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Eutrophication in the Mediterranean Sea: receiving capacity and monitoring of long-term effects

Report and Proceedings
of a Scientific Workshop

Bologna, Italy, 2-6 March 1987

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PART I : MEETING REPORT

PREFACE

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ABSTRACT

A scientific workshop convened from 2 to 6 March 1987, in Bologna, Italy, agreed on 'Guidelines for the Monitoring, Assessment and Control of Eutrophication in the Mediterranean Sea', and adopted certain recommendations with the aim of providing guidance to the scientific community and national authorities concerned. A summary report of the meeting including the Guidelines and Recommendations, appear in Part I of this document.

The deliberations and conclusions of the meeting followed the presentation of a series of contributions and a review paper on the present state of knowledge of the eutrophication phenomenon in the Mediterranean. This was illustrated by a number of case studies, including a special session on the North Adriatic. The texts of these papers are included in Part II.

The report and proceedings of this scientific workshop will also be reproduced by UNEP, as MAP Technical Reports Series No. 21.

RESUME

Les participants à une réunion de travail scientifique organisée du 2 au 6 mars 1987 à Bologne (Italie) ont établi d'un commun accord des principes directeurs pour la surveillance, l'évaluation et la maîtrise de l'eutrophisation dans la mer Méditerranée et ont adopté certaines recommandations visant à fournir des directives à la communauté scientifique et aux autorités nationales compétentes. Un rapport sur la réunion, qui comprend les principes directeurs et les recommandations, figure dans la première partie de la présente brochure.

Les débats et les conclusions des participants ont fait suite à la présentation d'une série de communications et d'une synthèse des connaissances actuelles sur le phénomène de l'eutrophisation en Méditerranée. Le sujet a été illustré par plusieurs études de cas et une séance spécialement consacrée au nord de l'Adriatique. Ces textes sont reproduits dans la deuxième partie de la brochure.

Le rapport et les actes de cette réunion de travail scientifique sont également publiés par le PNUE dans "UNEP/Unesco/FAO : Eutrophication in the Mediterranean Sea : Receiving Capacity and Monitoring of Long Term effects", MAP Technical Reports n° 21, UNEP, Athens, 1988".

RESUMEN

Del 2 al 6 de marzo de 1987 se celebró en Bolonia (Italia), una reunión de trabajo en la que se aprobaron unas "Directrices sobre la Vigilancia, Evaluación y Control de la Eutrofización en el Mar Mediterráneo" y se adoptaron algunas recomendaciones encaminadas a proporcionar orientaciones a la comunidad científica y a las autoridades nacionales interesadas. En la Parte I del presente documento figura un informe resumido de la reunión, que comprende dichas Directrices y Recomendaciones.

Los debates y conclusiones de la reunión fueron precedidos de la presentación de una serie de contribuciones, así como de un documento de síntesis relativo al estado actual de los conocimientos sobre el fenómeno de la eutrofización en el Mediterráneo. Algunos estudios monográficos permitieron ilustrar el problema; una sesión especial estuvo dedicada al norte del Adriático. Los textos de estas contribuciones figuran en la Parte II.

El informe y las actas de esta reunión de trabajo científica serán publicados también por el PNUMA con el título: "PNUMA/Unesco/FAO: La eutrofización en el Mediterráneo: capacidad de recepción y vigilancia de los efectos a largo plazo. Serie de Informes Técnicos del MAB, N° 21. PNUMA, Atenas, 1988".

РЕЗЮМЕ

На научно-практическом семинаре, проведенном 2-6 марта 1987 года в Болонье, Италия, были согласованы "Руководящие принципы мониторинга, оценки и контроля эвтрофикации в Средиземном море" и были приняты некоторые рекомендации с целью представления руководящих указаний научному сообществу и соответствующим национальным органам. В части I настоящего документа приведен краткий доклад о работе совещания, включая руководящие принципы и рекомендации.

После представления ряда материалов и обзорного доклада о нынешнем уровне знаний в отношении явления эвтрофикации в Средиземном море приведены результаты обсуждений и выводы совещания. Это проиллюстрировано рядом тематических исследований, включая специальное заседание по Северной Адриатике. Тексты этих документов включены в часть II.

Доклад и материалы этого научно-практического семинара будут также размножены ЮНЕП в качестве Серии технических докладов МАП № 21.

خلاصة

وافقت حلقة العمل العلمية التى عقدت من ٢ الى ٦ مارس / آذار ١٩٨٧ فى بولونيا ، بايطاليا ، على صيغة " خطوط رائدة بشأن مراقبة الانتاج العضوى الزائد فى البحر المتوسط وتقييمه وضبطه " ، واعتمدت بعض التوصيات الارشادية الموجهة الى الأوساط العلمية والسلطات الوطنية المعنية • ويتضمن القسم الأول من هذه الوثيقة تقريرا موجزا عن الاجتماع مع الخطوط الرائدة والتوصيات التى أصدرها •

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摘　要

1987年3月2－6日在意大利波洛尼亚举办了一期科学讲习班，就“监测、估计及控制地中海富营养化现象的指导方针”取得一致意见，并通过了一些建议，以便向有关的科学界和国家当局提出指导性的意见。讲习班的简要报告包括指导方针和建议，载于本文件的第一部分。

讲习班对会上提出的一系列论文及一篇关于对地中海富营养化现象认识现状的评论性文章进行了讨论并作出了结论。此外，还利用了若干实例研究，其中包括一届关于北亚得里亚海的特别会议说明了这一现象。这些论文和文章的全文载于第Ⅱ部分。

这期科学讲习班的报告和记录还将由环境规划署转载于地中海行动计划技术报告集的第21期。

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FOREWORD

Eutrophication is a problem which has been recognized for many years in freshwater ecosystems, and methods for assessment and control of the process have been well developed. It is now quite straightforward to predict what level of eutrophication will develop in a lake, if the nutrient concentrations, flows and retention times are known, and it is therefore possible to determine control strategies so that the water quality is not impaired for the required water uses.

In contrast, marine eutrophication is rather poorly understood, and is certainly more complex than in the freshwater system. The process has been rather neglected, perhaps because the seas, and in particular the Mediterranean, have been generally considered to be oligotrophic. Only in the last decade has it become obvious that there are severe problems of eutrophication occurring in some parts of the Mediterranean, giving rise to serious consequences for the marine ecosystem (mass mortalities of benthic organisms, including fish and shellfish), and seriously affecting the tourist industry (aesthetic problems; loss of water clarity, dead animals on shore, foul smells, toxic shellfish etc).

In this workshop the present state of knowledge is summarized with the aim of providing guidance to local, national and international authorities on the most suitable methods for the monitoring, assessment and control of eutrophication. Topics on which there is particular need for research are also identified.

SCIENTIFIC WORKSHOP ON EUTROPHICATION IN THE MEDITERRANEAN SEA: RECEIVING CAPACITY AND MONITORING OF LONG-TERM EFFECTS.

Bologna, Italy, 2 to 6 March 1987

SUMMARY

This account of the workshop proceedings is a summary of the major points which were discussed in the various sessions throughout the week , leading to the formulation of the Guidelines and Recommendations. The detailed agenda and timetable of the meeting is given in Annex I. Forty-two scientists, mostly from the Mediterranean countries, participated actively in the meeting. The list of participants is given in Annex 2. The full text of the contributed papers and case studies are given in Part II, so only brief abstracts of these are included in the main report. A summary of other papers presented to the special session on the Adriatic is also given in Part II.

1. OPENING SESSION

Dr S. Morcos (Division of Marine Sciences, UNESCO, Paris) opened the workshop by welcoming the participants who were gathered in Bologna specifically to produce Guidelines for eutrophication control, and to recommend the relevant monitoring needs arising from control programmes. The detailed text of his remarks is included as Annex 3 .

Prof. F. Roversi-Monaco (Rector of the University of Bologna) welcomed this important group of scientists, brought together by the combined initiative of the University of Bologna, the Regione Emilia Romagna, UNESCO and UNEP. For the University, he stressed that it was always necessary to work on practical aspects of problems, and to try to solve them. It was particularly appropriate that such studies should be undertaken in 1988 to celebrate the 900th anniversary of the University of Bologna.

Dr L. Turci (President, Regione Emilia Romagna) expressed his thanks to the University and to UNESCO for taking the initiative to arrange the workshop. He quoted the Adriatic as an example of what could be achieved with a positive approach to eutrophication control. Work in the Regione Emilia Romagna had been initiated 13 to 14 years ago, and some of the people participating in this workshop had been involved with this process from the beginning (noteably Prof. R.A. Vollenweider). The whole programme resulted from the co-operation of the University of Bologna, University Centre of Cesenatico and the Institute of Water in C.N.R. He recalled some of the difficulties of analysis and interventions which were faced 13 years ago; for example, having identified the phosphorus contained in detergents as one of the major causes of eutrophication, it took 10 years to pass a law to reduce concentrations of phosphates in detergents. Although phosphates are not the only factor affecting eutrophication, this illustrated the complexity of solving such problems. The lesson to be learned is that there need to be economic consequences before factors creating environmental stress are taken seriously. He thanked the participants for attending the workshop, and looked forward to new ideas emerging which will help in solving the problem.

Dr G.P. Gabrielides (FAO Project Officer, UNEP Mediterranean Action Plan, Athens) expressed his thanks to the University of Bologna and the Regione Emilia Romagna for their help in organizing this workshop within the framework of the Mediterranean Action Plan. He then emphasized the need for this meeting to provide guidelines on how to proceed in eutrophication control, and indications of which work programmes and research projects should be given priority.

Following the opening session, the meeting agreed on designating Professor Ezio Todini as Chairman, Professor Paul Nival as Vice-Chairman, and Dr Lilian Evison as Rapporteur.

The contributed papers and the draft Working Paper prepared by the Unesco Consultant were then presented and fully discussed according to the Agenda and Timetable (Annex 1).

2. CONTRIBUTED PAPERS

Contributed papers that covered specific subjects or case studies were prepared by J. and M. Aubert, D. Bellan-Santini and M. Leveau, A. Cruzado, K. Fedra, N. Friligos, J. P. O'Kane, R. Marchetti, G. Gagino and A. Provini, M. Stachowitsch and A. Avčin, E. Todini and A. Bizzarri. The full texts of these papers are given in Part II, so only brief accounts of these are included in this section of the main report.

By an ad hoc arrangement several other papers were presented to the special session on 'Eutrophication in the North Adriatic and the coastal waters of the Regione Emilia Romagna'. An account on this special session and abstracts of the presented papers are likewise included in Part II.

2.1 Eutrophication in the Pelagic Environment and its Assessment

A. Cruzado (Page 57)

This paper gave an overview of the extent and importance of the eutrophication throughout the Mediterranean Sea, indicating that it could be found to some extent everywhere along the coast where river outflows and urban outfalls occur. Urban outfalls tend to produce intense eutrophic conditions, but rivers with their larger flows and load of inorganic sediments tend to give greater dispersion of eutrophicants. The greater importance of benthic processes over pelagic processes was stressed, due to the long-lasting impact of settleable organic matter; this creates an oxygen deficiency which can, under critical circumstances, be exported upwards in the water column. Dissolved oxygen is an integrating variable for all the processes taking place in both the water column and sediments. Eutrophication is characterized by a diurnal formation of oxygen by photosynthesis in the euphotic layer, and a consumption by respiration at night and in the lower layers including the sediments. This imbalance is responsible for the deleterious effects of eutrophication.

The paper drew attention to the two complementary approaches to eutrophication studies:

a) Pelagic investigations, normally used for monitoring eutrophication.
b) Benthic investigations, normally used for assessment of the extent of eutrophication.

In discussion he explained that qualitative changes (e.g. in community composition) occurred as a preliminary stage in the development of quantifiable chemical changes, such as anoxia and increase in nutrients and chlorophyll. He claimed that, if anything could drastically alter living conditions in the Mediterranean Sea, eutrophication rather than other pollutants would play the greatest role. As there is not an obvious threat to human health the problem had received little attention in recent years, and he hoped that this attitude could be changed.

2.2 Eutrophication - Induced Modifications of Benthic Communities

M. Stachowitsch & A. Avcin (Page 67)

Benthic communities, through their high suspension feeding capacity, play in important role in the energetics and stability of shallow marine ecosystems.

By feeding on living (plankton) and non-living (organic and inorganic) particles from the water column and converting them into benthic biomass, such communities may act as a natural eutrophication control. Eutrophication may change the rate and direction of benthic community development. In conjunction with adverse meteorological and hydrographic conditions it may lead to oxygen deficiency and accompanying impoverishment or mass mortality of benthic fauna. The analysis of several shallow sea and coastal mortality events in which eutrophication is implicated shows a strikingly similar pattern of:
stable meteorological conditions in late summer, stratification of the water column, elevated input from the pelagic subsystem, oxygen depletion in the bottom water layers, and a similar sequence of mortality of epi- and infaunal organisms. Both the frequency and extent of such events appear to be increasing, and this trend inhibits

repopulation and destabilizes the entire marine ecosystem. Mechanical disturbance (dredging for bivalves, trawling) may aggravate this situation. The common features of such phenomena are of high predictive value; sensitive areas can thus be defined and monitored more closely during critical periods.

In discussion the enormous filtering capacity of the benthic fauna (e.g. certain ascidians, filtering 10-12 $l.h^{-1}$) was compared to the operation of a sewage treatment plant. Destruction of such systems by excessive eutrophication constitutes the removal of an invaluable self-purification system. Although recovery from an episodic benthic mortality gradually takes place, when these events occur with increasing frequency, ecosystem diversity is eventually lost, resulting in simple, impoverished communities.

The importance of long-term studies on benthic communities was stressed. Data from at least a 10 year period is needed so that long-term population cycles can be detected, since variations of three orders of magnitude have been detected in long-term studies in the North Sea. The need for both measurements of averages and variances was emphasized.

2.3 Pathological Effects of Marine Eutrophication

M. Aubert & J. Aubert (Page 81)

The paper described the effects of red tides, not only poisoning marine animals and causing mass mortalities, but also causing human illness following the consumption of molluscs or exposure to aerosols from such waters. The species of Dinoflagellates, Chloromonads and Chrysomonads were summarized, their distribution and incidents of illness described in different parts of the world, including Florida, Brazil, Portugal, Brittany and Normandy. Symptoms range from respiratory problems, high temperature, pains in joints, skin rash, to pruritis and gastro-enteritis; often brief hospitalization is required, and occasionally deaths occur.

