in general accord with the above estimations. After two years of monitoring, the sediment living macrofaunal assemblages at stations 005, 007 and 107 had obviously not yet achieved a "healthy" condition. Although the total species diversity was

roughly stabilized by the end of the first year after the mass mortality event (i.e. at station 005 at the level of about 50 to 60 species per 0.4 m², and 70 to 80 species at stations 007 and 107, respectively), the qualitative and quantitative structures point to further and unpredictable dynamics and alterations in community and population levels. The same could also be stated for the sediment living meiofauna, and nematodes in particular.

Some aspects were given particular attention. Firstly, according to the results of the present study the (at least apparent) recolonization of sediment infauna took place in much less time than Stachowitsch (1991) estimated to in order to obtain an *O-R-M* community, and multispecies clumps in particular. Secondly, a spatial recolonization and community recovery, under "undisturbed" environmental conditions, is highly dependent on the reproductive periods of newly settled species (Leppäkoski, 1969). The diversity differences in bivalves and polychaetes at the stations surveyed (Fig. 11) clearly contribute to this hypothesis.

However, many pioneer species which in a particular assemblage, at least in the early recovery period, have a dominant rank, usually are not typical of the community considered (Leppäkoski, 1971). At the stations observed, pioneer species were almost exclusively characterized by their wide ecological distribution, or their tolerance to limiting environmental factors. For example, the minute shellfish *Corbula gibba* is known as the first colonizer of intensively dredged areas suffering excessive turbidity (Bonvicini-Pagliai and Serpagli, 1988). At the stations monitored, along with the few adult specimens which had survived the anoxic catastrophe, in the early recovery period juveniles of this species appeared by hundreds per 0.4 m² of sea bottom, soon accompanied by the bivalve *Musculus marmoratus*, and some polychaetes such as *Owenia fusiformis*, *Eunice vittata*, *Myriochele heeri*, and others. A similar sequence and composition of colonizing macrofauna was also reported from other seas (Leppäkoski, 1971; Stachowitsch and Avèin, 1988; Stachowitsch, 1991).

The age, or more precisely the size of organisms present in samples can often influence decisively standing crop data. This became evident upon analysis of the data shown in Table 2; an extraordinary severe drop in community total wet weight noted at station 107 in April 1990, was obviously due to the absence of an adult shellfish population at the study site. The question remains, however, if this phenomenon was due to the species natural mortality period, to a patchy distribution of adults not noted previously, or due to an unusual local displacement of large adults.

It should be added that the results of the present study confirm previous hypotheses on special sensitivity of echinoderms to oxygen depletion, in particular, to anoxic conditions in the environment (Stachowitsch, 1984, 1991). In addition, the re-establishment of their populations probably takes place very slow. An *Amphiura* population recovery was noted about 1.5 years after the anoxic event, followed by the decline of the population in spite of individual juveniles noted fairly regularly in all grab samples taken within this period.

It is interesting that the recovery process in sediment living meiofauna is similar to that observed at the macrofaunal level. An abrupt increase in meiofaunal abundances only four to six months after a latent period of assemblage recovery (Travizi, 1992) (Fig. 8), was possibly linked

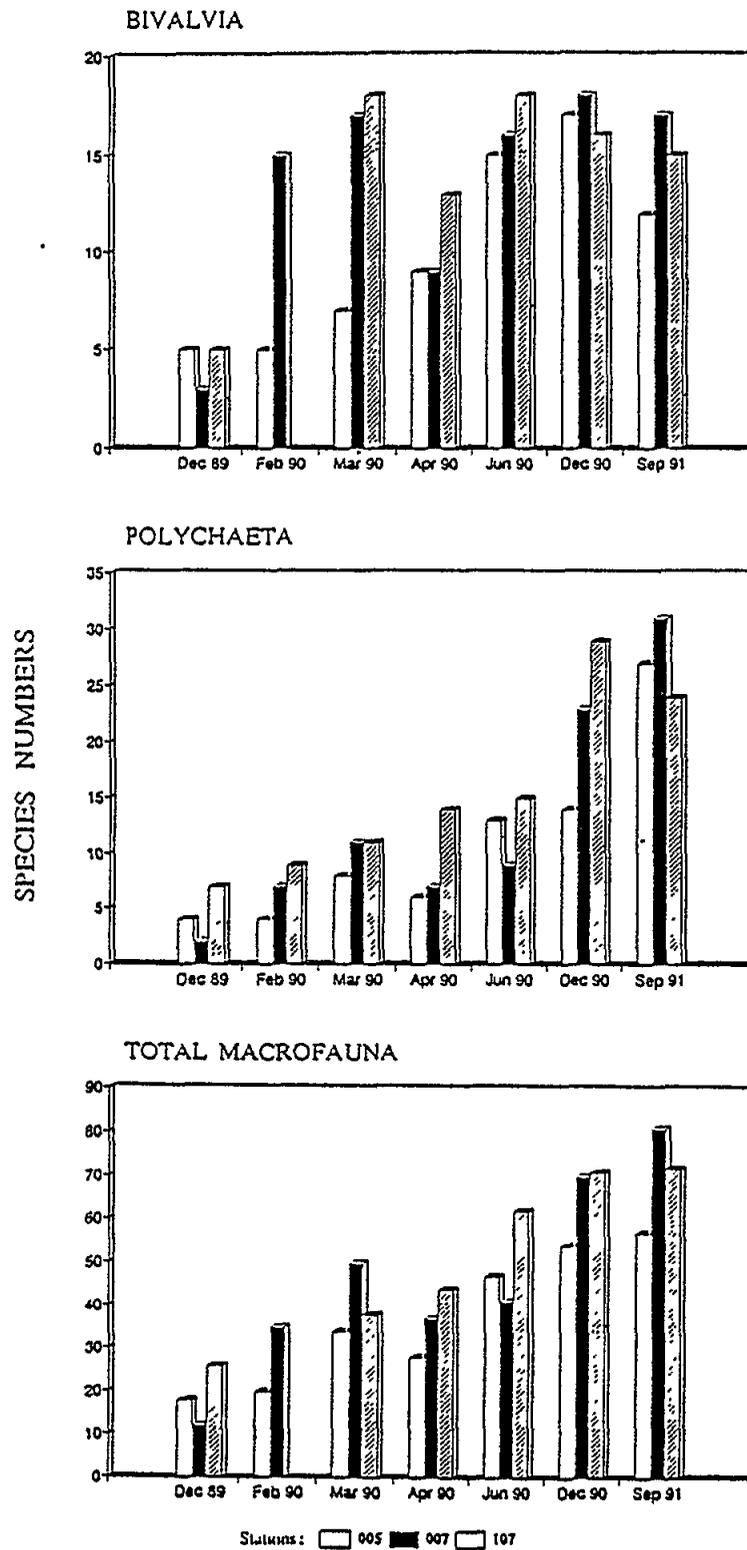


Fig. 11 Macrofauna diversity sequences at stations monitored in the communities recovery period 1989-1991

to reproductive strategies of species formerly dominant, particularly if a generally short longevity of typical meiofaunal species is considered. As observed for the macrofauna, the first colonizers at the meiofaunal level were apparently only few. For example, at station 005 in the early recovery period, of the total nematofauna the species Ptycholaimellus ponticus represented 40-50% of the specimens as observed for Corbula gibba at the macrofaunal level (Figs. 3, 4).

Another aspect not previously studied in relation to an anoxic event, is the spatial distribution of meiofauna in the sediment core. Just after the autumn 1989 anoxic conditions, the total meiofauna mortality at station 107 was estimated at about 85-90%: the survival rate of nematodes was 10-15%, and of copepods 2-7%. Within the core, the survivors were distributed fairly uniformly, while the layer below 6 cm depth at all three stations surveyed was not populated (Fig. 9, Table 3). The following month, i.e. in December 1989 the meiofauna had already invaded the 6-10 cm layer, but a characteristic stratified vertical distribution was restored some months later. The most persistent abnormalities in the meiofauna distribution within the sediment core were noted at station 107, possibly due to the local granulometric composition of the sediment, or that new environmental disturbances had intervened. Fig. 2 contributes to this hypothesis.