In discussion, the need for good epidemiological studies was stressed by several speakers. The Regione Emilia Romagna provides a very good location for prospective studies, and retrospective studies could be made on previous cases of skin irritation recorded at Cesenatico. The information must be interpreted with caution, since skin irritations can also result from increase in pH.

2.4 General Theory of Eutrophication

M. Aubert (Page 91)

The mineralization processes and metabolites of bacteria, and the production of phytostatic substances causing inhibition, were used to explain the relative abundance of Diatoms and Dinoflagellates in natural populations. Diatoms, stimulated by bacterial metabolites, produce substances antagonistic to Dinoflagellates, until nutrients limit growth. Subsequent Dinoflagellate growth leads to production of a substance which inhibits both Diatoms and Dinoflagellates, hence eventually Diatoms re-establish dominance.

The normal pattern may be disrupted when certain pollutants discharged in sewage cause breakdown of the Dinoflagellate auto-inhibitor, therefore enabling Dinoflagellate blooms to persist and Dystrophic conditions to develop.

In discussion, the need to clarify the terminology used in marine eutrophication was stressed; the term 'Dystrophy' had been introduced in Scandinavia for freshwater systems with low productivity due to humic acids, but in Latin countries the term is now used for waters of very high productivity. To avoid further confusion, it was suggested that the term 'Hypertrophic' should be adopted in marine systems, and that clear definitions should be established so that the terminology could be applicable in both temperate and tropical conditions. However, it seems that "dystrophy" describes more exactly the observed phenomena with modification of the distribution of phytoplankton and bacteria species.

It was suggested that there were not always such clear distinctions between Diatom and Dinoflagellate blooms as had been suggested in the paper; often concurrent blooms of Diatoms and Dinoflagellates occur, contradicting the theory of mutual exclusivity. Nevertheless antagonistic actions between these two phytoplankton groups have been demonstrated by many authors and concomitant blooms are very scarce in the same marine zone.

2.5 Systems Analysis and Ecological Modelling for Assessment and Control of Marine Eutrophication

K. Fedra (Page 95)

The Systems Analysis approach to the coastal marine environment allows all relevant aspects, including socio-economic and political considerations to be taken into account, as well as ecological processes. This approach can be used to integrate available information, identify gaps in knowledge and understanding of important phenomena, and be used as a decision-support tool to provide information on alternative courses of action, priorities, sensitivities and trade-offs. In the Mediterranean, rational and co-ordinated development of a multi-national catchment plan is required, to use information from economics, industrial and sanitary engineering and environmental sciences in such a way that the planner and decision maker can understand and act on it. Systems analysis can bridge the gap between the level of detail and complexity of scientific data and methods, and the information requirements at a strategic planning and policy level. However, new methods of applied systems analysis and new means of communicating scientific and technical information have to be developed, and improvement introduced in man-machine communication to produce an interactive, attractive and educational format.

2.6 Case Study: Eutrophication in the Golfe du Lion

D. Bellan-Santini & M. Leveau (Page 107)

The Golfe du Lion is bathed by oligotrophic waters of the Liguro-provencal stream; the main features of the weather are low rainfall and predominance of strong North winds. Four sources of eutrophication can be distinguished : winter vertical mixed waters and coastal upwellings, effluents of towns and industrial zones, natural run-off of the drainage basin, and lastly, the inputs of the Rhone. This last is by far the most important. The impact of the Rhone flow ($1600m^3.s^{-1}$) in an oligotrophic zone of water provokes a strong development of plankton in a defined area. These blooms rapidly use the nutrients and, depending on the weather conditions, they can sediment in place or be dispersed throughout the water mass.

The quantities of suspended solids fluctuate as a function of dry periods and floods. A combination of dilution of seawater and eutrophication induces the development of an unstructured phytoplankton system, with low diversity, immature, with a great abundance of small size species. Using remote sensing (CZCS), the presence of 'coloured patches' and their evolution in time and space demonstrates the influence of weather conditions on the stability of the phytoplankton system.

At certain periods of the year, particularly in summer when hydroclimatic conditions are favourable, red tides develop near to the mouth of the Rhone and near to the coast. This phenomenon is, however, limited in time and space.

A much more extreme example of eutrophication - L'étang de Berre - was also described. This is a shallow, semi-enclosed environment with a strong, almost permanent stratification of water, induced by the spread of freshwater at the surface, over the seawater trapped at the bottom. Anoxic conditions are so prevalent at the bed that the benthos has almost totally disappeared.

2.7 Case Study : Eutrophication of Saronikos Bay

N. Friligos (Page 123)

The Saronikos Gulf has no run-off from rivers, and the Athens sewage outfall located at the north of the gulf is a very large single source of chemical contaminants to the gulf. Thus, the upper Saronikos Gulf and Elefsis Bay are influenced by domestic waste discharges and industrial effluents, so that the conditions in these areas (eutrophic) are different from those found in the lower Saronikos Gulf (oligotrophic).

The outer gulf water presents low values of nutrients and a well defined annual phytoplankton cycle.

In the outfall area, the benthic community has been degraded, Coliform bacteria range from 10^4 - 10^6. $100ml^{-1}$ and D.D.T. concentrations of 1.5 ppm have been found in the sediments.

In the inner gulf water, high values of nutrients and active phytoplankton blooms are observed. It should be noted that the appearance of red tides coincides with fish mortalities.

The western Saronikos Gulf (a basin of 420 m depth, with an 80 m sill) appears to accummulate portions of the effluent to such a degree that present oxygen values at the bottom of around 2 $ml.l^{-1}$ occur and it is only a matter of time before the deep basin becomes anoxic.

The Elefsis Bay developes anoxic conditions in the lower layer during the warm season of the year. Eutrophic conditions affect the periodicity of phytoplankton (irregular pattern of blooms) and greatly reduce the species diversity of zooplankton. Benthic organisms as well as demersal and pelagic fish kills occur during summer.

In areas such as the Saronikos Gulf, primary treatment may be preferable to secondary treatment, and biological treatment would be possible only if the domestic wastes are separated from the industrial effluents.

2.8 Case Study : Eutrophication in the Lake of Tunis*

M. Belkhir

Eutrophication of the Lake of Tunis is caused by the increasing discharges of sewage into the lake, and the concurrent recycling of nutrients due to the biological activity of bacteria and reefs of *Ficopomatus enigmatica* feeding on decomposing phytoplankton. As a result of these excessive nutrient inputs there is very high productivity, rapid growth and heavy biomass of macroalgae such as *Enteromorpha* and *Ulva*, followed by concomittant proliferation of planktonic and benthic organisms. *Ulva* presents the greatest problem; it grows (and declines when conditions are critical) from late spring to mid-autumn. Its decomposition increases the oxygen demand in the late summer, when there is high irradiation and elevated levels of salinity, up to $56^o/oo$. The algal decomposition gives rise to the development of anaerobic conditions within the water column, which turns to a milky red colour. Ultimately this leads to massive fish

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* No text is included in Part II, for further details see: UNESCO, 1984. "Eutrophication in coastal marine areas and lagoons. A case study of Lac de Tunis", UNESCO Reports in Marine Sciences, No.29, 54pp.

kills (several tons at a time) due to the production of hydrogen sulfide, >13 $mg.l^{-1}$. The decomposition of macroalgae as well as phytoplankton and detritus increases the organic matter reserves and fuels the cycle described. This is perhaps the best example of a hypertrophic lagoon in the world, and there is great need for detailed studies on this and similar lakes in the Mediterranean region. It is atext-book example of the succession of bacteria involved in nutrient cycling, particularly the sulphur cycle; successions of phytoplankton, interaction between species and plankton-sediment interactions can also be closely studied.

2.9 Case Study : Red Tides in the Northwest Adriatic

R. Marchetti, G.F. Gaggino & A. Provini (Page 133)

Red tides, or more generally, algal blooms in the Adriatic Sea have been well-known since the last century. From 1975, algal blooms have become more commonplace in the Emilia Romagna coastal waters. The general trend is for blooms of Diatoms to develop at the end of winter in both coastal and open waters, with densities of tens of millions of cells per litre, lasting until summer. Generally Dinoflagellate blooms reach maximum intensities between August and October, developing mainly in coastal waters.

The Emilia Romagna coastal waters are generally rich in nutrients, the concentration of which is inversely related to salinity. Phosphorus was found to be the limiting factor in 87% of 6038 samples collected during 1978-1984, and its influence on the algal growth has been shown also in laboratory experiments with natural phytoplankton populations.

There are indications that nutrients transported by the river Po cause the generalized enrichment and rapid growth of Diatoms and Dinoflagellates. The growth of these last organisms can also be positively influenced by nutrient salts and organic substances coming from the many small rivers located along the coast.

2.10 Eutrophication in the Coastal Area of the Regione Emilia Romagna

E. Todini & A. Bizzarri (Page 143)

The paper described the results of an international workshop which was organized to assess the feasibility of using mathematical models to analyze the processes of eutrophication in the Emilia Romagna coastal waters, and as a tool for evaluating alternative control procedures.

The four phases of the workshop consisted of:

Familiarization with the problem
Data extraction and punching
Systems analysis to identify sources contributing to the problem
Development of Biological and Hydrodynamic models, and
simplification of these to useful forms.

The workshop focussed on the coastal eutrophication problem, in relation to the river Po delivery and other local inputs. Data was collected on the hydrology of the Po and other rivers, and this was used to compute the relative nutrient (N, P, Si) contributions for the Po and other inputs.

A simple, classical, hydrodynamic coastal water circulation model was constructed, and calibrated by water density measurements.

Two biological models were developed : One Box (relatively simple)
Big Box (more complex)

Within the four week period of the workshop, the One Box model ran successfully to predict phytoplankton blooms in late summer (see paper by J.P. O'Kane). However, attempts to run the more sophisticated Big Box model were unsuccessful, due in part to lack of a suitable data bank oriented towards this problem, and the scattered and sometimes unsatisfactory information available for some parameters (especially sunlight and wind).

2.11 A Simple Model of Eutrophication on the Adriatic Coast - with a Field Experiment to Disprove the Model

J.P. O'Kane (Page 153)

The components of the One Box model were described, with zooplankton, phytoplankton and nutrients as state variables, river flows, temperature and sunlight as forcing functions, and flow of nutrients as the control function.

Mass flow rates of nutrients in the system due to 1) death of zooplankton 2) endogenous respiration of phytoplankton 3) zooplankton excretion and 4) photosynthesis by phytoplankton were modelled by One Box, with allowance being made for the nutrients washed out of the box by the through-flow. The exchange flow was determined from salinity data; exchange of nutrients with the superficial sediments on the bottom of the box was ignored.

Running the model with zero exchange between the box and the outer Adriatic, plus judicious selection of parameter values, could produce algal blooms in June, or two or three blooms between April and August. However, when the exchange flow was calculated from the salinity data and the model run again, the results showed a sharp phytoplankton peak in September-October, which is when Dinoflagellate blooms normally occur in the Emilia Romagna coastal waters. During the peak the residence time was about 35 days, allowing the phytoplankton to grow, whereas at other times of the year, with residence times around 5 days, the phytoplankton were washed out of the box. Zooplankton did not respond rapidly enough to the transient phytoplankton bloom during September and October to control it.

This hypothesis could be tested by a simple field experiment, in which coastal waters are enclosed in large translucent bags. If blooms occur within the bags but not in the surrounding waters, this would be strong evidence to support the hypothesis.

3. WORKING PAPER

Eutrophication in the Mediterranean Sea
Scientific Background for the Preparation of Guidelines for the Assessment of Receiving Capacity for Eutrophying Substances.
J. Stirn (Page 161)

This review paper which was prepared in advance by Unesco Consultant Prof. J. Stirn is included in Part II. The paper is an attempt to cover all the important aspects of eutrophication (man-made and from other sources), and was the basis for much of the discussion which led to the formulation of the 'Provisional Guidelines' and the 'Recommendations' on the monitoring, assessment and control of eutrophication in the Mediterranean Sea.

It was suggested that the paper had oversimplified some of the intricate biochemical transformation processes involved in the eutrophication phenomenon, and that the synergism between bacterial cycles and phytoplankton cycles should be mentioned, in relation to lagoon systems.

The increase in heterotrophic activity as a result of eutrophication needed to be mentioned including the role of particulate matter, settlement and regeneration.

There was considerable discussion on the use of the term 'Limiting Nutrient', since primary productivity is rarely limited by nutrients but rather by other factors, such as light. 'Controlling Nutrient' was suggested as a more appropriate term, although it will be difficult to persuade engineers to change to this, as the concept of phosphorus limitation is so useful.

An important distinction was drawn between

a) Stoichiometric limiting nutrient and

b) Kinetic limiting nutrient or nutrients.

The stoichiometrically limiting nutrient for an alga is that nutrient which exhibits the smallest ratio of concentration in the water surrounding the alga, to concentration in the alga. Clearly, there can be only one limiting nutrient at any given time.

In contrast, a nutrient is kinetically limiting if an increase in its concentration in water stimulates the algal growth rate. Many nutrients may satisfy this criterion at any given time. This definition is the starting point for mathematical models of algal dynamics. In discussions it is important to distinguish between these concepts and their elaboration.

Finally, the need to take physico-hydrodynamic factors into account in nutrient cycling processes was stressed, and it was agreed that a section should be incorporated in the Guideline document to clarify the effects of these physical processes.

4. GUIDELINES FOR THE MONITORING, ASSESSMENT AND CONTROL OF EUTROPHICATION IN THE MEDITERRANEAN SEA (Annex 4)

Following the discussion of the contributed papers, and the review paper on the scientific background for the preparation of guidelines for the assessment of receiving capacity of eutrophying substance, the meeting considered in four working groups the following specific topics: sources of eutrophicants, eutrophication control, modelling, monitoring and assessment of eutrophication. The draft texts produced by these working groups were discussed by all the workshop participants.

After introducing certain modifications and amendments, the meeting agreed on a draft, the edited version of which is presented in Annex 4.

As it was felt at the Workshop that scientific knowledge on certain subjects is insufficient to make final statements, the guidelines as provided by this document are considered to be provisional and should be reviewed and developed as more scientific information becomes available.

The main points made during the discussion of this text are summarized in the following paragraphs.

General

There is an urgent need to develop a clear set of guidelines on eutrophication control in order to be able to advise Governments how they should dispose of their land-based sources of pollution, and how much of their wastes can be disposed of in the sea. The workshop should provide an indication of what monitoring is necessary, which methodologies should be used and what are the special areas of research which should have priority.

The Eutrophication Concept and Definition

It was suggested that a quantitative indication of eutrophication, e.g. concentrations of nutrients, or comparison (e.g., double) with background levels should be given here, but there is not yet sufficient information to specify precisely when Mediterranean coastal waters should be considered as eutrophic. The increasing frequency of significant phytoplankton blooms is perhaps the best indication of the onset of eutrophication. It was agreed to include examples of different types of eutrophication in the guideline document.

The Causes of Eutrophication

Although soluble nutrients are of prime importance in eutrophication, the importance of nutrients bound as organic matter in settleable particulates, readily mineralized by bacterial action should not be overlooked.

- Nutrients. There was some discussion on the concentrations of nitrogen and phosphorus which should be specified as typical for eutrophic waters. The quoted values should be taken as typical of the surface waters, with probably higher values in the bottom water.

- The "Limiting Nutrient". Suggested alternative terms were 'most limiting nutrient' (which would include Silicon), or 'controlling nutrient', but the current term was retained here because of its widespread acceptance.

- Factors Reducing Herbivorous Consumption of Algae. There was considerable discussion on the importance of grazing organisms in controlling phytoplankton blooms. It was generally agreed to be a significant factor, although there are few well documented examples in the marine ecosystem.

Sources of Eutrophying Substances and Estimation of their Inputs

- Sewage It was suggested that it would be useful if some indication was given on the proportion of inputs to the Mediterranean which were raw and treated. However, insufficient information is available to be able to do this at the present time.

- Sources of Nutrients There was comment that this section was not sufficiently specific about what to measure and which methodology to use, but it was agreed that other documents could be referred to for this information.

Monitoring and Assessment of Eutrophication

- Monitoring

  This section of the guidelines was discussed at length. Although only the water column was considered in these guidelines, it was suggested that there ought to be a section on monitoring the benthic domain. However, this aspect is well covered in the FAO/UNEP Manual on Ecological Assessment of Pollution Effects which concentrated on benthic rather than pelagic, methodology, so it was agreed that it was unnecessary to include it here.

The techniques referred to in these provisional guidelines are all simple to perform, although it was strongly held by some participants that more complex measurements, such as the rate of primary production, ought to be incorporated. Although it was suggested that biological aspects such as community changes and diversity ought to be included in monitoring, it was argued that these were not suitable techniques for non-specialists.

Remote Sensing. Reservations were expressed about the inclusion of this technique, on the basis that it is an expensive and rather insensitive method, more appropriate for research than for monitoring. Although it may be useful for showing the extent of river plumes, outfalls, etc., it is certainly difficult to use as a monitoring tool.

Major Variables to be sampled

- Nutrients. It was emphasized that fractioning of samples was important to understand the distribution of N, P and Si in water and solids/sediments, but the significance of dissolved phosphate was stressed, for indicating the potential for eutrophication.

- Dissolved oxygen. The relevance of salinity and temperature to the dissolved oxygen must be considered. It was suggested that this is one of the most useful parameters for indicating areal extent of eutrophication: it is much better to a wide range of surface samples rather than one at several depths - in other words, horizontal is more cost effective than vertical monitoring.

- Turbidity. In spite of the limitations of the Secchi disc this was strongly supported as being a valuable guide to the development of eutrophication phenomena. It was agreed that nephelometry or fluorimetry are more accurate, but often not practical.

Location of sampling sites and frequency of sampling.

The importance of establishing the areal extension of eutrophication (or space-gradients) was emphasized, particularly in long-term monitoring programmes. Rather than only 2 reference stations, it is necessary to have several, some near the source, some in a relatively stable, affected zone, and some in an unaffected zone. The phenomenon of blooming occurs over only a few days, therefore it is necessary to have two types of measurements

1) of eutrophication parameters, e.g. nutrients (always there)

and

2) of algal blooms, by other parameters (e.g. chlorophyll *a*, species composition).

For long-term monitoring a combination of measurements of chlorophyll concentration at the surface and oxygen at depth was suggested, although there is need to clarify the term 'surface', since maximum chlorophyll may be found at depths down to 30 m. Precise decisions should be left for a more formal body.

Environmental Capacity/Mathematical Models

It was suggested that in one or both of these sections Remote Sensing should be mentioned, but since it was included in the Monitoring section, this was not supported. In planning land use, eutrophication of nearby areas is a factor which should be taken into account by the planning agencies. Although this point was not incorporated in the Guideline document, it should be brought to the attention of the relevant authorities.

5. RECOMMENDATIONS (Annex 5)

This document is a result of the deliberations of the workshop participants, intended to enable scientists, policy-makers, international and regional organizations to recognize eutrophication problems, and to take action to control them.

Most of the statements were unanimously agreed by the participants, and points of detail only were discussed.

Considerable discussion took place on what should be included in the 'Scientific Research' section. Rather than specify particular topics in the document, it was decided to include a list of objectives. Participants considered that the following additional topics are particularly important:

- Establishment of indicator species.
- Sedimentation rates and transformations of living and non-living particles.
- Relation between flux of organic matter and the structure and dynamics of communities.
- Relationship of eutrophication and fish jelly fish growth, and red tides.

There was also considerable discussion on what should be incorporated in the final section of the recommendation. A strong, positive section was needed, indicating items for immediate action. It was finally agreed that the Modelling section met this requirement and the Recommendations were unanimously approved.

6. CLOSING REMARKS

Professor Ezio Todini thanked Dr. Selim Morcos for his initiative in organizing the workshop.

Dr. S. Morcos thanked the participants for their active contribution to the workshop, and thanked the host institutions, in particular:

- Dr L. Turci, President, Regione Emilia Romagna
- Prof. F. Roversi-Monaco, Rector, University of Bologna
- From the Regione Emilia Romagna, Environmental Department.
  - Mr G. Nespoli, Head
  - Ms. P. Testoni, Administrator
  - Ms. A. Ghetti, Biologist
  - Ms. S. Bologna
- Prof. E. Todini (Chairman), University of Bologna
- Dr L Evison (Rapporteur), University of Newcastle upon Tyne

Dr G.P. Gabrielides, on behalf of FAO/UNEP thanked the participants for accepting the invitation to attend the workshop. He also thanked the Chairman and Rapporteur, and the participants for their contributions to the final Guideline and Recommendation documents.

Before the workshop he had believed that all the information was available to solve the problem, but during the workshop had come to realize that some aspects are still not fully understood and he hoped that future research would fill in these gaps in our knowledge. He suggested that the participants should help by:

1) Bringing the eutrophication problem to the attention of national advisors;

2) Submitting proposals to funding agencies for consideration.

Mr G. Nespoli on behalf of the Regione Emilia Romagna said they had been honoured to host such an important meeting. where so much experience in the field of eutrophication had been gathered together. The Regione Emilia Romagna hope to use the suggestions from the scientific meeting in planning their future actions in control of eutrophication. Already 3000 x 10^9 lire had been spent in reducing effluents from cities, but clearly other actions still need to be taken which may interact heavily with the social and economic life of the Regione. It is extremely important therefore to take the opinions of the scientific world into account.

Prof.E.Todini closed the workshop with a final acknowledgement to Dr.L. Evison (Rapporteur) and Miss M Turner (Secretary) Division of Marine Sciences, UNESCO, Paris.

ANNEX 1

SCIENTIFIC WORKSHOP ON EUTROPHICATION IN THE MEDITERRANEAN SEA :

RECEIVING CAPACITY AND MONITORING OF LONG TERM EFFECTS

Bologna, Italy, 2 to 6 March, 1987

AGENDA AND TIME-TABLE OF THE MEETING

2 March

9.30am - 1.0pm   Opening Session & Presentation of Papers
2.30pm - 6.0pm

A.	Welcoming Address on behalf of UNESCO	S.A. Morcos
	Welcome by Rector of University of Bologna	F. Roversi-Monaco
	Welcome by President of Regione Emilia Romagna	L. Turci
	Welcome on behalf of FAO/UNEP	G.P. Gabrielides
B.	Designation of : Chairman	E. Todini
	Vice Chairman	P. Nival
	Rapporteur	L.M. Evison
C.	Presentation of Contributed Papers and Case Studies	
1.	**Eutrophication in the Pelagic Environment and its Assessment**	A. Cruzado
2.	**Eutrophication - Induced Modification of Benthic Communities**	M. Stachowitsch and A. Avcin
3.	**Medical Aspects of Eutrophication**	M. Aubert and J. Aubert
4.	**Case Study : Golfe du Lion**	D. Bellan-Santini and M. Leveau
5.	**Case Study : Saronikos Bay**	N. Friligos

3 March

9.30am - 1.0pm

6.	**Case Study : Lake of Tunis**	B. Moheiddine
	PRESENTATION OF DRAFT WORKING PAPER Eutrophication in the Mediterranean Sea : Scientific Background for the Preparation of Guidelines on the Assessment of Receiving Capacity for Eutrophying Substances	J. Stirn

2.30pm - 4.0pm Discussion on Draft Guidelines

4.0pm - 6.0pm Working Groups on Specific Sections of Guidelines

4 March

9.30pm - 1.0pm Discussion on Designing a Monitoring Programme for Eutrophication Studies

2.30pm - 8.0pm Special Session : Eutrophication in the North Adriatic and the Coastal Waters of the Regione Emilia Romagna

1.	**Introduction**	R.A. Vollenweider
2.	**Red Tides in the North West Adriatic**	R. Marchetti G.F. Gaggino A. Provini
3.	**Eutrophication Processes the Coastal Area of the Regione Emilia Romagna**	E. Todini A. Bizzarri
4.	**A Simple Model of Eutrophication on the Adriatic Coast - with a Field Experiment to Disprove the Model**	J.P. O'Kane
5.	**Eutrophication Problem in the Northern Adriatic Sea. Total Phosphorus Dispersion Model and Statistical Distribution of Chlorophyll Data : A Methodological Approach**	F. Giovannardi G. Montinari A. Rinaldi

6.	**Northern Adriatic and River Po : In situ Investigations, Modelling and Remote Sensing as a Contribution to the Understanding of Transport Phenomena**	F. Clement P. Franco L. Nykjaer P. Schlittenhardt
7.	**Determination of Phytoplankton Concentration in the Adriatic by Satellite (CZCS, TM)**	B. Sturm S. Tassan
8.	**Circulation of the Emilia-Romagna Coastal Water and its Correlation with Eutrophication Phenomena**	E. Acerboni A. Michelato
9.	**Biostimulation with Algal Natural Populations : Field and Batch Assays**	G.F. Gaggino M. Mingazzini G. Montanari A. Rinaldi
10.	**Considerations on the Modelling of Trophic Processes in Coastal Marine Environments**	B. Cescon

<u>5 March</u>

9.30am - 11.30am	Preparation of Recommendations
11.30am - 2.0pm	Final Discussion on Guideline Sections : Ecological Monitoring and Assessment Sources of Nutrients Analysis and Control Policy Analysis and Modelling Prevention and Control
3.0pm - 5.0pm	Discussion of Recommendations Adoption of Recommendations
5.0pm - 5.30pm	Closing Remarks
6.0pm	Travel to Hotel Romea, Ravenna
8.30pm	Workshop Dinner 'Al Porto', Lido di Ravenna

<u>6 March</u>

8.00am - 10.30am	Visit to Centro Universitario Risorse Biologiche Marine, Cesenatico, and Oceanographic Boat, Daphne,	
	Introduction	R. Viviani
	Guides	A. Rinaldi G. Montanari

ANNEX 2

SCIENTIFIC WORKSHOP ON EUTROPHICATION IN THE MEDITERRANEAN SEA :

RECEIVING CAPACITY AND MONITORING OF LONG TERM EFFECTS

Bologna, Italy, 2 to 6 March, 1987

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ANNEX 3

SCIENTIFIC WORKSHOP ON EUTROPHICATION IN THE MEDITERRANEAN SEA : RECEIVING CAPACITY AND MONITORING OF LONG TERM EFFECTS

Bologna, Italy, 2 to 6 March 1987

WELCOMING ADDRESS

by
Dr. Selim Morcos

Division of Marine Sciences, UNESCO

Signor Presidente della Regione Emilia Romagna,
Rettore Magnifico dell'Universita di Bologna,
Colleagues, Ladies and Gentlemen,

No more than two decades ago, eutrophication was considered by those of us who work in marine sciences, as a problem of freshwater lakes, first in the sense of a slow, natural process of lake-ageing, then as man-made overfertilization, leading to excessive algal blooms, followed by anoxias and other harmful consequences. Although there was evidence of this in similar developments in the Baltic Sea, as well as early warnings of eutrophication cases in the Mediterranean, we were generally inclined to consider any eutrophic state in the seas and oceans in a positive sense. Such an attitude is indeed understandable since large scale natural fertilizations of surface waters, as a result of the upwelling phenomena or river discharges, means also an enhanced coastal and oceanic bioproductivity, and hence the wealth of exploitable living resources. Actually, we have been much more concerned with the "poverty" rather than the "richness" of nutrients in the marine environment, searching even for artificial means to enrich the oligotrophic areas, which are typically found in the Mediterranean Sea.

The Mediterranean is, in fact, characterized by relatively low concentrations of nutrients in deep waters, rather weak vertical circulations and in general, narrow shelves which all combine to make this sea one of the most nutrient-depleted basins of the world oceans. This is manifested by an oligotrophic pelagic environment and its extremely transparent water of a bright azure colour, which gives the famous beauty of "mare nostrum". As we all know, this beauty no longer presents just an abstract aesthetic value; it is now the very attraction of millions of tourists who are contributing substantially to the national economies of Mediterranean countries. Therefore, keeping the Mediterranean Sea oligotrophic, i.e. preventing eutrophication, means not only the preservation of our natural heritage, but also the economically justified protection of an important natural resource.

There is a considerable number of references showing a steady increase in the number of localized cases of eutrophication which usually leads to various harmful effects. As will be presented by this workshop, eutrophication unfortunately affects quite large areas too; the most critical being the North Adriatic where it became a real hindrance, both to tourism and to fisheries.