In summary, it is evident that phytoplankton blooms occurring in the pelagic ecosystem, and in the upper euphotic zone, in a strongly stratified water column cannot directly affect the benthic ecosystem below the thermocline and pycnocline. At shallower sites, i.e. along the shore, the benthos can be positively affected by an excess in oxygen concentration and possibly, by the additional food web available to filter feeders (Revelante and Gilmartin, 1992). Adverse effects however, can be expected due to secondary phenomena accompanying the microphytic blooms, such as the appearance of mucous aggregates (sea snow and strings) and their sedimentation to the bottom. According to SCUBA observations, while sinking, the fine material can be retained for some time in the pycnocline layer (Stachowitsch et al., 1990; present results), although the bulk of slimy material deposits on the bottom covering sessile animals, seaweeds, and seagrass beds (Zavodnik, 1977; Stachowitsch, 1984; Zavodnik et al., 1989). The adverse effects of deposited material are mostly mechanical: the mucous web prevents the normal circulation of sea water necessary for oxygen and food supply; animal gills and similar organs can become obstructed; sedentary animals can become entangled in the "web" (Zavodnik, 1977; Stachowitsch and Avèin, 1988). The decay of the organic mucous material and dead plankton, aided by bacterial activity (Herndl, 1988; Fanuko et al., 1989; Revelante and Gilmartin, 1992), leads to a third stage phenomenon: oxygen depletion. This is the most harmful stage which could become fatal to many benthic organisms, depending on its intensity and its duration (Stachowitsch and Avèin, 1988).

Previous research has much contributed to the understanding of the particular phases and the elucidation of mechanisms related to pollution and eutrophication and accompanying phenomena such as microphytic and macroalgae blooms in the marine environment, particularly in the north Adriatic. However, a great diversity and unpredictability of events is especially expressed in a benthic ecosystem. For this reason, the present study focused on a community recovery study at the macrofaunal and the meiofaunal levels following an anoxic event which was preceded by a phytoplankton bloom.

5. CONCLUSIONS

In the research period 1989-1992, phytoplankton blooms occurred several times, in offshore and coastal north Adriatic areas. Mucous aggregates ("sea snow", "strings", "carpets") were assessed as a visual, i.e. secondary, effect of microphytic blooms.

Mucous aggregations can be displaced by means of wind/waves and currents, and can be accumulated locally. Under special hydrographic and meteorological conditions, mucous aggregates can accumulate and deposit on the sea bottom, thus directly affecting adversely the benthic flora and fauna by smothering and/or provoking oxygen depletion in the bottom layer.

In the area surveyed, bottom oxygen depletion was limited in space and time. Following the mass mortality of benthic organisms at station 107 in November 1989, biological anoxia was noted repeatedly in 1990 and 1991. It was noted that these events affected the population and community recovery process.

If hydrographical monitoring is too extended with regard to measuring periods, short term hypoxia cannot be checked and estimated in situ: its occurrence may be subsequently determined by the response of benthic fauna, at least at the meiofaunal level.

Oxygen depletion provoked an unusual behavior of individuals, gave rise to local displacement and disappearance of populations, and finally, a mass mortality causing an apparently complete extermination of particular species.

Among the macrofauna, the most sensitive organisms to biological anoxia proved to be sponges, some polychaetes, echinoderms and tunicates, while actinians appeared to be the most resistant. Of the sediment living meiofaunal taxa, copepods were affected much more than nematodes.

At both the macrofaunal and meiofaunal levels, the infaunal response to oxygen depletion, and the strategies of species populations and assemblages recoveries were similar and comparable. The recovery of macrofaunal populations occurred gradually. At the stations monitored, the "normal" community diversity was roughly achieved in about one year. It appears that the recovery of infauna is faster than the recovery of sessile epifaunal assemblages.

At the meiofaunal level, the "latent" recovery period lasted about six months. A subsequent sharp abundance increase of total meiofauna occurred at the end of spring, but an apparently "normal" nematode diversity was established about nine months after the 1989 disappearance.

The blooms of some benthic species indicated a phenomenon of "free space" in a few months subsequent to anoxia and mass mortality.

Of the macrofauna, with respect to abundance, the outstanding pioneer species was the bivalve Corbula gibba. In meiofauna, the most numerous first settler was the nematode Ptycholaimellus ponticus. Later, during the community recovery period, both species diminished in importance.

With respect to biomass (wet weight) data, the community diversity and population abundance indexes are more appropriate for the assessment of community recovery.

Population recovery strategies differed with regard to the main taxa. At the macrofaunal level, the most successful settlement was noted in bivalve molluscs and polychaetes, while echinoderms failed to show a swift recovery.

The recovery of macrofaunal and meiofaunal populations was successful and most rapid in species whose reproductive period immediately followed the period of stress conditions.

New invaders not characteristic of an autochthonous community, can locally and temporarily achieve an ecologically important rank, thus influencing the recovery success of autochthonous species.

After the two-year recovery period, the communities monitored at the macrofaunal and meiofaunal level, had not yet stabilized, possibly due to new invaders and other ecological disturbances which occurred in this period.

The recovery of soft bottom communities is a slow process which, because of the community instability, is very sensitive to interactions of biotic and abiotic environmental factors.

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MECHANISMS OF INITIATION AND PERSISTENCE OF A RED TIDE
IN SOME POLLUTED AREAS

by

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ABSTRACT

Under conditions of persistent and substantial input of nutrients and organic matter of anthropogenic origin into Kaštela Bay, summer red tides with the dominance of the species Lingulodinium polyedra (Stein) Dodge, have become quite a frequent phenomenon in the last decade. Since the monitoring of the red tide organisms in 1988 some chemical and hydrographic parameters have also been monitored.

The purpose of this work was to determine whether there is an interaction between red tide organisms and temperature, nutrients, pH and oxygen saturation.

Analysis of the red tide monitoring results shows that the nutrient content in Kaštela Bay is sufficient and does not represent a limiting factor in the red tide development.

It was shown that the initiation and termination of red tide blooms in the bay depends on the sea water temperature. The red tide increases when the water temperature reaches about 20°C.

Temporary and resting cysts of L. polyedra play an important role in the persistence and recurrence of red tide blooms in the bay.

Under bloom conditions copepod grazing was considerably low and contributed to the development of extensive blooms.

1. INTRODUCTION

Studies on the relationship between phytoplankton density and hydrographic and meteorological parameters in Kaštela Bay were first carried out in the late thirties (Ercegovic, 1940). Since 1980 a red tide associated with the dinoflagellate Lingulodinium polyedra (Stein) Dodge bloom has been observed regularly every summer. Occasionally, it caused mortality of marine organisms (Marasovic and Vukadin, 1982; Marasovic and Pucher-Petkovic, 1985, 1987; Marasovic, 1989). At first, the red tide was observed only in the eastern part of the bay, not earlier than mid-summer, and lasted for one to two weeks. In the last few years, however, it has extended over the whole summer, and occasionally throughout Kaštela Bay. It has been suggested that the red tide is initiated from resting cysts which reside at the bottom of the bay (Marasovic, 1989). The largest part of the sea bed in the bay is covered by fine-grained sediment, of grain size less than 63 µm (Fig. 1).

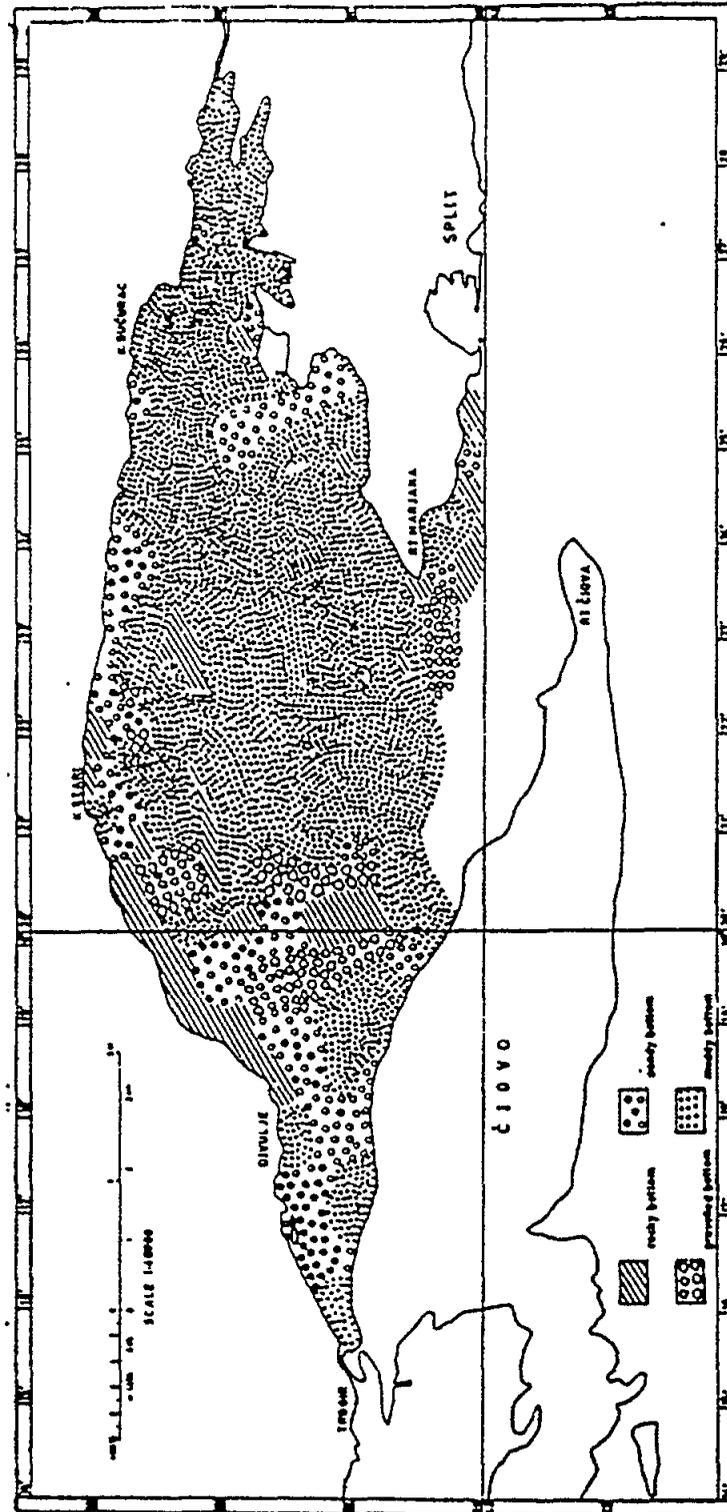


Fig. 1 Sedimentary chart of Kaštela Bay (Alfirević, 1980)

This composition of the sediment is very favourable for the existence of L. polyedra resting cysts (Lewis, 1988).

The nutrient input into the bay through industrial and domestic waste waters is very great; studies of red tide mechanisms were based on the assumption that the nutrient content is sufficient and does not represent a limiting factor for red tide development.

Therefore, the purpose of this study was to determine factors which are most important for the initiation, persistence, temporal variations and termination of red tide blooms in Kaštela Bay.

2. MATERIALS AND METHODS

Sampling and measurement stations (Fig. 2) were selected on the basis of earlier bloom occurrences. Four stations were sampled at two depths (0.5 m and near the sea bed) at approximately weekly intervals from June to September. Additionally, a station in the centre of the bay (RS) was sampled for comparison. At this station the red tide was usually much weaker than in the eastern part of the bay. Measurements included temperature, salinity, oxygen, pH, nutrients and phytoplankton.

Chemical parameters were analysed by standard oceanographic methods (Grasshoff, 1965; Armstrong *et al.*, 1967; Strickland and Parsons, 1968; Solorzano, 1969; Head, 1971).

Phytoplankton was analysed using the Utermöhl method on an inverted microscope after sample preservation in a 2% formaldehyde solution and 24 hours sedimentation.

Zooplankton samples were collected occasionally by vertical Hensen net hauls, preserved in neutral formaldehyde solution and counted, using standard methods (1/20 of sample), on a binocular microscope.

Meteorological observations were carried out daily.

Additionally, several experiments were performed under laboratory conditions to study the L. polyedra life cycle.

3. RESULTS

During the entire study period a strong vertical concentration gradient of phytoplankton was particularly marked, as well as a strong vertical concentration gradient of chemical indicators of biological activity, that is the dissolved oxygen content and pH of the sea water (Tables 1, 2 and 3). On several occasions during blooms, anoxia and fish mortality were found to occur.

The greatest vertical gradients of L. polyedra cell concentration were found at the deepest station (V₁, 18 m depth) where rather large gradients of oxygen content, pH and temperature were also observed.

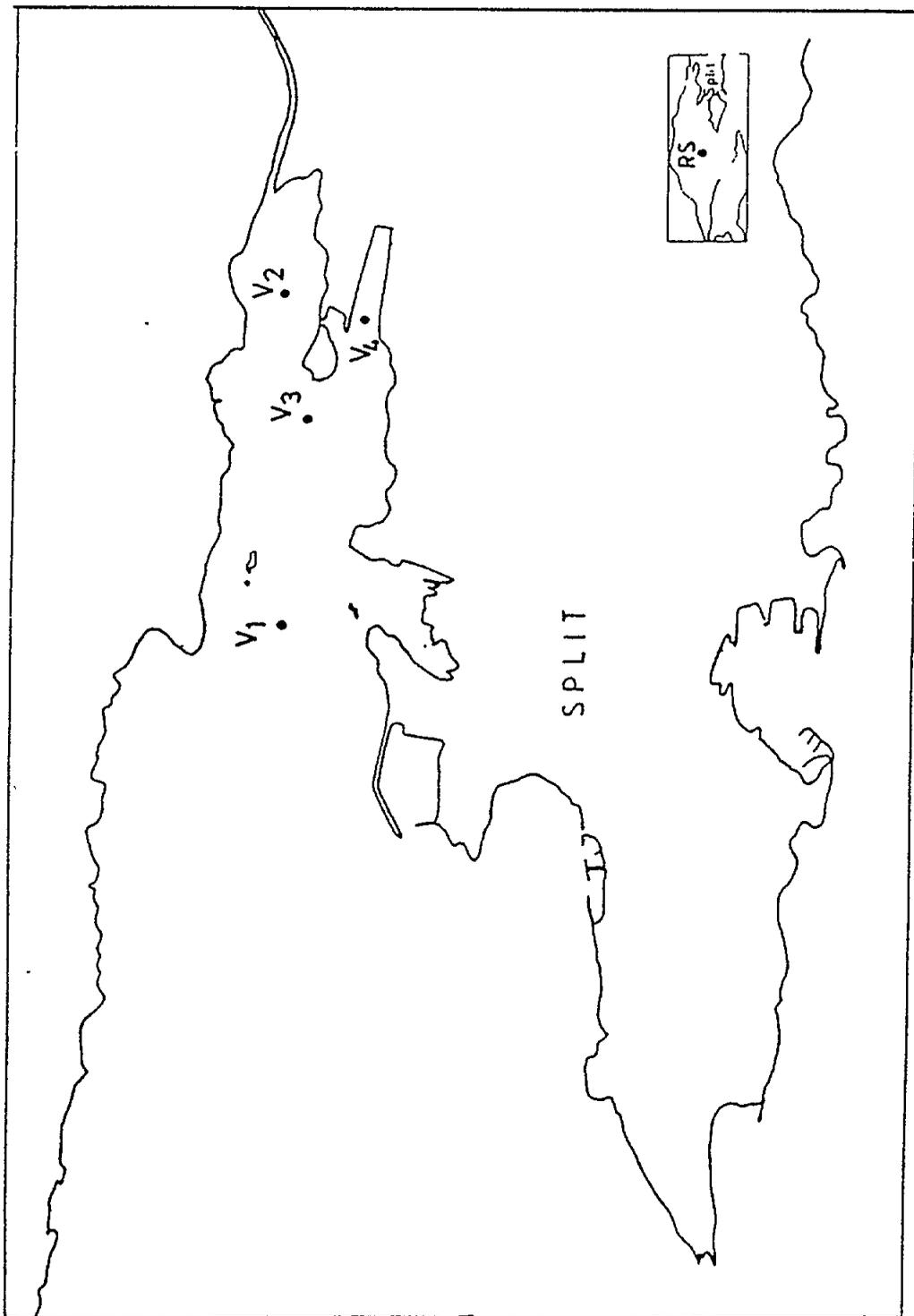


Fig. 2 Location of sampling stations in Kaštela Bay

Table 1

Concentrations of L. polyedra cells (N dm⁻³) in the surface and bottom layers (summer 1989 and 1990).