Yet, as regards fisheries, the attitude towards eutrophication among those interested in living resources tends to be quite different. They are well aware that the bulk of catches from the Mediterranean Sea originates from naturally and/or anthropogenically eutrophied areas, such as the above mentioned North Adriatic, the Alboran Sea and the 'Golfe de Lion'; hence they may still consider eutrophication from a positive angle. However, recalling the lessons learned in the North Adriatic, where heavy "blooms" and "red tides" are followed by anoxic and toxic conditions, leading to massive fish and invertebrate mortality, the prevention and control of eutrophication must therefore be considered as an imperative task, regardless of which point of view one is dealing with.

It is needless to stress that to do this the requirements are quite demanding, both materially as well as in the sense of "know-how". Therefore, the very purpose of this workshop is to agree, within the limits of the current available knowledge, on guidelines that will enable the Mediterranean countries to take appropriate decisions regarding the eutrophication problem.

As you know, this meeting is one of the main activities under MED POL Phase II of the Mediterranean Action Plan, and is the result of close co-operation between UNESCO, FAO, IOC and UNEP on matters related to the marine environment in the Mediterranean. The main objective of the meeting is to agree on "Guidelines for the Assessment of Receiving Capacity for Eutrophying Substances and for the Monitoring of Long Term Trends of Eutrophication in the Mediterranean". We hope these guidelines will lay the groundwork for effective co-operation in both the scientific and management domains required to protect the coastal environment of the Mediterranean from the negative effects of eutrophication.

To this goal, the Regione Emilia Romagna has a great commitment and a pioneering role. In August 1985, some of us had the opportunity to attend, here in Bologna, an International Workshop on Red-Algal Blooming in the Adriatic Sea. Our meeting today benefits also from the great moral and financial support of both the Regione Emilia Romagna and the University of Bologna, who are co-sponsors of this activity along with UNESCO, FAO and UNEP. On behalf of the three U.N. organizations, I should like to extend my sincere thanks to our hosts for their generous support to this scientific activity, which we hope will be a step towards the safeguard of the Mediterranean environment.

Finally, let me wish you all a successful meeting and a very pleasant stay in Bologna and Ravenna.

Thank you.

ANNEX 4

SCIENTIFIC WORKSHOP ON EUTROPHICATION IN THE MEDITERRANEAN SEA :

RECEIVING CAPACITY AND MONITORING OF LONG TERM EFFECTS

BOLOGNA, ITALY, 2 to 6 MARCH 1987

GUIDELINES FOR MONITORING, ASSESSMENT AND CONTROL OF EUTROPHICATION IN THE MEDITERRANEAN SEA

The "Scientific Workshop on Eutrophication in the Mediterranean Sea-Receiving Capacity and Scientific Monitoring of Long-term Effects" was convened by UNESCO, UNEP, FAO and the Regione Emilia Romagna in the framework of the Long-term Programme for Pollution Monitoring and Research in the Mediterranean (MED POL Phase II) and was held in Bologna, Italy, from 2 to 6 March 1987 at the kind invitation of the Regione Emilia Romagna.

On the basis of the scientific papers presented at the meeting, and the ensuing discussions and deliberations, the following guidelines for monitoring, assessment and control of eutrophication the Mediterranean Sea were adopted.

1. The Eutrophication Concept and Definition

Ecologically speaking, and in the broadest sense, eutrophication means a substantially increased trophic level beyond the prevailing conditions in a given ecosystem, due to an unusually rich supply of nutrients in the euphotic layer. Under natural conditions this is usually induced by upwellings and river discharges (provided they are not polluted, which is rarely the case), hence the consequence is natural eutrophication. Anthropogenic (cultural or man-made) eutrophication refers to the same process, but is a consequence of pollution by sewage and related biodegradable effluents, agricultural fertilizers and polluted atmosphere; often these pollutants are combined in rivers with natural background loads of nutrients. Considering the conceptual views on natural versus anthropogenic eutrophication, one could logically conclude that since there is no significant difference between the final effects of both processes, the concepts should be similar. However, elementary ecological analysis shows a dramatic difference which is essentially related to time-controlled developments:

- Natural eutrophication is a relatively slow process (time scale 10^3-10^4 years) that allows evolutionary ecosystem adaptations to elevated trophic conditions.

- Anthropogenic eutrophication introduces sudden changes (time scale 10 years or less) and hence non-compensated ecosystem disequilibria, a stressed environment and possible substantial harm to living resources.

2. The Causes of Eutrophication

From the standpoint of control of anthropogenic eutrophication, it is appropriate to restrict this subject to those factors which society is able to control, at least indirectly. Therefore the natural causes of marine bioproductivity and related processes are not considered here, although they are primarily controlled by natural components*: light, temperature, stability, disposition and dynamics of water masses, autochthonous nutrient pools and deposition and/or recycling conditions, structure and efficiency of trophic chains, etc. As shown in the enclosed schematic presentation of the factors involved in the eutrophication processes (Figs. 1 and 2), in principle any change in factors and their interrelationships may have a causative response. However, since the practical target of eutrophication control is the reduction of excessive primary production, priority is given here, pragmatically, to consideration of the following relevant factors:

- Nutrients

Unlike terrestrial and to some extent fresh-water plants which may be limited in growth and reproduction due to a short supply of and of the essential bioelements (C, H, O, N, S, Si, P, Mg, K and Ca), marine algae are normally exposed to an adequate supply of most elements, except for N, P and Si compounds, i.e., the nutrients sensu stricto. As a rule, silicon may become limiting only for diatoms, and then only towards the end of heavy spring blooms; in contrast the supplies of phosphorus and nitrogen are always of critical importance.

Phosphorus appears in the marine environment in particulate, colloidal and dissolved inorganic and organic forms. Orthophosphate is the form preferred by algae, yet the ability to utilize other forms, such as polyphosphates and dissolved organic phosphorus, seems to be widespread. Hence, in polluted environments, organic phosphorus and polyphosphates from detergents may support the growth of algae when orthophosphate concentrations have been reduced. Generally, the concentrations of phosphorus in surface waters of the Mediterranean Sea are extremely low: expressed as values for orthophosphate,

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* Some of them can be modified by man directly or via eutrophication-induced changes, e.g., locally increased temperature by heated effluents, reduced depths of euphotic layers due to mineral turbidity or shading by blooming phytoplankton, modified trophic chains, etc.

0.03 μmol. dm^{-3} P-PO_4 or less; typical concentrations for eutrophic coastal waters are above 0.15 and for highly eutrophied systems, well beyond 0.30 μmol. dm^{-3}.

The most abundant form of nitrogen in sea water is dissolved molecular gas (N_2) which occurs in concentrations almost tenfold the sum of particulate and dissolved inorganic nitrogen compounds. However it does not enter biological processes, except by nitrogen fixation in bacteria and some blue green algae. In principle ammonium salts are the form of nitrogen preferred by algae, and only when ammonium concentrations are depleted to < 0.15 μmol.dm^3 will nitrate and nitrite be utilized. However, there is a large body of literature providing experimental evidence for partial or sole utilization of various organic nitrogen compounds such as urea and amino-acids as the source of nitrogen for the algal growth, particularly in circumstances where the concentration of inorganic forms is becoming depleted e.g., in "post-bloom" conditions. Obviously this is quite relevant to anthropogenic eutrophication, although very little information is available. Nitrogen in the form of inorganic compounds, is quite depleted in the surface waters of the Mediterranean Sea although not to the same extent as are phosphates. Generally, the concentrations are about 0.1 μmol. dm^{-3} of N-NO_3, 0.5 of N-NH and 0.1 of N-NO_2; in eutrophic waters concentrations are usually increased at least by a factor of 2, and in heavily eutrophied coastal waters by a factor of more than 5; in waters which are directly polluted by sewage or substantially mixed with river discharges, the concentrations are as a rule much higher, i.e., above 35 μmol.dm^{-3} N-NO_3 and 20 μmol. dm^{-3} N-NH_4.

The "limiting nutrient"

Considering the generally oligotrophic nature of the Mediterranean Sea, the decisive role of phosphorus as a limiting factor of pelagic productivity, as suggested by many authors, appears indisputable: the N:P ratio is as a rule significantly higher than the assimilatory optimal (N:P = 15:1), usually above 19:1. For moderately eutrophic waters such as the central and easter parts of the North Adriatic the above appears to be true, however there are indications of bimodal limitations, and experimental evidence also that nitrogen is indeed limiting, at least during the winter season. Highly eutrophic waters, regardless of whether they are fertilized by rivers or man-made effluents, are fairly steadily receiving phosphorus inputs at levels approaching the optimum for growth of mixed phytoplankton at a eutrophic level (i.e. above 0.3 - 0.5 μmol. dm^{-3} P-PO_4). It would appear logical that under such conditions nitrogen might be the prevailing limiting factor; however this has apparently never been experimentally proved in the Mediterranean, although widely known for other marine environments. More research is required in order to understand and apply the limiting concept adequately, as it may be misleading if used rigidly in systems that are not in a steady state - and eutrophied marine ecosystems are not.

Biomicroelements

There are a number of microelements essential to the growth of marine algae. The total concentration of individual micro-elements is unlikely to limit phytoplankton growth, but an essential element may be present in a form which is not assimilable by the organisms. This is particularly true for iron which has a very low ionic concentration, although algae are able to make use of some particulate and colloidal forms, provided there is a chelating mechanism active in the surrounding sea water. Oceanic and open coastal waters contain quite a variety of natural chelating substances whose chemical identity is still obscure. Also present are "classic" ligands of humic-complex compounds (Gelbstoff) which have an autochthonous marine origin. Similar material also reaches the coastal waters from discharging rivers, estuarine-lagoon marshes, and from digested sewage as well as other biodegradable organic effluents. Phytoplankton growth, even in cases of highly eutrophic conditions of coastal waters or during moderate diatom blooms, does not appear to be significantly limited by reduced availability of trace elements, in particular Fe. In the case of Fe, much evidence exists that its availability may trigger the development of the true, i.e., dinoflagellate "red tides", acting as a complementary factor to the basic requirements of high concentrations in the N/P nutrient pool. A parallel function of chelating substances in "red tide" development is the detoxication of free copper ions which would otherwise be present in estuarine and polluted coastal water at concentrations high enough to inhibit dinoflagellate growth.

Organic Stimulants of Algal Growth*

It has been known for many decades that even when algal cultures are supplied with nutrients and biomicroelements, growth will often not take place unless trace amounts of specific organic compounds are present; similar observations have been made for phytoplankton in natural conditions.

The most extensively investigated in this respect are the vitamins: thiamine (B_1), cobalamine (B_{12}) and biotin. It is well known that, for efficient growth, practically all marine flagellate algae require exogenous supplies of one or more vitamins; certain diatoms also show similar requirements, among them species responsible for heavy diatom "blooms", e.g. *Skeletonema costatum* requirement for B_{12}. Although these vitamins are produced by microorganisms and through autolysis and decomposition in normal marine environments, the major input seems to be from estuaries, marshes and land-based sources, and in particular from sewage.

Sewage, and probably also similar biodegradable waste materials, present a source of a great variety of organic compounds some of which appear to have stimulatory effect on algal growth. As a

* For review and details see: M. and J. Aubert, 1986. Eutrophie et dystrophie en milieu marin, *R.I.O.M.*, Nice, 84, p.302.

rule, the organic stimulants show biological activities which are quite similar to those of phytohormones, e.g., auxins, yet their chemical identity remains unknown; it was proved, however, that these are substances of a relatively low molecular weight, i.e. < 30,000.

Biostimulants probably do not significantly influence the overall primary productivity in normal marine environments, yet they and the contrasting bioinhibitors* may critically control the species compositions and the temporal successions of phytoplankton generally, and particularly the space-time patterns of "blooms".

Experimental evidence exists that biostimulants control the growth of high-density populations of just those species which are responsible for the most massive and long-lasting blooms in heavily polluted coastal environments, e.g., Lake of Tunis, such as *Nannochloris*, *Stichococcus*, *Eutreptia* and "naked" dinoflagellate species.

- Factors Reducing Herbivorous Consumption of Algae

"Hyperproduction"** and an "excessive biomass"** of algae is a focal problem of anthropogenic eutrophication basically caused by substantially increased inputs of eutrophying substances as described above.

However, an "excessive biomass" may also develop in a less eutrophic system with moderate primary productivity, yet with significantly reduced rates of herbivorous feeding, i.e., due to reduced populations of herbivorous zooplankters (copepods, cladocerans, etc.) and benthic herbivores polychaetes, gastropods, crustacea echinoderms and fishes), suspension-feeders (mainly pelecypods, ascidians, serpulids and sponges) and deposit-feeders (polychaetes, pelecypods). In principle, the following man-made impacts may lead to significant reductions in populations of consumers, i.e., secondary producers;

- Acute and/or sublethal toxicity of coastal waters due to industrial or domestic effluents which contain active levels of toxic metals, detergents, pesticides, phenols, ammonia, H_2S, etc.

- "Mechanical" destruction of respiratory-filtering organs of filter-feeders by consistently elevated concentrations of dispersed mineral particles or by temporary but massive siltings due to dredgings, coastal engineering works, etc.

- Destruction of inshore or bottom hard substrata for sedentary filter-feeders by the above activities or due to oil spills and chronic shore-based oil pollution.

- Damage or destruction of benthic herbivores and filter-feeders by fisheries operations, particularly by shellfish dredgers.

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* Mainly extrametabolites of algae.

**This terminology has a relative meaning, i.e., as compared to the typically oligotrophic ecosystem of the Mediterranean.

3. Appearance and Effects of Anthropogenic Eutrophication in the Mediterranean Sea

Weak exchange of water masses with adjacent oceans and seas, a narrow shelf, great mean depth, lack of strong vertical circulation and very poor nutrient reserves in deep waters make the Mediterranean Sea an extraordinarily nutrient-depleted, hence oligotrophic sea. Measuring the trophic state simply by phytoplankton standing stocks, the typical concentration of chlorophyll *a* is usually below 0.5 μg. dm^{-3}, and phytoplankton densities range between 10^4 - 10^5 cells. dm^{-3}.

3.1 Moderate Inshore Eutrophication

This is the most common form, which can be currently seen almost everywhere along the Mediterranean shores adjacent to urban agglomerations and tourist resorts. Locally, the trophic level is elevated overall; in the pelagic zone this is difficult to distinguish from natural fluctuations, but at the shore the modifications are quite evident by dominating nitrophilic vegetation of green macroalgae (*Ulva* and *Enteromorpha*).