Date 1989	Station V ₃		Station V ₂		Station V ₁		Station V ₄	
	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
15.06	6	0	6	10	2	0.1	6	12
30.06	100	0	210	0	52	6	170	12
07.07	480	1	310	1	240	2	780	3
14.07	220	0.3	450	0.4	410	0.3	280	0
21.07	260	0	410	0.2	4400	8	410	32
04.08	430	0.3	1200	16	880	32	700	48
17.08	260	0	130	2	160	28	110	4
25.08	18	30	78	98	19	18	18	0.2
06.09	6	0.3	0.2	0	0.2	6	0.3	8
20.09	52	12	110	26	180	16	72	18

Date 1990	Station V ₃		Station V ₂		Station V ₁		Station V ₄	
	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
28.05	-	-	-	-	-	-	-	-
28.06	-	-	-	-	-	-	-	-
05.07	86	64	180	38	230	20	90	28
13.07	140	110	1100	160	220	0	120	170
26.07	280	44	190	12	22	58	170	18
13.08	610	16	600	32	120	14	430	290
20.08	380	33	270	56	280	9	230	56
29.08	-	-	-	-	-	-	-	-

The results of nutrient measurements confirmed an earlier assumption that, in the summer, nutrients are not a limiting factor of red tide development in Kaštela Bay. During the entire period of investigation, concentrations of nutrients were sufficient to support an extensive bloom (Table 4). It was also shown that during this season, land runoff of nutrients was the most important factor, whereas the process of nutrient resuspension was quite negligible (Fig. 3). Concentrations were lower in the bottom layer. A correlation between nutrients and bloom intensity was not observed (Fig. 4).

The correlation between temperature and bloom intensity was very high (Fig. 5) as was the correlation between pH, oxygen saturation and bloom intensity (Figs. 6 and 7). The influence of sea water temperature on bloom initiation and bloom intensity is shown in Fig. 8. It is clear that a temperature of 20EC is of crucial importance for the development of a L. polyedra bloom, whereas the phytoplankton also responded positively to further temperature increases. The red tide intensity suddenly increased when the water temperature reached 20EC. Temporary drops of red tide organism concentrations were due to vertical mixing induced by the local wind but termination of the bloom did not take place until the water temperature fell below 20EC.

Table 2

Oxygen saturation for the surface and bottom layers (summer 1989 and 1990).

Date 1989	Station V ₃		Station V ₂		Station V ₁		Station V ₄	
	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
15.06	110	103	125	109	132	100	129	120
30.06	91	71	130	80	126	92	111	84
07.07	181	144	147	70	120	92	184	39
14.07	168	82	209	82	190	63	176	57
21.07	137	32	186	33	198	52	126	62
04.08	129	49	143	82	277	71	216	120
17.08	113	30	182	20	128	39	138	14
25.08	59	73	73	62	98	53	85	69
06.09	68	70	89	56	70	89	76	91
20.09	201	57	221	47	236	132	219	104

Date 1990	Station V ₃		Station V ₂		Station V ₁		Station V ₄	
	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
28.05	132	82	142	76	157	76	126	83
28.06	249	65	275	106	258	94	233	122
05.07	86	31	154	15	163	-	119	186
13.07	125	103	177	105	132	112	128	111
26.07	121	64	126	39	118	84	108	81
13.08	195	62	210	79	127	73	242	114
20.08	138	51	87	72	94	44	134	87
29.08	16	19	12	-	70	103	16	37

The relative contribution of different copepod species was separately examined during red tides (Table 5); copepod gut contents were also examined. The number of copepods was considerably lower at station V₁ than at the reference station in the center of the bay.

The gut contents of dominant copepod species (Acartia clausi and Centropages kröyeri) were examined. Guts of A. clausi were half empty and guts of C. kröyeri contained mostly Prorocentrum micans and L. polyedra. At the same time tintinides which contained large quantities of L. polyedra cells were observed in the sea water samples.

In addition, the relationship between temporary and resting cysts of L. polyedra was examined under laboratory conditions. Preliminary results of these experiments lead to the hypothesis that temporary cysts can be transformed into resting cysts under extended periods of unfavourable environmental conditions (Table 6 and Fig. 9) (Marasovic, 1993).

Table 3

pH values of the sea water for the surface and bottom layers
(summer 1989 and 1990).

Date 1989	Station V ₃		Station V ₂		Station V ₁		Station V ₄	
	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
15.06	7.97	8.08	8.09	8.10	8.14	8.11	8.04	8.09
30.06	8.02	7.96	8.20	8.02	8.20	8.06	8.14	8.04
07.07	8.29	7.98	8.24	7.98	8.18	8.02	8.38	7.90
14.07	8.00	8.00	8.00	8.00	-	-	8.00	8.00
21.07	8.38	8.02	8.45	7.96	8.53	8.04	8.37	8.15
04.08	8.25	8.04	8.33	8.16	8.74	8.10	8.58	8.36
17.08	8.00	8.00	8.00	8.00	-	-	8.00	8.00
25.08	8.05	8.17	8.20	8.18	8.26	8.21	8.73	8.16
06.09	8.08	8.11	8.17	8.14	8.16	8.16	8.11	8.18
20.09	8.19	7.79	8.38	7.82	8.22	7.90	8.30	7.93

Date 1990	Station V ₃		Station V ₂		Station V ₁		Station V ₄	
	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
28.05	8.38	8.25	8.51	8.24	8.55	8.24	8.42	8.27
28.06	-	-	-	-	-	-	-	-
05.07	7.82	7.89	8.26	7.88	8.38	8.06	8.34	7.86
13.07	8.17	8.18	8.30	8.23	8.23	8.13	8.22	8.21
26.07	8.19	7.97	8.22	7.90	8.20	8.07	8.15	8.04
13.08	-	-	-	-	-	-	-	-
20.08	8.31	8.12	8.18	8.20	8.25	8.05	8.43	8.25
29.08	-	-	-	-	-	-	-	-

4. DISCUSSION

The analysis of the red tide monitoring results shows that temperature is the triggering mechanism of a L. polyedra bloom in Kaštela Bay. This confirms an earlier hypothesis (Marasovic, 1990; Marasovic *et al.*, 1991). The results obtained can also be related to the hypothesis that the red tide in Kaštela Bay is initiated from the resting stages of L. polyedra. Mass excystment takes place when the temperature of the sea water reaches a critical value. Analysis of the data of the 10-year biological time-series in the bay, showed that L. polyedra usually appear in April or May and disappear in October. During the rest of the year this organism is present in the bay only as the resting stage (Marasovic, 1990). The red tide suddenly occurs when the sea water temperature reaches 20EC, which is probably the minimum excystment temperature for L. polyedra. The red tide persisted as long as the bottom temperature was above 20EC. Therefore, it may be concluded that when a red tide in Kaštela Bay has been triggered it will persist for as long as the thermal conditions are favourable. Short-term changes in phytoplankton concentration are caused by vertical mixing and horizontal advection induced by wind and not by variations in nutrient concentrations. Temporary changes in phytoplankton concentration during the bloom are

Table 4

Concentrations of nitrates (m mol m^{-3}) in the surface and bottom layers (summer 1989 and 1990).

Date 1989	Station V ₃		Station V ₂		Station V ₁		Station V ₄	
	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
15.06	2.33	2.23	2.82	2.36	22.0	2.25	2.16	2.50
30.06	7.00	11.0	20.0	9.00	6.00	11.0	6.00	7.00
07.07	82.0	40.0	6.50	14.5	7.00	7.50	24.0	10.0
14.07	0.84	0.50	6.55	2.52	1.00	1.01	0.60	0.47
21.07	2.09	3.37	0.63	2.29	1.44	3.20	1.20	0.62
04.08	31.0	6.00	25.0	5.50	8.00	11.0	92.5	6.50
17.08	2.07	1.65	0.70	0.00	0.77	1.00	1.00	0.65
25.08	1.85	0.36	1.00	1.01	1.01	2.07	0.60	1.00
06.09	2.65	0.73	2.20	1.00	0.86	0.47	1.42	0.64
20.09	1.60	2.10	0.71	0.55	0.71	0.55	2.92	2.90

Date 1990	Station V ₃		Station V ₂		Station V ₁		Station V ₄	
	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
28.05	14.6	25.1	28.2	27.0	24.2	24.1	22.9	18.0
28.06	9.49	16.4	2.85	2.77	-	-	4.6	3.34
05.07	-	2.62	0.61	4.39	6.94	-	1.14	7.44
13.07	6.13	1.38	3.22	-	1.39	8.71	3.14	5.10
26.07	2.82	5.16	5.99	2.64	4.93	4.90	3.00	-
13.08	1.27	0.30	0.62	1.03	11.9	0.34	1.27	0.30
20.08	0.60	0.82	0.72	0.39	0.35	-	-	0.21
29.08	2.33	1.28	-	5.89	0.38	0.63	0.66	0.11

caused by unfavourable environmental conditions ie hypoxia. Depletion of oxygen under red tide conditions occurs as a consequence of phytoplankton biomass degradation, due to high bacterial activity. A mass formation of L. polyedra temporary cysts is then initiated.

Temporary cysts of L. polyedra are short-lived protective forms produced during unfavourable environmental conditions (changes in temperature, oxygen, pH, light and nutrients). When these unfavourable conditions do not persist, any change is immediately followed by the transformation of temporary cysts into vegetative forms (Marasovic, 1989). However, if unfavourable conditions persist (for more than five to seven days), temporary cysts will develop (or transform) into resting cysts. It appears, that this mechanism is important in relation to the persistence and recurrence of red tides in this area throughout the summer.

Preliminary results of copepod grazing during the red tide in Kaštela Bay indicate that low grazing by dominant copepod species (A. clausi -relative contribution over 70%) also favours the extensive dinoflagellate bloom.

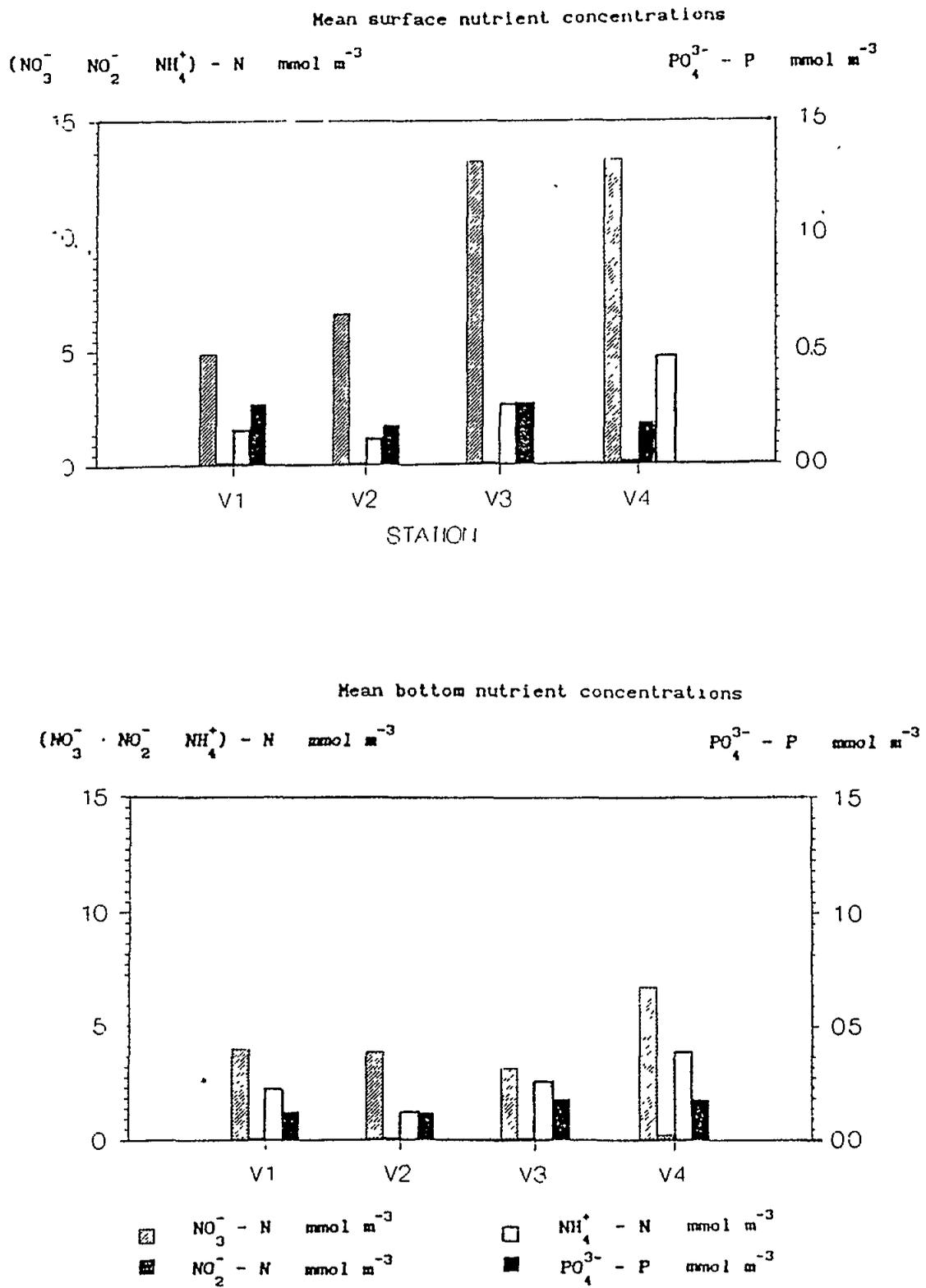


Fig. 3 Mean nutrient values in the surface (above) and bottom (below) layers (Kušpilić *et al.*, 1991)

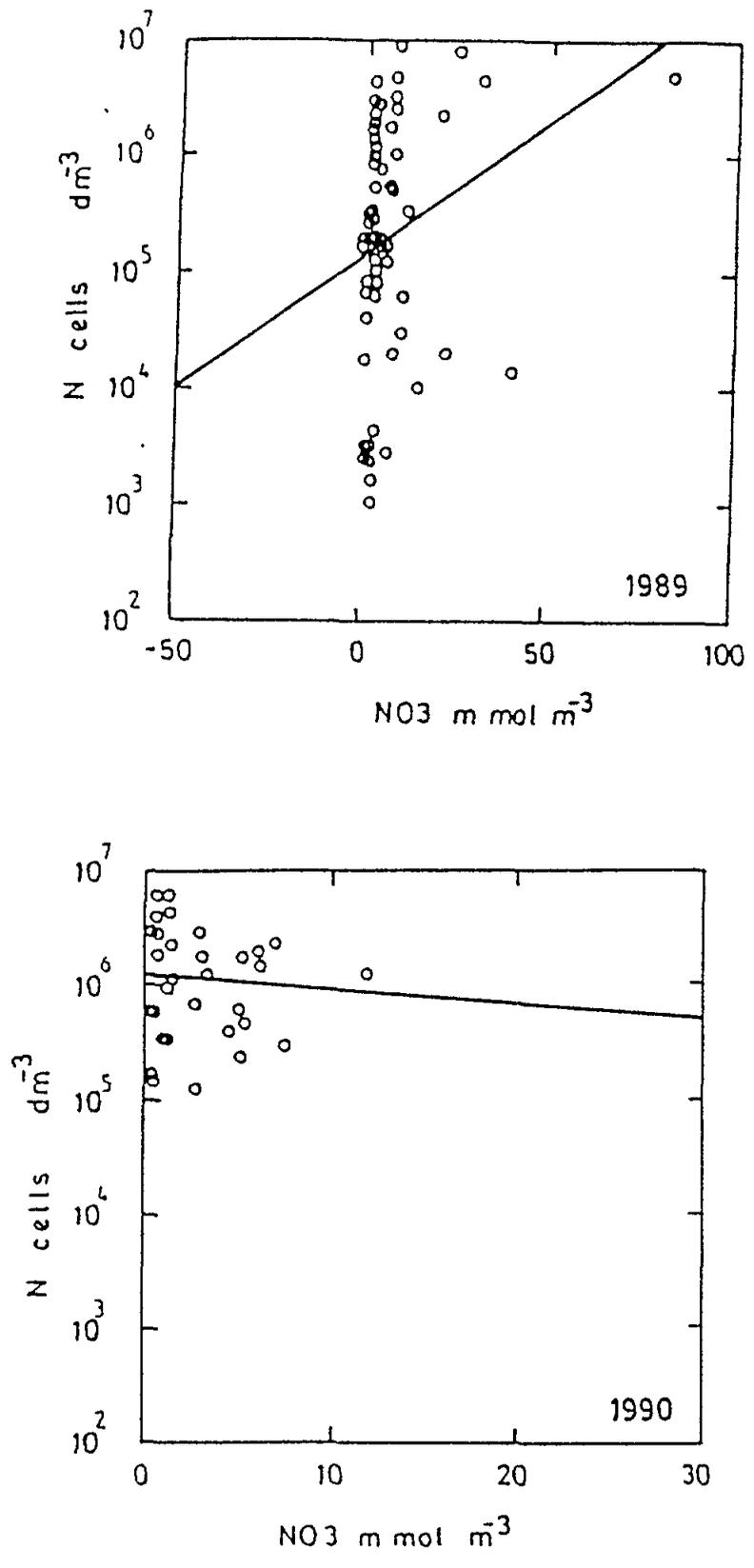


Fig. 4 Relationship between nitrate concentration and phytoplankton cell numbers (1989 and 1990)

Table 5

Composition of the copepod community at the stations studied.