3.2 Localized Heavily Eutrophied Systems

In an increasing number of lagoons, semi-enclosed bays and larger port areas, continuous inputs and poor flushing conditions induce full eutrophication development; this more or less follows the stages shown in Figs. 1 and 2. For further information on the bacterial cycles, and their interaction with phytoplankton, see paper by M. Aubert & J. Aubert, this Workshop. In semi-enclosed bays (e.g., the Saronikos Bay; for details see the paper by N. Friligos, this Workshop) overall trophic levels are increased - chlorophyll *a* 0.5 - 1.0 $\mu g.dm^{-3}$, phytoplankton 10^5 - 10^7 cells.dm^{-3}. A second example of this type is the Kastela Bay in the middle Adriatic, where the development of eutrophication has been monitored for 35 years, primary productivity has reached 244 g $Cm^{-2}y^{-1}$, numbers of phytoplankton reach 10^7 cells.dm^{-3} and red tides and mass mortalities now regularly occur*.

The Lake of Tunis is an example of a heavily polluted lagoon (see UNESCO Rep. Mar.Sci. 1983, 1984 and the contribution by M. Belkhir, this Workshop). In such extremely trophied systems chlorophyll *a* concentrations exceed 100 $\mu g.d^{-3}$ and phytoplankton densities reach a level of 10^7 cells.dm^{-3}. As a rule, such systems regularly or sporadically suffer anoxic conditions and subsequent mass mortalities, leading to completely modified benthic communities.

3.3 Extensive Eutrophication

There are two large areas of the Mediterranean Sea in which trophic levels are elevated due to combined nutrient inputs from rivers and man-made effluents: the Golfe du Lion to some extent

*Purcher-Petkovic, T. & I. Marasovic (1980) *Acta-Adria* vol.21 (2) p.79-93 Marasovic, I. & I. Vukadin (1982) *Biljeske*-Notes vol.48 p.1-7.

and the North Adriatic. This latter shows a quite drastic eutrophication phenomena, particularly in the western part, under the direct influence of the Po and a number of smaller rivers. Both cases are considered in detail in pertinent papers of the Workshop (D. Bellan-Santini and M. Leveau; R.Marchetti et al.; E.Todini and A. Bizzari). The example of the North Adriatic shows an elevated trophic level throughout with typical chlorophyll *a* concentrations above 1 $\mu g.dm^{-3}$, an increasing frequency of atypical summer "blooms" with phytoplankton densities of 10^7 $cells.dm^{-3}$, anoxic conditions and benthic mass mortalities (see papers by M. Stachowitsch and A. Avčin, and by J. Stirn, this Workshop). However, in the western part, particularly along the shores of Emilia-Romagna, successions of heavy blooms (chlorophyll *a* above 50 $\mu g.dm^{-3}$, algal densities 10^7 - 10^8 $cells.dm^{-3}$), anoxic conditions and mass-mortalities have become a chronic phenomenon during the last decade, affecting both tourism and fisheries.

Linking the views from purely ecological standpoints with the practical targets of beneficial uses, and considering the immediate effects as well as the long term effects, it is suggested that any degree of anthropogenic eutrophication which is considered as being, in principle, harmful to the ecosystem, will probably also be harmful to its beneficial uses. The only exception from the above principle would be a controlled eutrophication employed in aquaculture or a similar enhancement of marine food production. In addition to subtle ecological effects of eutrophication, there are a number of harmful impacts related to beneficial uses, namely:

- The reduction of tourist-recreational value of coastal waters due to reduced transparency, changes in the colour of sea water, phytoplankton blooms and related mucus production, modified shore communities etc.

- Health effects of algal toxic extrametabolites, directly or by accumulation in sea-food organisms.

- The loss of fisheries resources, mainly as:
  - mass mortalities of demersal fish and invertebrates,
  - reduced or collapsed recruitment of inshore, estuarine and tidal lagoon fish,
  - hindrance of aquaculture and/or impairing the quality of its products.

4. Sources of Eutrophying Substances and Estimation of their Inputs

Generally, the sources of these substances, chiefly as nutrients, are as follows:

4.1 Atmosphere

Considering the cycling of phosphorus, the atmosphere plays a minor although not negligible role, contributing to the ocean roughly 1 - 2% of the total input, i.e., about 5 $mg. yr^{-1}.m^{-2}$ of sea surface, and probably significantly more in coastal areas close to large industrial agglomerations. The atmospheric input of nitrogen compounds other than N gas that ultimately enter the nutrient pool in rain (NO_2, N_2O, NH_3, and ionic NH_4 and NO_3)is almost tenfold higher (8 - 18%). The amounts of nitrogen oxides are significantly higher in areas of heavy atmospheric pollution (urban-industrialized areas) and high levels of ammonia may also occur, evaporating from highly fertilized agricultural land. Typical concentrations of nutrient-forms of phosphorus and nitrogen in rain waters are 0.08 and 0.7 mg. dm^{-3}, respectively.

4.2 Rivers and Runoff from Catchment Areas

Although there are almost no rivers entering Mediterranean coastal waters that can be considered as "clean", it is appropriate to mention their typical natural background concentrations of nutrients:* 0.01 - 0.05 mg.dm^{-3} P-PO_4 and 0.1 - 0.6 mg.dm^{-3} N (mainly as nitrate). Taking the Adriatic Sea as an example, where river-borne inputs are estimated at 79,000 tons $year^{-1}$ of phosphorus and 250,000 tons $year^{-1}$ of nitrogen, the natural input of phosphorus would thus present 8% and that of nitrogen up to 30% of the total.

Since in the majority of cases the lower flows of rivers collect practically the total runoff from intensively fertilized agricultural land, drainage and domestic effluents from urban agglomerations, and a great variety of industrial effluents, the levels of nutrients in rivers are of course drastically increased.

4.3 Sewage

This abundant effluent is no longer composed just of human excreta for it is invariably mixed with other diverse waste materials, and particularly with detergents which cause a significant increase in concentrations of phosphorus resulting in an N/P ratio of about 4:1. Typical nutrient compositions for various types of sewage effluents are shown in the table below.

TYPE OF EFFLUENT	Nutrient Concentration mg.dm^{-3} of N, P			
	N_{tot}	NH_4	NO_2+NO_3	P_{tot}
Raw Sewage	45	25	7	9
Primary Treatment	31	15	7	6
Secondary Treatment	25	2	13	6
Oxidation Ponds	11	7	1	6
PO_4-Precipitation	23	2	13	2

* This refers to the upper flows of alpine rivers; concentrations in karstic rivers might be even lower.

4.4 Industrial Effluents

Some inorganic and most organic industrial effluents can contribute considerable amounts of nutrients. However, in the Mediterranean region the majority of these loads are carried by rivers, so "point" sources along the coastal zones usually contribute less than 5% of total N/P loads.

4.5 Sources of Organic Algal Growth-Promoting Substances

As mentioned previously these substances are produced mainly in aquatic environments with intense bacterial activities, especially where there are significant masses of dead organic matter, e.g., in biological treatment plants, swamps, marshes, lagoons and estuaries. Outlets from such locations are major sources of these substances for coastal waters, the most important being river deltas and estuaries.

4.6 Sources of Nutrients

In considering sources of particular nutrients, a major distinction must be drawn between point and distributed sources. Inputs from domestic sewage effluents and industrial effluents are major point sources, while atmospheric inputs, and inputs from agricultural practices within contributing catchment areas and from sediments may be classed as distributed sources. The magnitudes of the loadings from these different sources will be a function of geographical location along the Mediterranean coast. River loadings for 10 geographical areas in the Mediterranean* range from 42 - 93% of the total load for P and 38 - 91% for N. In northern parts of the Mediterranean where the major, densely populated and highly developed river basins occur, it is estimated that point sewage loadings to coastal waters account for only 5% of total N and P, while for arid and less developed areas, the estimated figures are 12% for P and 25% for N. Since the loadings of nutrients from rivers derive from both point and distributed sources, it is difficult to quantify the overall contribution from sewage in total nutrient discharges into coastal waters.

4.6.1 Estimating Inputs from Distributed Sources

Agricultural practices represent the most important distributed sources of nutrients, and loadings will reflect these practices as well as the hydrological conditions prevailing in the contributing catchment areas. Loadings from surface runoff events are transient in nature and are related to flow rates as well as to pre-storm antecedent conditions (e.g., lengths of preceding dry periods). These pollution episodes sometimes appear to play a role in triggering major eutrophication events, making it necessary to try to quantify the transient loadings of nutrients which they generate, as well as the total loads of N and P deriving from distributed sources over longer periods of up to a

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* From UNEP, 1978. *Pollutants from land-based sources in the Mediterranean.*

year or more. Within contributing catchment areas, it is frequently found that continuous measurements of concentrations of nutrients such as nitrate and phosphate are not available, and that only spot measurements at various points in time have been taken. However, measurements of catchment outflow are generally available on a continuous (e.g., daily) basis and so a relationship (e.g., a simple linear or non-linear regression) can be sought between nutrient load or concentration and flow rate (and, possibly, a measure of antecedent conditions). Such a relationship can then be used to estimate nutrient loadings over time. Loadings from domestic sewage and industrial effluents will be included in the estimated loadings. In cases where domestic sewage loadings reflect tourist activity, loadings from these sources will exhibit a peak in the high tourist season.

4.6.2 Estimating Inputs from Point Sources

In attempting to identify nutrient loadings from different sources, the estimation of loadings from point sources is, in principle, straightforward. However, monitoring of effluent discharges from domestic and industrial sources is not always undertaken, therefore indirect estimation may be necessary. For domestic sewage, estimation of loadings will be a function of population and of the level of treatment; typical nutrient concentrations are given in the table above (Section 4.3). For industrial effluent, loadings will reflect the sizes and nature of industrial undertakings.

4.7 Distinction Between Analysis and Control of Nutrient Loadings

In quantifying nutrient loadings for an existing system with associated policies for the disposal of effluents from point (e.g., domestic, industrial) and distributed (rearing of livestock, arable farming) sources, the historical data may be analyzed as described above to quantify the total loadings. If it becomes necessary to explore the impact of different policies for controlling loadings deriving from different sources within the contributing catchment areas and along the coast, then the individual sources (both point and distributed) of nutrient loadings must be quantified. This is relatively straightforward for point sources along the coast, but loadings within the contributing catchment areas must be associated with each different source (point and distributed) at the appropriate spatial location within the catchment.

5. Monitoring and Assessment of Eutrophication

5.1 Monitoring

In the pelagic domain, monitoring of eutrophication should be relatively straightforward. The only difficulty may be in finding the most cost-effective strategy. Two major strategies are available, namely remote sensing and direct measurements in the field.

a) Remote sensing

Remote sensing may be successfully employed when eutrophication extends over large areas such as the northern Adriatic Sea. Although the satellite operated Coastal Zone Color Scanner (CZCS) has been terminated, the possibility of using LANDSAT's thematic mapper or SPOT's sensors still exists: their low sensitivity is overcome by the high chlorophyll content of the upper layers of the eutrophic areas. Another possibility is the use of airborne spectral scanners or even aerial photographs to monitor the extent of eutrophication.

b) Direct measurements made in the field

No single analytical tool is adequate to measure the degree of eutrophication of a given body of water. Instead, most experts believe the best approach is to measure many different parameters and to synthesize the results into a general model providing an overall, somewhat integrated degree of eutrophication for the water. Unless proper selection of the parameters to be measured is made, the amount of work required to assess the extent and intensity of eutrophication may be rather costly.

Much in the same way that the information provided by remote sensors on the surface layer is used to evaluate the entire water column, direct measurement of surface variables may be used to infer what is happening at deeper layers. However, subsurface and near bottom waters should also be monitored, particularly in relation to monitoring of the benthic domain.

Direct observations by SCUBA or underwater TV can also be very useful in detecting changes in benthic populations, especially in the early stages of deterioration.

5.1.1 Major variables to be sampled

Various parameters such as suspended solids, light penetration, chlorophyll, dissolved oxygen, nutrients, organic matter, etc. may be determined either at the surface or at various depths.

If only limited means are available, determination of those parameters that synthesize the most information should be retained. Chlorophyll determinations for example, although not very precise representations of the system, are data which provide a great deal of information. Reliable data on nutrients are extremely useful indicators of potential eutrophication. Turbidity and water colour may also be a good measure of eutrophication, except near the mouths of rivers where inert suspended solids may be extremely abundant. Dissolved oxygen is one parameter that integrates much information on the processes involved in eutrophication, provided it is measured near the bottom or, at least, below the euphotic zone where an oxycline usually appears.

- Nutrients

  The concentrations of plant nutrients reflect the balance between a large number of physical and biotic processes. Therefore nutrient concentrations (N, P, Si) in every form (organic, inorganic, dissolved, particulate) should be determined. Although phosphorus has been the most popular nutrient determined in fresh water systems, there are good reasons to believe that nitrogen in any of it forms may play a more important role in most, though not all, marine systems. Silicate is a good indicator of fresh water dispersion and of the potential for diatom blooms.

- Bacteria

  It is suggested to monitor the total aerobic, and possibly anaerobic, bacterial count using sampling opportunities of sanitary monitoring programmes.

- Standing crop of algae

  Volume or dry weight of plankton in a vertical haul of a plankton net from bottom to surface can provide an estimate of potential grazing intensity by mesoplankton.

- Dissolved oxygen

  One of the more frequently used parameters for assessing the eutrophication of water bodies is the oxygen concentration in the lower layers. Oxygen depletion in the lower layers, particularly when there is a strong stratification, is probably the most widely used index that distinguishes between eutrophic and oligotrophic waters. The rate of depletion of oxygen from the lower layers depends, of course, to a large degree on the hydrodynamics of the region.

- Turbidity

  Light penetration, an inverse function of water turbidity, is one of the most widely used measurements in aquatic monitoring. If possible a light profile should be determined, or at least a Secchi disk reading must be taken. Although sometimes criticized because of its simplicity, the Secchi disk is an important tool in marine studies on eutrophication, and the determination of water colour (Forell scale) is also important.

5.1.2 Sampling and analytical techniques

Sophisticated instrumental techniques exist for the automatic measurement of the above variables. Normally however, some of the analyses are carried out in the laboratory, therefore field sampling and sample preservation are required.