SPECIES	NUMBER OF ORGANISMS	
	STATION V ₁	STATION RS
<u>Calanus tenuicornis</u> (DANA)	0	40
<u>Paracalanus parvovus</u> (CLAUS)	180	2
<u>Clausocalanus pergens</u> (FARRAN)	0	20
<u>Centropages typicus</u> KROYER	20	460
<u>Centropages kröyeri</u> GIESBRECHT	120	0
<u>Temora longicornis</u> (MULLER)	0	240
<u>Acartia clausi</u> GIESBRECHT	1380	3100
<u>Oithona sp.</u>	0	20
<u>Euterpina acutifrons</u> (DANA)	5	
Copepodids and other copepods	280	880
Total number of copepod species	8+1	6+1
Total number of copepod species/sample	5	7+1
Total number of specimens/sample	1985	4762
Total number of copepod specimens/m ³	330	484

Table 6

Oxygen concentrations, pH values and abundance of L. polyedra cells in an experimental microcosm.

Date	O ₂ ml ⁻¹	pH	cells l ⁻¹
28 September	10.61	8.5	3.2 X 10 ⁷
30 September	1.92	7.9	temporary cysts
15 October	0.28	7.4	resting cysts

The relatively high grazing of tintinides is not sufficient to control an extensive L. polyedra bloom.

Figure 10 depicts a hypothetical model of a L. polyedra red tide bloom in Kaštela Bay.

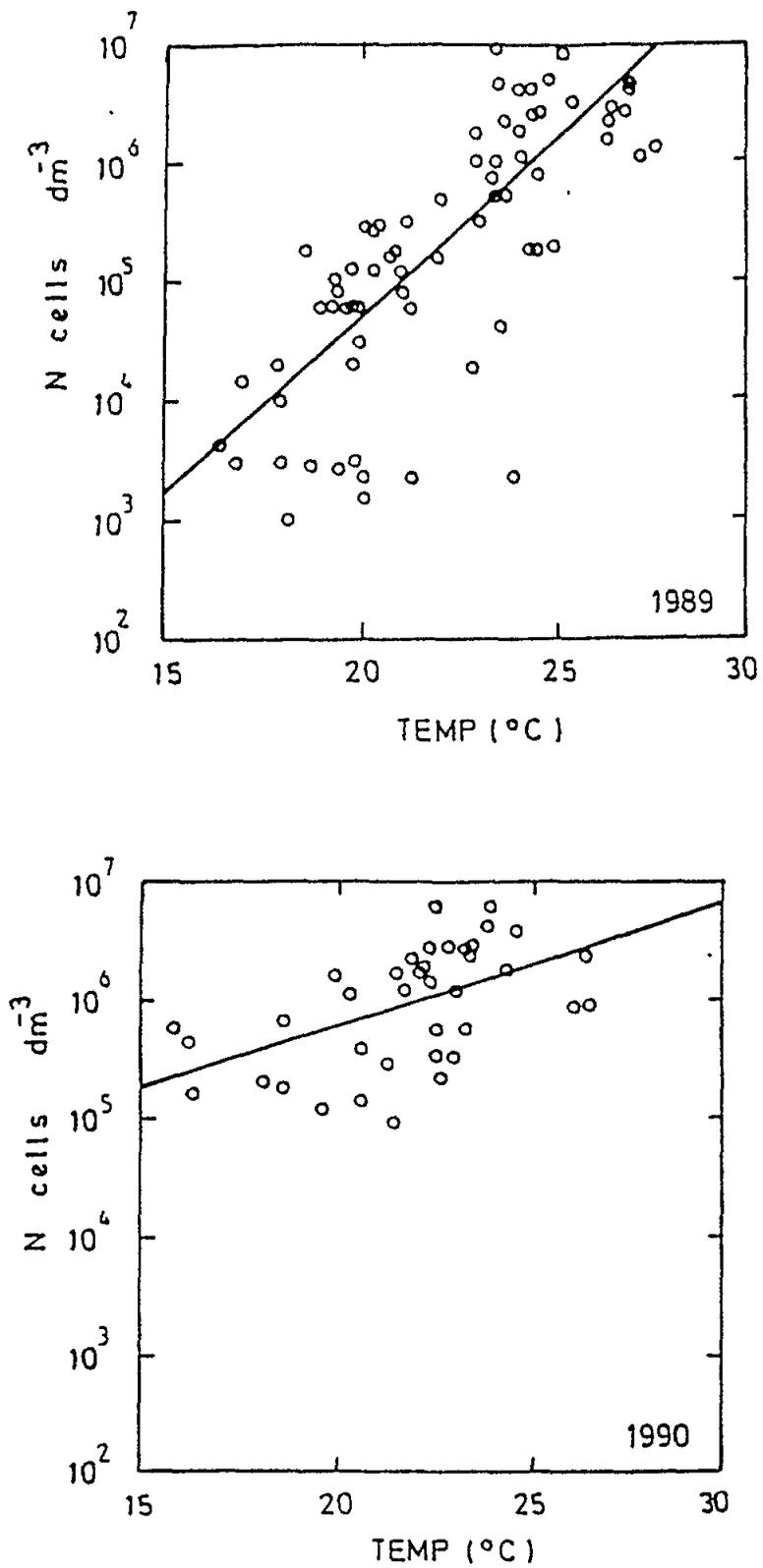


Fig. 5 Relationship between temperature and phytoplankton cell numbers (1989 and 1990)

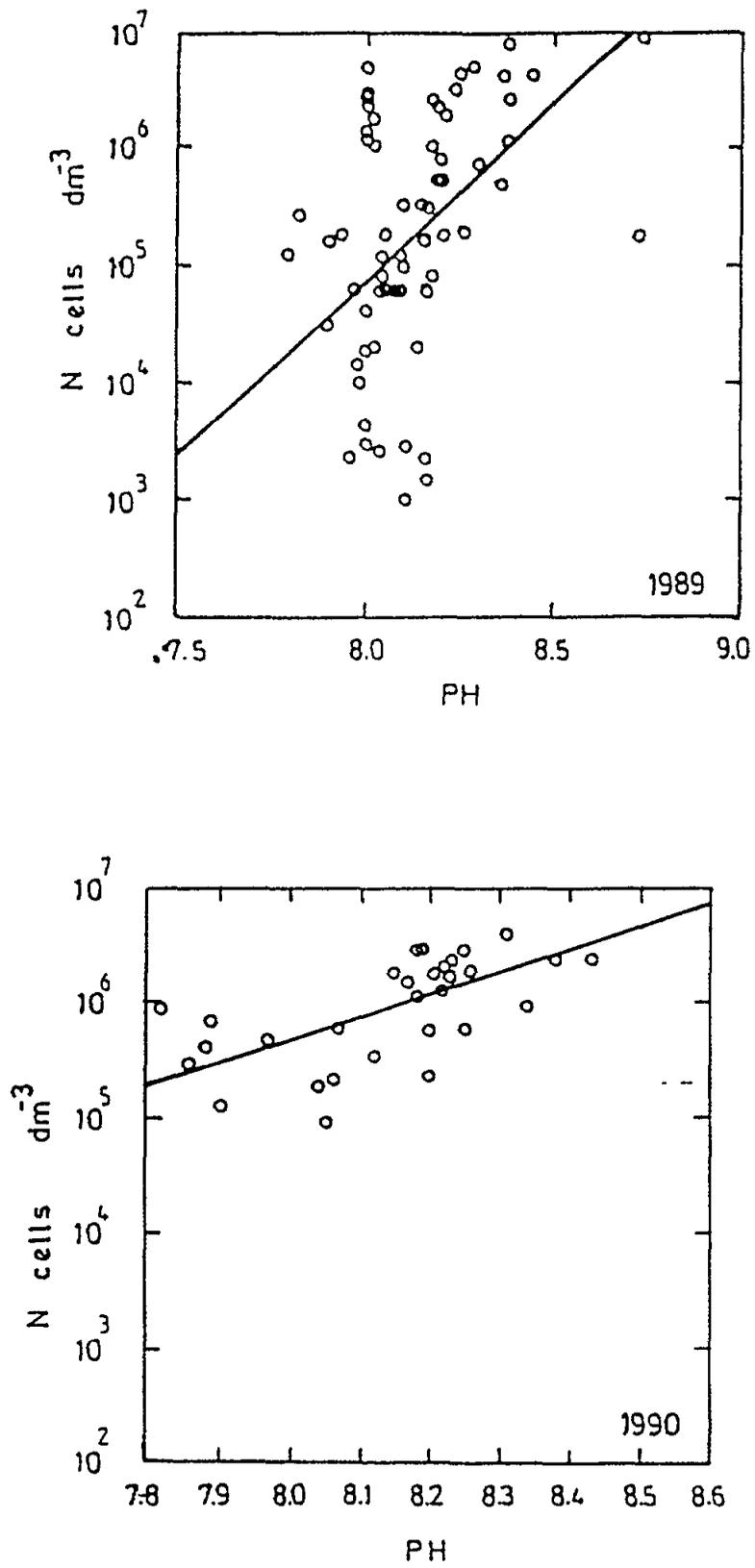


Fig. 6 Relationship between pH values and phytoplankton cell numbers (1989 and 1990)

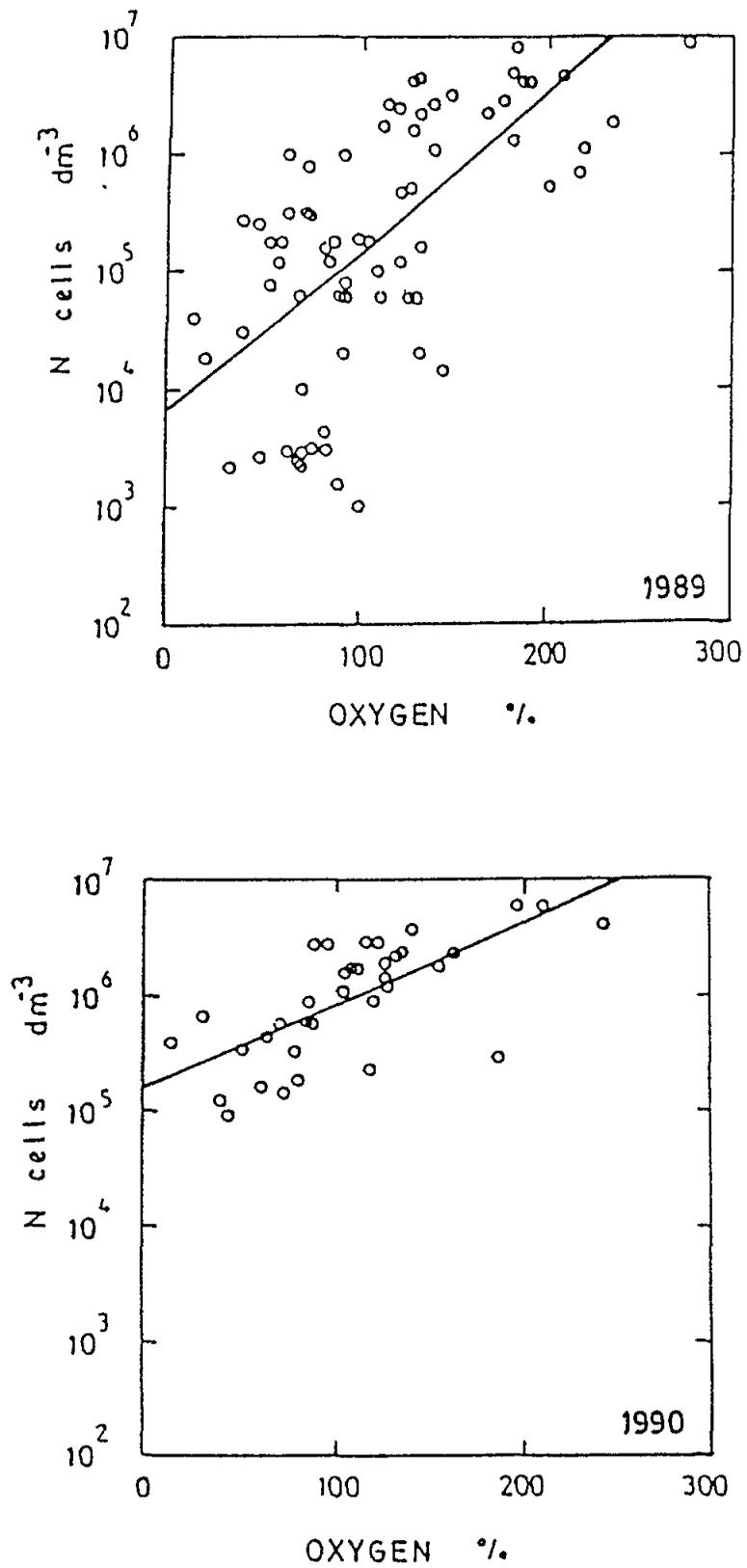


Fig. 7 Relationship between oxygen saturation and phytoplankton cell numbers (1989 and 1990)

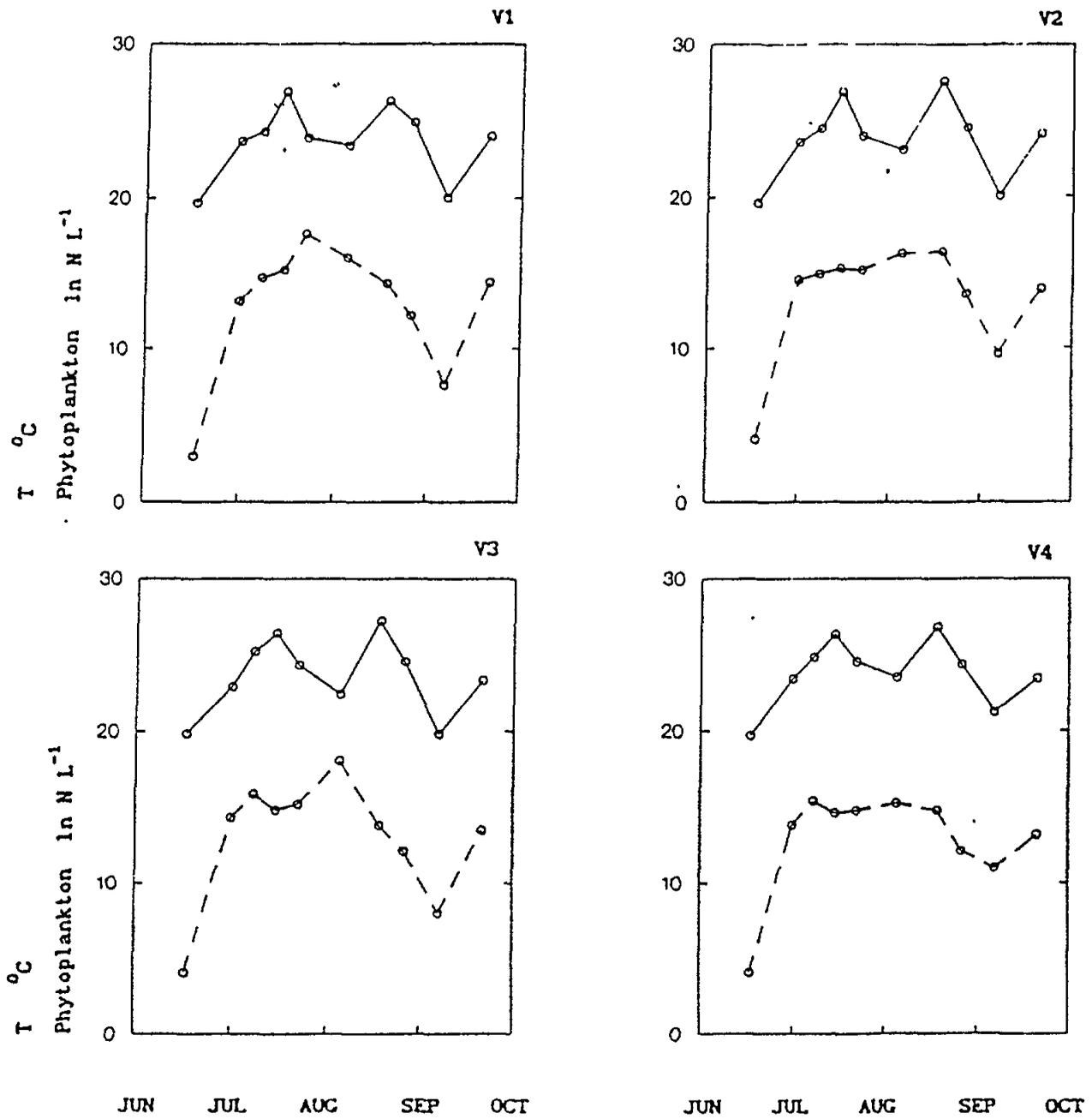


Fig. 8 Variation of temperature (solid line) and total number of phytoplankton cells (broken line) in the surface layer of the four stations during the summer months (Kušpilić *et al.*, 1991)