Most scientists use fully comparable techniques, some of which have become practical standards. However, an effort should be made to harmonize those sampling and analytical techniques considered to be the minimum required to monitor eutrophication phenomena. This alone can enable comparison of the results obtained by various research groups.

5.1.3 Location of sampling sites and frequency of sampling

The location of the sampling stations should be selected on the basis of previous knowledge of the morphological and hydrodynamic characteristics of the area. Good coverage of the sources of eutrophicants is extremely important, as is the choice of stations. These should cover the full range of environmental conditions from near-shore eutrophic waters to offshore, more oligotrophic waters.

Direct measurement by moving ship of many of the variables previously mentioned, when used in conjunction with computerized date acquisition, allows for a practically real time display of the conditions encountered in the area.

In order to estimate the variation of potential eutrophication, a monthly frequency is recommended. The frequency should be increased during critical periods, which may be identified during sanitary monitoring programmes.

Because of the great variability of the pelagic system, strongly correlated to meteorological changes, bursts of intensive sampling and/or measurements (round the clock) during one day periods, may be preferable to more sparse sampling campaigns.

Monitoring of long-term changes over at least 5 to 10 years is necessary, and must concentrate of selected variables which are easy to estimate. On a long-term scale it is most useful to measure changes in the area in which the surface chlorophyll concentration is above a certain value, and the oxygen concentration in the lower layers is below a certain value.

5.2 Ecological Assessment of Eutrophication - induced Ecosystem Modifications

A significant input of eutrophying substances into the marine environment inevitably induces ecosystem modifications. Therefore, the consequences appear as changes in the ecosystem's energy circuits and food webs, as well as in population dynamics and the structure and diversity of its communities (Fig.1 & 2).

Although any of these ecosystem modifications can be considered as needing a theoretical basis for the ecological assessment of the state and the extent of eutrophication, investigations of community structure and diversity are of primary importance. If properly studied, communities provide records of prevailing environmental conditions over long periods of time and are, in contrast to physico-chemical analyses, relatively insensitive to temporary fluctuations of the environment.

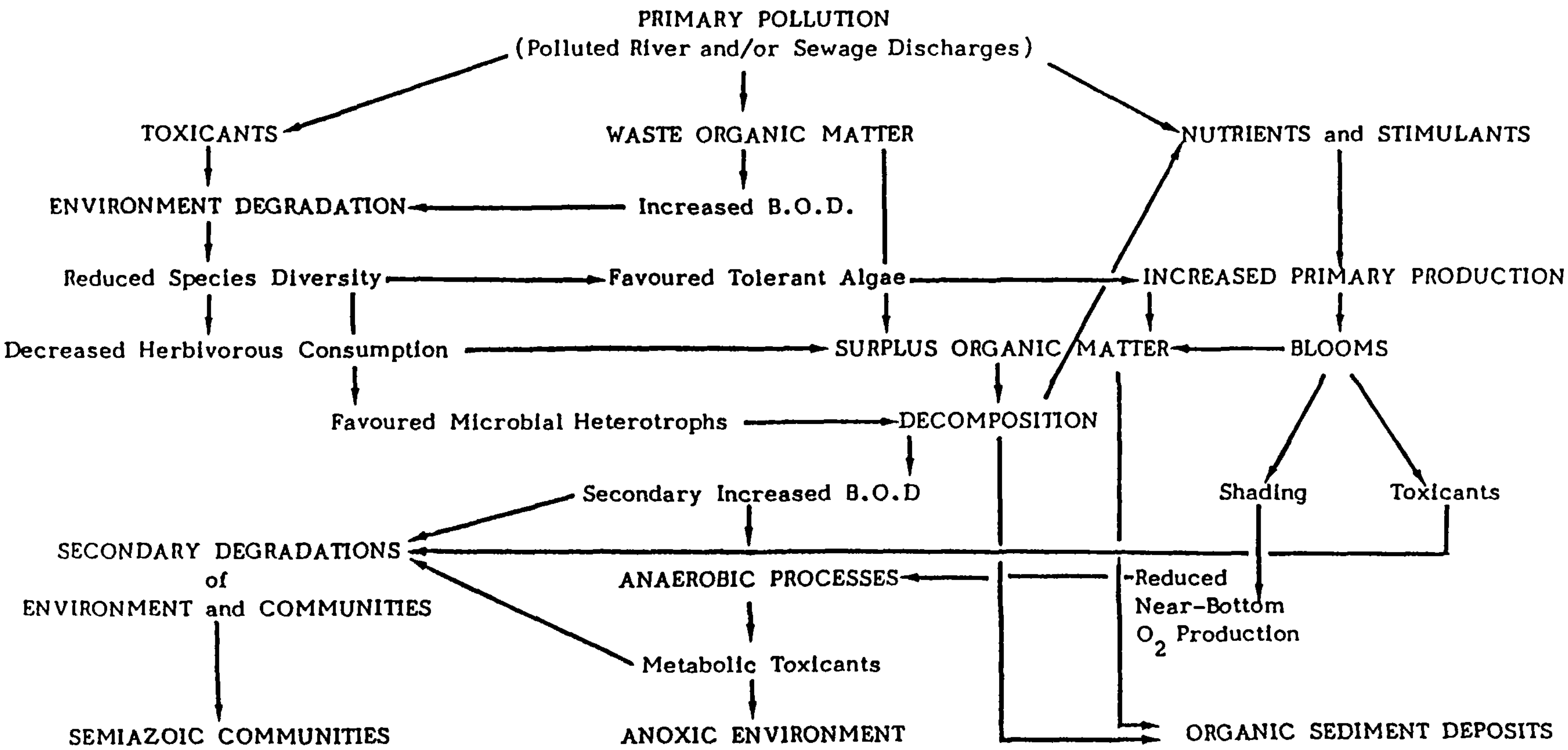

Figure 1 : Schematic presentation of eutrophication processes
From J. Stirn, 1987. Eutrophication Workshop, Bologna

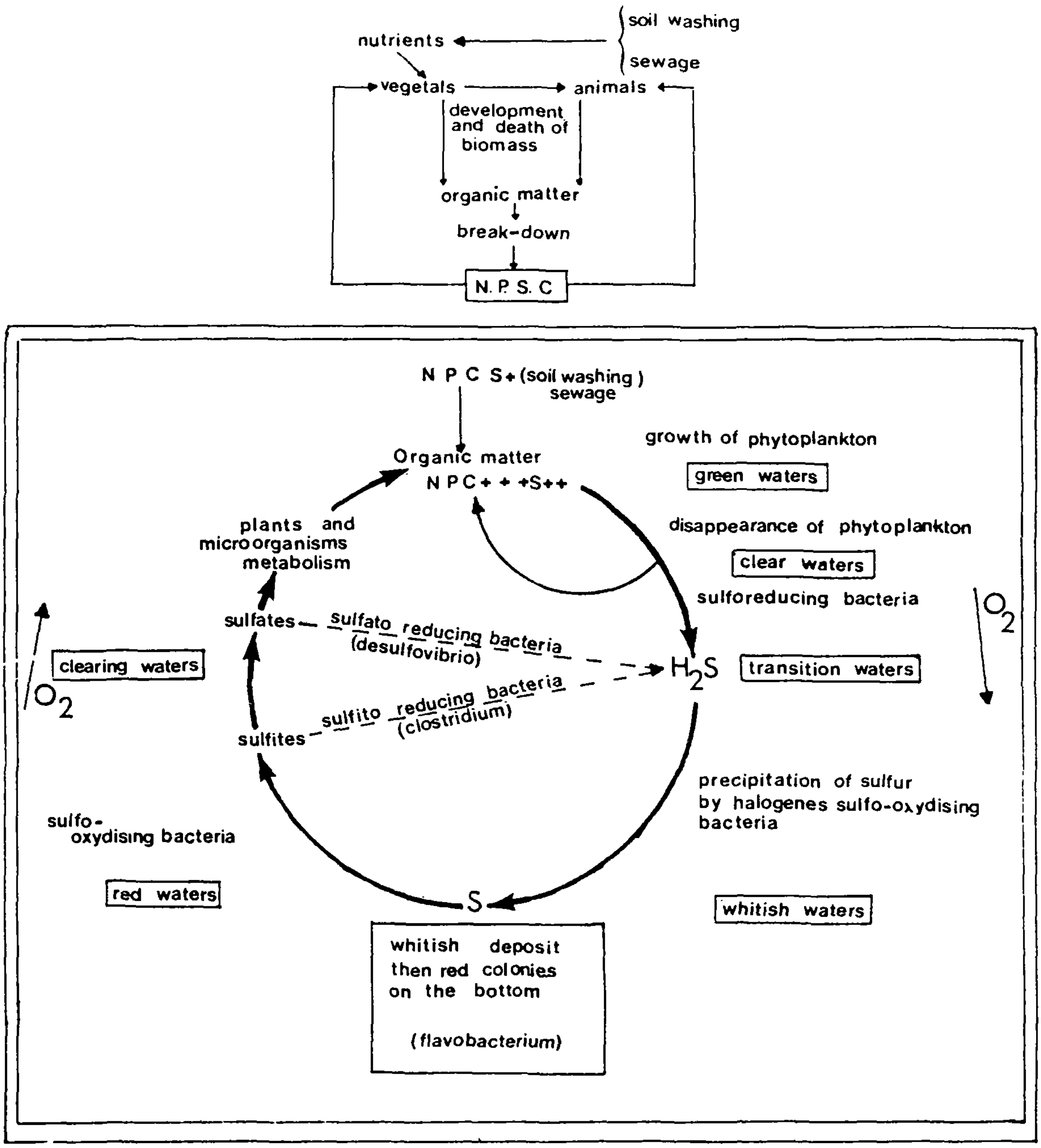

Figure 2 : Schematic presentation of bacterial cycle in eutrophied shallow waters. From M. & J. Aubert, 1986, R.I.O.M. 83-84.

Ecological effects on phytoplankton can be assessed on the community as well as the species level. The following criteria for evaluation of the response of the phytoplankton community to changed in the trophic nature of the marine environment can be applied:

- Indices utilizing population size classes
- Primary production rates
- Species dominance and diversity

The species tolerance to eutrophication may be evaluated by identifying those members of the community that are most sensitive to eutrophication and have suffered essential changes in abundance or seasonality*.

The relative stability of benthic communities in time and space with regard to hierarchical structure makes them suited for the study of eutrophication-induced modifications. Rapid changes in such communities, either with regard to composition or extent, indicate major disturbances. It is recommended to consider several compartments, i.e. micro-, meio- and macrobenthos (in-, epi- and endofauna) in order to assess the magnitude of the disturbances. Studies may be conducted on the species or community level, or ecological aspects such as feeding types may be considered. Indicator species, diversity indices and modelling are suitable approaches for this purpose.

A description of methods and techniques to be applied is available in the UNEP/FAO *Manual on Ecological Assessment of Pollution Effects* (FAO Fish. Techn.Pap. 209, 1981) whose second edition is being updated according to recommendations by the MED POL meeting on the *Effects of Pollution on Marine Ecosystems* (Blanes 1985; FAO Fish.Rep. 352).

6. Policy Analysis and Modelling

6.1 Policy Analysis

Environmental managers seek clear advice on which policies to pursue in managing the problem of eutrophication. Modelling, field data collection, and laboratory and field experimentation have an important role to play in the evaluation of these policies. The results of policy analyses presented to the manager can be regarded, in their simplest form, as a table or score care on a single page which facilitates the complex trade-off which must be made in the making of a decision.

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* For evaluation methods see: Ignatiades et al., 1986. *Oceanol. Acta*, vol.9 (4),p. 449-456.

The score card consists of an array of squares. Each square contains a number or qualitative index, which measures, or scores, the performance, impact, cost or benefit of each policy option under chosen political, economic, social, legal and environmental headings. Models, whether they are socio-economic or ecological mathematical models solved on a computer, or mesocosms in the laboratory are the tools which provide the entries in the score card. Hence, modelling should always be governed by a question to be answered, in this case: what value should be entered in a given square of the score card and what is its uncertainty ?

When there are significant aspects of the eutrophication phenomenon which are not understood (for example, the response of plankton species to a new nutrient control technique) a combined application of mathematical modelling, field data collection, laboratory and field experimentation can be recommended. In this case also, modelling is governed by a question to be answered.

Since models are always a simplification of reality, the question posed guides the simplification. The resulting model is a limited set of working hypotheses to be confronted with laboratory and field experiments which are designed to test them. The qualitative and quantitative comparison of model predictions with field and laboratory data may force a revision of the model, and the emergence of new hypotheses.

6.2 Environmental Capacity

According to the definition given by GESAMP Reports and Studies No. 30, the use of the marine environment for waste disposal should be based on an assessment of the local capacity to accommodate a rate of waste discharge, without unacceptable impacts on the environment. The acceptability of the impact is a subjective judgement which should be reflected in environmental standards set nationally or internationally. From a purely scientific point of view, following again the GESAMP definition of marine pollution, any discharge which has no deleterious effects on the important components of the ecosystem or on the various uses of the marine environment, is acceptable.

Assessment of this capacity must take into account such physical processes as dilution, dispersion, sedimentation and upwelling, as well as chemical, biological and biochemical processes which lead to the degradation or removal from the impacted area of eutrophicants, until they lose their potential for unacceptable impact.

The environment capacity of an area for eutrophicants may be calculated, appropriate models providing a preliminary assessment that can be progressively refined by the inclusion of more parameters and variables and by experimentation.

6.3 Mathematical Models

Mathematical models provide a means for synthesizing available knowledge and for testing control hypotheses.

The models should elucidate the most important factors affecting the ecosystem, and the principle of parsimony should be advocated in order to reduce the large number of physical, chemical and biological state variables to an essential and sufficient number compatible with the questions to be answered.

A careful choice of space and time scales, boundaries and boundary conditions, should be made in relation to the morphology and stratification of the area and the nature of the problem.

Models of eutrophication may be based on the following principles:

- conservation of mass, momentum and energy,
- process kinetics,
- stoichiometry.

From these, a set of simultaneous non-linear differential equations is derived in terms of the chosen state variables. "Process kinetics" provide some of the terms of the right hand sides of the chemical and biological equations, for example, specific growth and death rates of populations of plankton and bacteria. Laboratory and field experimentation is essential for the precise specification of their dependence on forcing functions such as temperature and light. When the model contains several subsystems interconnected by mass flows due, for example, to ingestion and excretion, the stoichiometric conversion factors must also be determined.

Forcing functions such as inflows of nutrient, light, temperature and wind, drive the model. Those forcing functions which are subject to alteration by man are called control variables or functions. Some of the following control variables will always be present in a eutrophication model:

. mass discharge rate of nutrients from point and diffuse sources,
. location of the discharge points,
. harvesting of biomass,
. dredging of nutrient-rich sediments,
. burial of nutrient-rich sediments with inorganic material,
. biocide inputs, etc.

"What-if" experiments can be made with the model in order to support the decisions of the manager. If the chosen control strategy achieves the predicted response, the hypotheses of the model stand. Any disagreement between predicted and observed response of the trophic system necessitates a revision of the model. Clearly, the approach presented here demands the co-operation of many different specialists and provides a focus for it.

7. Eutrophication Control

There is evidence that in some coastal areas of the Mediterranean Sea the inputs of eutrophying substances, particularly phosphorus and nitrogen, exceed the capacity of the receiving environment.

Since the Mediterranean is generally an oligotrophic sea, small sewage discharges on open coastline shores, if properly spaced, can normally be disposed into the sea without extensive treatment, via submarine pipelines with diffuser outlets at an appropriate depth and distance from shore.

For larger discharges or the concentration of several small ones in an area, especially when situated within bays, additional treatment or other measures for reduction of nutrient loads, e.g. reuse of waste waters, recycling in aquaculture, is required.

The type of treatment and disposal design* depends on the overall inputs and environmental receiving capacity. This should be decided on a case-by-case basis, taking into consideration all the loads of existing and planned discharges versus the receiving capacities.

When important loads, carried by rivers and originating from point and distributed sources, overwhelm the point discharges along the shores, the simple control of the latter is not sufficient. In these more complex situations, such as in the North Adriatic, it is essential to add appropriate interventions in order to reduce the inland nutrient loads.

The definition of most appropriate strategies of intervention requires a preliminary cost-effectiveness evaluation, in an overall policy analysis framework, of the role of the different factors which relate to the origin, transport and dispersion of nutrients. The analysis of the point sources (urban and industrial effluents), of the distributed sources (diffuse and linear erosion, fertilizer run-off, etc.), of the transport and diffusion mechanisms, as well as the biological and ecological processes which are driven by the meteorological, hydrological, hydrochemical conditions, is of increasing complexity.

Therefore, the quality management of coastal waters should be derived from an integrated model which will include:

- "point" and "distributed" nutrient sources;
- transport of nutrients;
- hydrodynamics of the coastal waters;
- a description of the ecological and physiological processes triggered by the excessive nutrient loading and the consequent environmental degradation phenomena.

The use of models will allow for the evaluation of the effectiveness of the management policies such as:

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* For pertinent Guidelines etc. see UNEP/WHO, 1982. *Waste Discharge into the Marine Environment*. Pergamon Press, Oxford.

- point source control by means of sewage treatment and disposal;
- distributed source control by means of soil conservation techniques and fertilizer restrictions;
- inland water management;
- improvement of dispersion of nutrients in the coastal waters;
- waste water reuse and recycling in aquaculture.

The fundamental steps in the decision-making processes at the strategic planning and policy level can only be performed through the improvement of knowledge, as obtained by research, assessment and monitoring.

ANNEX 5

RECOMMENDATIONS

The Workshop on Eutrophication in the Mediteranean Sea, meeting in Bologna, Italy, from 2 to 6 March 1987

Considering :

1. that the phenomenon known as eutrophication is affecting, to a greater or lesser extent, many coastal areas all around the Mediterranean Sea, particularly in shallow or land-locked basins,

2. that the causes are the discharge into coastal waters, either directly or through the catchment basins, of substances originating from land, mainly nutrients (phosphorus, nitrogen, etc.) and biodegradable organic matter containing nutrients,

3. that the effects of intense events, even if temporary, often cause massive mortalities of marine organisms due to anoxia and consequent production of toxic H_2S, and a foul smell of the waters and shorelines due to decomposing materials, therefore seriously impairing the legitimate uses of the sea by threatening the living resources, the natural inheritance including genetic resources, and the recreational and aesthetic amenities,

4. that there is ample scientific evidence of the increase in the expanse and intensity of eutrophication in some areas that might also endanger natural equilibria in larger areas of the Mediterranean Sea,

5. that there are nevertheless clear gaps in the scientific knowledge of the important physical, chemical and biological processes which control the intensity of the phenomenon in the various areas.

6. that methods already exist for the abatement of the intensity and extension of the phenomenon through proper policy analysis and the use of legal, technical and other measures envisaged inter alia in the Mediterranean Action Plan,

Having agreed on the "Guidelines for Monitoring, Assessment and Control of Eutrophication in the Mediterranean Sea",

Recommends to the scientific community, the policy-makers and decision-makers, and the concerned international and regional organizations to recognize the importance of the eutrophication phenomenon, and to take immediate action on any preventive and collective measures that may be required to improve the conditions and to combat anthropogenic eutrophication and its adverse effects, by mobilizing the available scientific knowledge and technology,

Further recommends, as a high priority, that adequate support be given to the following aspects relevant to the study and control of eutrophication :

1. Monitoring

Considering that the increasing number of sources and loads of eutrophicants along the coast and in the catchment basins of rivers which discharge into the Mediterranean Sea are making eutrophication a general phenomenon which could in the long term damage extensive areas, the meeting recommends that a monitoring programme be established to keep track of the development of eutrophication in those areas which might be considered as more critical (for example, the estuaries of major rivers and discharges from major cities, whether waste treatment exists or not).

To this goal, the following steps should be taken :

1.1 Prepare a reference manual which includes sampling methods, in situ measurements, and analytical techniques for eutrophicants and parameters which are most relevant to the phenomenon;

1.2 Extend the monitoring component of the Programme for Pollution Monitoring and Research in the Mediterranean (MED POL - Phase II), within the framework of the Mediterranean Action Plan, to cover those areas showing clear signs of eutrophication, to cover the inputs of eutrophicants and those physical, chemical and biological parameters and variables cited in the guidelines (Section 5.2). In establishing this extension, the spatial characteristics of the impacted areas, the ease of assessment, and the appropriateness of the measures taken should be considered;

1.3 The monitoring of and research on eutrophication, which are being carried out or planned, should be mutually supportive and beneficial to each other.

2. Assessment

The ecological assessment of the state and the extent of eutrophication requires an investigation of community structure and diversity, which should consider the different compartments of plankton and benthos, and indicate the activity at different levels : species, populations and communities. as indicated in the guidelines (Section 5.1).

3. Inventory of land-based sources

When producing an inventory of land-based sources of pollution in the Mediterranean Sea, attention should be paid especially to those substances which cause eutrophication and, whenever possible, to the effects they cause around the discharge sites.

4. Scientific research

4.1 It is necessary to complement the monitoring and assessment efforts, and to provide scientific information as required for modelling and control policies, by conducting specific research focussed on the following objectives :

1. Factors controlling eutrophication processes:

2. The structure and function of eutrophic ecosystems and the relevant hydrodynamics, as the basis for the determination of their receiving capacities for eutrophicants;

3. Classification of the stages and degrees of eutrophication on the basis of quantitative parameters;

4. Investigation of the recovery processes in ecosystems that have been modified due to anoxia and mortalities induced by eutrophication;

5. Further development of scientific methods as needed, particularly for the monitoring and ecological assessment programmes.

4.2 As an initial and immediate task, it is strongly recommended to develop and implement, within the framework of MED POL Phase II, an internationally co-ordinated research project on anthropogenic eutrophication cases in the Mediterranean as well as a few non-polluted reference areas.

4.3 It is also recommended that consideration be given by those participating in EUREKA and COST, as well as in other international programmes relevant to the marine environment, to the development and deployment of new instruments and techniques which could contribute to a better knowledge of eutrophication.

5. Policy analysis

It is recommended that the policy analysis of eutrophication be strengthened in order to take account of the complex socio-economic, legal and political factors which influence both the perception of the problem and what should be done about it. Reliance on legal instruments alone, e.g. the protocol on land-based sources of pollution, in some cases may not be an effective means of managing the open-access common-property marine resources of the different parts of the Mediterranean.

6. Modelling

It is recommended that a problem-oriented approach be pursued in addressing particular cases of anthropogenic eutrophication. Mathematical modelling should be used as a means for (1) co-ordinating the work of multidisciplinary teams of physical, chemical and biological specialists in the interpretation of the phenomenon, (2) improving the design and operation of monitoring networks, and (3) testing control techniques. However, mathematical modelling should not be regarded as a substitute for the scientific approach; on the contrary, an integrated programme of data collection, field and laboratory experimentation and modelling which addresses specific and concrete questions is the best way forward.

PART II : SCIENTIFIC PAPERS

EUTROPHICATION IN THE PELAGIC ENVIRONMENT AND ITS ASSESSMENT

by

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EUTROPHICATION IN THE PELAGIC ENVIRONMENT

Eutrophication, usually the result of introducing large amounts of nutrients and/or organic matter into the aquatic enviroment, is a widespread phenomenon in coastal areas and estuaries all around the world. Although concern about this phenomenon usually arises from the fact that it may be anthropogenic, the processes that concur to its existence are fundamentally natural although the end result may be quite far from the natural equilibrium.

Many areas of the worlds oceans are naturally eutrophic due to intense energy input which brings about an elevated fertilization of surface waters. Upwelling, whether coastal or open sea, is one example of a condition which induces natural eutrophication. Many estuaries are eutrophic because of the large amounts of nutrients and organic matter discharged by the rivers. Spring blooms in some temperate seas may have a lot in common with permanently eutrophic areas.

Although the major consequences of eutrophication are observed at the sea bed (high percentage of organic matter in the sediments, anoxia, etc.), the pelagic domain may also be strongly affected by eutrophication. The main features usually encountered are:

- High nutrient concentrations

- High phytoplankton densities

- High densities of herbivores and predators (unless anoxia is permanent)

- High dissolved oxygen concentrations near the surface and low (even anoxic conditions) in waters near the sea bed.

- Presence, at times, of red tides or other such algal blooms

Other less obvious features can also be mentioned, including:

- High concentrations of suspended particulate matter
- High concentrations of dissolved organic matter
- Presence of substances (S^-, CH_4, NO_2^-, etc) not found in oligotrophic or mesotrophic areas, or found in very small amounts.

Whether inorganic nutrients or nutrient-containing organic matter are introduced in the marine environment the result is the enhancement of the cycle

$$CO_2 + \text{nutrients} + \text{light} \xrightarrow[\textit{respiration}]{\textit{photosynthesis}} \text{organic matter} + O_2$$

This cycle works in one direction with photosynthesis and in the other with respiration. Photosynthesis is carried out basically in the pelagic domain by planktonic algae (some green bacteria may also contribute to the process), while respiration is carried out by all organisms whether they are bacteria, plants or animals.

Dissolved nutrients and organic matter will remain in the pelagic domain until taken up by pelagic organisms and included in their own body, or aggregated through biological or physicochemical processes into large particles. In contrast, nutrients and organic matter found in the particulate fraction may sink and thus disappear from the pelagic domain. However, such disappearance may be transitory since they may be resuspended by storms or diffused into the water after biochemical transformations in the bottom sediments.

Allochthonous nutrients and organic matter will thus promote the growth of local populations (autochthonous organic matter) which will then feed a denser ecosystem with more rapid energy transformations.

The oxygen cycle is linked to the carbon/nutrient cycles. Oxygen, as a gas, should in principle be in equilibrium with the atmosphere. However, due to photosynthetic activity, oxygen supersaturation is often observed even in non eutrophic systems. When this occurs, oxygen tends to escape to the atmosphere through the air/sea interface in order that equilibrium can be reestablished.

On the other hand, due to sinking of particulate matter and respiratory activity, oxygen is consumed and may even be totally depleted in the lower layers. Aquatic ecosystems may thus be seen as a bi-lateral machine (Cruzado, 1978):

1. They produce oxygen at the surface which may be evolved to the atmosphere.

2. They consume oxygen in the lower layers which may bring about anoxic conditions at or near the sediments.

These two processes are greatly enhanced in eutrophic ecosystems and it is indeed the dislocation of the above mentioned production cycle that makes eutrophication undesirable from many points of view. In particular, in spite of a greater primary productivity, it may reduce the fish stocks and the amenities through the turbidity of the waters and fouling of the sediments. The area may eventually smell of H_2S and mercaptans.

Caution must be used in assessing the impact on the fish stocks because organic matter (whether autochthonous or allochthonous) may be consumed by organisms entering the area temporarily (even if it is anoxic). This process will certainly increase the food availability to fish populations and therefore their density at the outer boundaries of the eutrophic area.

In very shallow areas, onset of anoxic conditions will be hampered by the stirring due to the wind which may penetrate, under stormy conditions, down to the bottom. However, in waters of greater depths, particularly if the bottom layers have restricted circulation as is the case in some fjords and enclosed seas, large bodies of water may turn anoxic (Black Sea, Baltic Sea, Cariaco Trench, etc.). If deep circulation is not restricted but the extent and intensity of the eutrophication phenomenon is large, minimum oxygen layers develop over large areas of the oceans (Southeast Pacific, Alboran Sea, etc.).

Estimates of the oceanic nitrogen budget indicate that the annual supply of combined nitrogen to the oceans by river run off and by precipitation on the sea surface exceeds the loss by burial in sediments by 10 to 70 x 10^{12} g of N. If a steady state is to be maintained in the sea, this excess nitrogen must be released to the atmosphere (Hattori, 1983). Denitrification appears to be the mechanism by which this is accomplished. In the above estimates, input of combined nitrogen by biological nitrogen fixation is not included. Dissimilatory nitrate reduction not only supports marine life under anoxic or oxygen-depleted conditions but also plays an important role for the balance of combined nitrogen in the sea. Denitrification in coastal and estuarine areas is also the subject of active investigation because of increased eutrophication caused by increase in anthropogenic input.

Introducing eutrophicating materials in the aquatic environment greatly enhances the turnover of the various elements in the ecosystem. Economists have known for years that addition of a given amount of money to a national economy produces a much larger change in the gross national product due to a so-called multiplier effect. The multiplier effect accounts for the fact that the added money cycles through many transactions. A similar multiplier effect occurs when nutrients added to the ocean are cycled between producers and consumers. The multiplier effect is especially pronounced in coastal areas, where recycling from the sediments may be quite efficient (Laws, 1983).