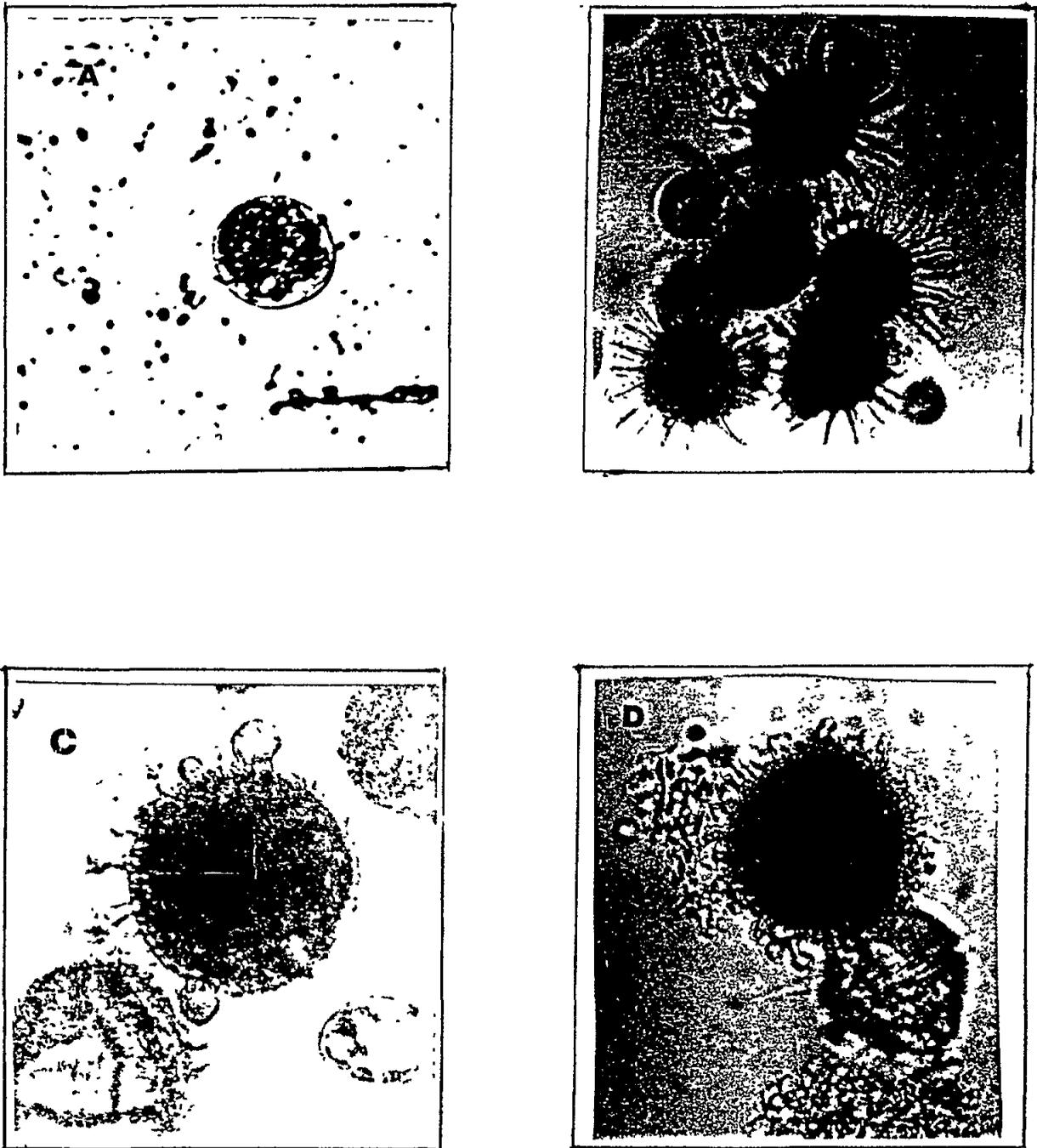
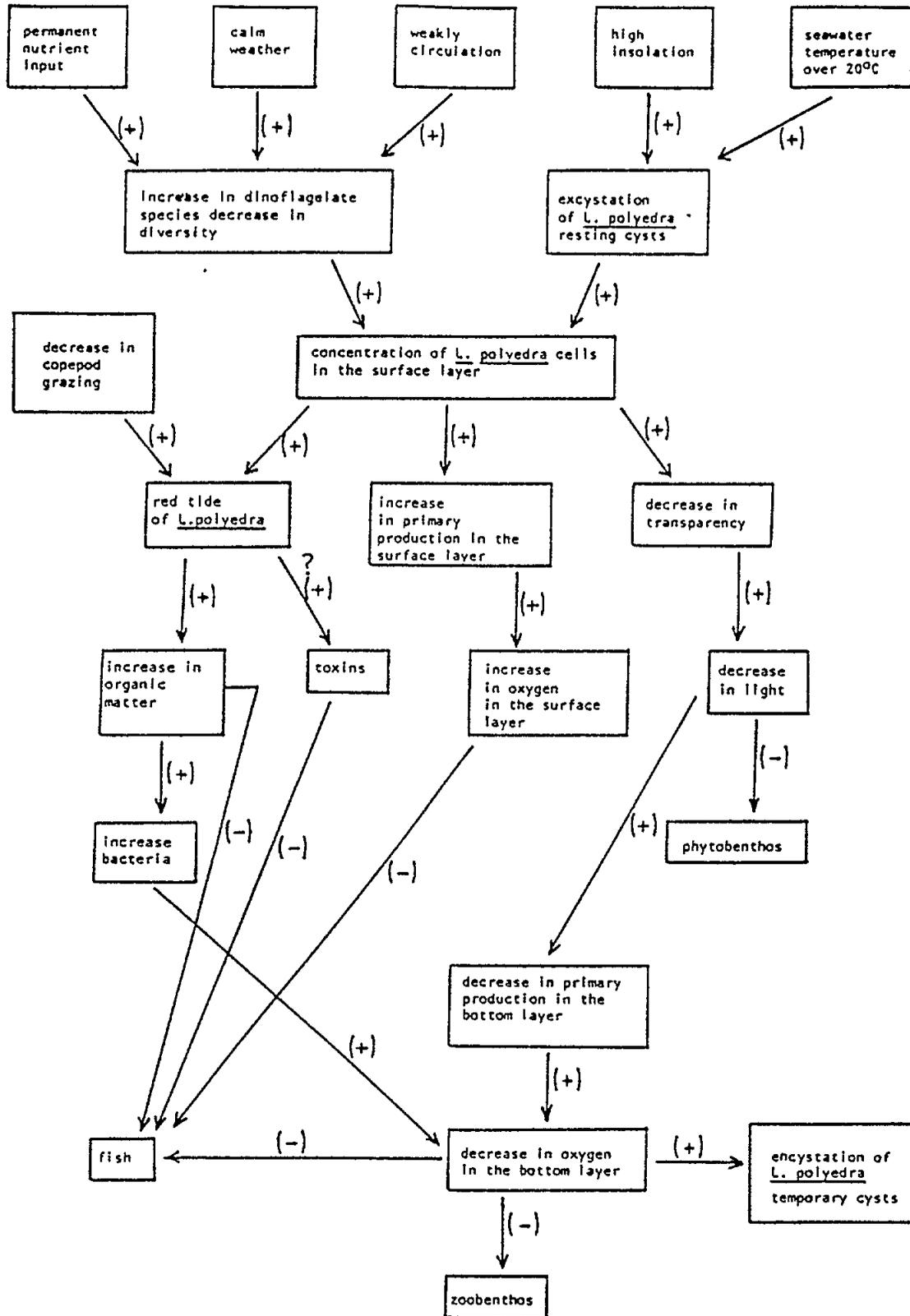


Fig. 9 Lingulodinium polyedra: A. Temporary cyst. B. Aggregations of resting cysts. C. Beginning of resting cyst formation (thick wall). D. Processes beginning to form on resting cysts



Results:
mortality of fish and shellfish
changes in community structure

Fig. 10 Rough qualitative model of the red-tide in Kaštela Bay

5. CONCLUSIONS

The following conclusions can be drawn:

a) Temperature is a triggering mechanism of a L. polyedra red tide in Kaštela Bay. The temperature of 20°C is considered as the minimum excystment temperature of L. polyedra resting cysts.

b) The initiation and termination of a L. polyedra red tide in the bay depends on temperature.

c) A very important mechanism in relation to persistence and recurrence of a L. polyedra bloom is the formation of temporary and resting cysts.

d) The nutrient content in Kaštela Bay is not a limiting factor for red tide development.

e) Insufficient zooplankton grazing contributes to the development of an extensive dinoflagellate bloom.

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