Shallow systems are more complex because of the interactions between the benthos and water column. Our understanding of how changes in N-loading rates affect N cycling in these systems is qualitative at best. Low N-loading rates tend to produce systems in which biomass is dominated by benthic plants and their associated predators, whereas high N-loading rates favour dense plankton concentrations and a benthic community dominated by filter feeders. The pattern of N cycling in these two types of systems differs greatly (Laws, 1983).

MONITORING

Monitoring of eutrophication in the pelagic domain should be relatively straightforward. The only difficulty may be finding the most cost-effective strategy. A number of tools are available, namely remote sensing and direct measurements on the field.

Direct measurements made in the field

There is no one single analytical tool to measure the degree of eutrophication of a given body of water. Instead, most experts feel the best approach is to measure many different parameters and to synthesize the results into a general model which will give an overall degree of eutrophication for the water. However, unless proper selection is made of the parameters to be measured, the amount of work required to assess the extent and intensity of eutrophication may be rather costly. On the other hand, sediment composition being a reflection of the processes that take place in the water column above, it may sometimes be better to monitor the sediments rather than the water itself. However, this topic is dealt with elsewhere in this report.

In spite of the great changes observed in the characteristics of the water layers caused by water movements, monitoring the characteristics of the water is still the most direct way of assessing eutrophication. Various parameters such as suspended solids, light penetration, chlorophyll, dissolved oxygen, nutrients, organic matter, etc. may be determined either at the surface or at various depths.

If only limited means are available, determination of those parameters that synthesize most of the information should be retained. For example Secchi disk or chlorophyll determinations, though not being very precise representations of the system, are parameters which retain a great deal of information. Nutrients (both inorganic and organic, dissolved and particulate) are extremely useful indicators of eutrophication. However, they may not be very meaningful at the outer boundaries where the nutrients are completely taken up by phytoplankton. Turbidity may also be a good measure of eutrophication, except in the neighbourhood of river mouths, where inert suspended solids may be extremely abundant. Instrumental techniques for the measurement of most of these parameters exist allowing very efficient ship operation.

Dissolved nutrients

According to Spencer (1985), the rationale of using plant micro-nutrient data to provide indices of the extent of eutrophication is an extension of some of the practices used in fresh water systems. The quasi-steady state concentrations of the plant micro-nutrients reflect the balance between a large number of physical and biotic processes. Changes in this balance cause a high degree of variability in the records and it is unlikely that systematic changes (trends) can be detected unless they approach a catastrophic magnitude.

Data from the winter months when biotic removal processes are minimal, might be expected to measure the maximum extent of enrichment of the water. However, in open systems such as inshore sea water, the maximum concentrations recorded in winter are not necessarily a good indication of the total quantities of these nutrients which will be available during the spring and summer to support primary production.

Standing crop of algae

Numbers of planktonic algae present may be a good estimate of the current degree of eutrophication. Unfortunately, it is extremely difficult to collect the samples and enumerate and identify the organisms present. Often, the standing crops of phytoplankton in eutrophic areas show high irregularities. The occurrence of algal blooms may indicate possible impacts of anthropogenic inputs on the ecosystem. Algal blooms are controlled by numerous physical, chemical and biotic factors which must work in concert for them to be established. Therefore, such events are irregular in appearance and difficult to study.

In order to circumvent this difficulty, numerous methods have been proposed for assessing the total biomass of planktonic algae:

Volume of algae

To overcome part of the difficulties met in identifying and counting individual cells, some authors have proposed that the volume of algae be used, i.e. the amount that would be obtained in a graduated centrifuge tube. Under extreme conditions of eutrophication this can give some estimate of the total numbers. However, for lower numbers of cells, the method may not be very suitable. Another way of determining the volume of algae is by means of a Coulter Counter, although, the problem of living versus nonliving matter must be considered.

Amount of chlorophyll

One of the most frequently used methods to assess the standing crop of algae is by extracting chlorophyll from the filtered sample. Chlorophyll is present in all plants in sufficient amounts that it can be extracted with various solvents and estimated by means of a spectrophotometer. The problem with chlorophyll is that it works reasonably well for relatively pure cultures of one type of organism. However, with mixed populations of organisms, particularly where the type of organism changes from week to week, it is found that frequently the correlation between the chlorophyll content and the total numbers or mass of algae in the water is very poor.

Amount of suspended solids

The suspended solids in the water are sometimes used as a measure of the density of algal populations. The problem with suspended solids is that the majority of the suspended solids in most waters are nonliving materials. In some lakes, there is roughly ten times more nonliving than living particles present in the sample (Lee, 1970) and the same may be true in estuarine areas.

Photosynthesis

Many investigators have proposed that a measure of the photosynthesis by the organisms present in the water be used as criteria for determining the degree of eutrophication of a body of water. Here, the problem is primarily one of correlating the activity as measured by photosynthesis with water quality.

Dissolved oxygen

One of the more frequently used parameters for assessing the eutrophication of water bodies is the oxygen concentration in the lower layers. Oxygen depletion in the lower layers, particularly when there is strong stratification, is probably the most widely used index that allows distinction between eutrophic and oligotrophic waters. The rate of depletion of oxygen from the lower layers depends to a large degree on the morphology of the region, for example, when there is a sill that isolates a sea area from the main ocean (such is the case of the Cariaco trench, the Baltic and Black seas or the Sea of Marmara).

Light penetration

Light penetration is probably the most widely used measure of eutrophication. Although sometimes criticized as being an extremely crude instrument (Edmondson, 1980), the Secchi disk, which consists of a plate of about 30 cm in diameter painted white, or black and white in quadrants, attached to a metered rope or line, is an important tool in oceanographic investigations involving eutrophication. One of the most significant effects of eutrophication on the water quality is a decreased clarity of water. This decreased clarity of water results from light scattering from the microscopic plants that are suspended in the water. The depth to which a Secchi disk can be lowered and still be visible is an estimate of the amount of phytoplankton present in the water. Although this technique has some problems, it is an important one in that it is inexpensive and can be readily performed by almost any individual. In almost every case where it has been used it is clearly shown that as a water body becomes more eutrophic, the depth to which a Secchi disk can be seen decreased significantly.

<u>Remote sensing</u>

Remote sensing may be successfully employed when eutrophication extends over large areas such as the case of for example the northern Adriatic Sea. Although the satellite operated Coastal Zone Color Scanner

(CZCS) has been definitely stopped there is still the possibility of using the LANDSAT's thematic mapper or SPOT's sensors since their low sensitivity is overcome by the high chlorophyll content of the upper layers of the eutrophic areas. Another possibility is to use airborne spectral scanners or even aerial photographs to monitor the extent of eutrophication. However, remote sensing may often be difficult to use while research vessels may be more readily available.

Continuous surface measurements

In much the same way that information provided by remote sensors on the surface layer is used, with proper algorithms, to evaluate the entire water column, direct measurement of surface variables from a moving ship may be used to infer what is happening at deeper layers.

Continuous determination of many of the parameters normally used in the definition of eutrophication, when used in conjunction with computerized data acquisition, allows for a practically real time display of the conditions encountered in the area (Ballester et al., 1972).

INTERCALIBRATION

Intercalibration of sampling and analytical techniques used for monitoring eutrophication has been the subject of lengthy discussions with the International Biological Programme and an OECD programme aiming at monitoring lakes, in which extensive use of satellite and field observations were correlated.

In the marine environment no attempt has so far been made. Yet, it appears feasible if agreement was reached on which of the proposed techniques best represents the coastal system. Unfortunately, we are far from having standard methods to assess the degree and extent of eutrophication.

SAMPLING DESIGN

Sampling design will vary according to the morphological characteristics of the area to be monitored, its hydrodynamics and the sources of eutrophicating substances. However, it appears the best strategy to scan a large area with a measuring system composed of a hose through which water is continuously pumped for on deck analysis with associated Temperature, Salinity and Oxygen sensors. In vivo fluorescence, nephelometry and nutrient analysis may be carried out with relatively little effort.

Surface sampling is usually carried out, but two level sampling may be done if enough analysers are available.

PROCESSING AND EVALUATION OF DATA

Processing and evaluation of data should be carried out having predefined a model of the system under study.

Models of the aquatic ecosystem may be good tools for monitoring eutrophication efficiently. Since no one of the above parameters alone can provide a good account of the extent and/or intensity of eutrophication, numerical models in which quantitative relationships among the various characteristics are given, allow an overall assessment of the phenomenon to be made with a small number of field and/or laboratory measurements.

For example, chlorophyll concentration and light penetration are strongly related, although their relationship is far from simple due to the existence of other substances which absorb and scatter light. In addition, the size of chlorophyll-containing particles may also affect such a relationship. Megard et al (1980) analyzed the relationship existing between vertically averaged chlorophyll contents and Secchi disk depths. Assuming that the contribution of water and chlorophyll to the attenuation coefficient is well represented by a linear equation of the type

$$k = k_w + k_c\ c$$

they found for a number of lakes a good correlation between chlorophyll *a* concentration $\underline{c}$ and the reciprocal of the Secchi disk depth $\underline{z}$ according to the equation

$$c = a/z + b$$

where $a = \ln(I_o/I_z)/k_z$

and $b = -\ k_w/k_c$

This is just an example of how the simple observation of Secchi disk disappearance may be used to determine the average chlorophyll *a* concentration over the water column down to the Secchi disk depth.

More elaborate models may similarly assist in evaluating complex variables by just measuring a few simple parameters eventually with continuously profiling devices.

Patten in 1968 reviewed the major plankton productivity models that had been proposed so far. Since then a large number of phytoplankton production models including various stages of the nutrient uptake and regeneration have been proposed. Lehman et al (1975) examined the rationale of the phytoplankton dynamics and elaborated a model to simulate the growth of the algae in the epilimnion of a lake during a one year period. On the other hand, Pace et al. (1984) have proposed a simulation analysis of continental shelf food webs including detritus, dissolved organic matter, bacteria, etc. thus accounting for the remineralization processes.

Fransz & Verhagen (1985) included the nutrient cycles within each compartment of a relatively simple model which considers three dissolved nutrients: Si, P, and N as essential to pelagic algae. Si is only used by diatoms. Zooplankton grazed on algae, but the filtering by benthic organisms was ignored. Dead organic matter was pooled in detritus, which partly sedimented to the bottom. The model distinguished the carbon and the nutrients in the detritus. Nutrients returned to the dissolved phase by respiration and excretion of organisms, and mineralization of detritus. The pelagic components were subjected to transport by water movements. In the model the carbon and nutrient fluxes were determined as functions of current values of state and environmental variables.

Much remains to be investigated, such as assessment of environmental capacity, for models to be of practical use in monitoring eutrophication or any other phenomenon in marine ecosystems.

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EUTROPHICATION-INDUCED MODIFICATIONS OF BENTHIC COMMUNITIES

by

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EUTROPHICATION

It is one of the fundamental principles of ecology that, through mutual interaction, animal and plant communities and the environment they occupy undergo change. This process ideally consists of a series of transitory seral stages leading to a predictable, more stable climax stage. Such a long-term community development will be super-imposed by seasonal or annual, short-term fluctuations in species abundance and composition. Due to the relative chemophysical stability of the marine environment, examples of wide-scale community succession in the sea are not well known. It has become increasingly obvious in recent years, however, that human activity is capable of changing the rate and direction of community development in both marine and terrestrial environments. In addition to engineering measures, pollution with toxic substances, and selective commercial exploitation, eutrophication is one of the anthropogenic influences frequently cited as altering natural ecosystem structure beyond that expected due to "natural" variability.

The eutrophication concept has been variously interpreted in this century according to biotope and field of research, but can generally be understood as "an over-enrichment of a water body with nutrients, resulting in excessive growth of organisms and depletion of oxygen concentration" (Lincoln et al., 1985). In contrast to the pelagic subsystem, where the analysis of eutrophication involves nutrient concentrations, bacteria counts, BOD analysis, and plankton populations, the symptoms most frequently cited in the benthic subsystem are - with decreasing degree of water renewal - increased biomass, faunal impoverishment, and mass mortality. The present contribution will focus on oxygen depletion and associated mortalities as the most conspicuous manifestation of eutrophication-promoted changes in benthic populations.

BENTHOS

The benthos may be defined as those organisms living on (epifauna) or in (infauna) the sea floor - as opposed to pelagic organisms either passively floating or actively swimming in the water. The composition of the benthos varies according to a wide range of interrelated physical and chemical parameters including water movement, light intensity, salinity, temperature, and substrate type. Most of these parameters are related to water depth, and a detailed terminology has been developed to differentiate the vertical zonation (e.g., supralittoral, eulittoral/intertidal, sublittoral, bathyal, abyssal, hadal). A second major descriptive component of the benthos, again related to water movement and depth, is substrate type. Thus, rock bottoms indicate strong wave action or current, with a wide range of increasingly smaller particles (boulders, cobbles, pebbles, granules, coarse-, medium-, and fine sand, silt and clay) indicating calmer conditions. A wide range of animal-sediment relation studies has shown a correlation between benthic communities and substrate type, with specific groups of meiofauna organisms, macro-infauna, and -epifauna best adapted to specific sediment textures. Because eutrophication is a phenomenon no doubt restricted to shallow seas and shelf areas, this contribution will focus on sublittoral soft bottoms; these extend, depending on authority, from below the tidal zone to either the greatest depth at which plants can grow or to a depth of approximately 200m (corresponding to the edge of the continental shelf). Such bottoms comprise only 8% of the surface area of the oceans, but are biologically the most productive, are of greatest commercial and recreational interest, and at the same time the direct recipients of wastes.

Benthic communities play an important role in such shallow water ecosystems. A wide range of species, including deposit feeders, filter and suspension feeders, grazers, and predators have a major influence in reworking and stabilizing the sediment. Of particular importance with regard to eutrophication is the ability of suspension and filter feeding communities to remove large quantities of seston and plankton from the water column. The result is a conversion of pelagic biomass with a high respiration/unit biomass into benthic biomass with a lower respiration/unit biomass - in effect a natural eutrophication control (Ott & Fedra, 1977; Officer et al., 1984). Disturbances altering the trophic structure of such communities (i.e., suspension feeding to deposit feeding) may therefore destabilize the entire system. The relative stability of benthic vs. pelagic populations provides an opportunity to distinguish between natural variability and anthropogenically induced disturbances.

OXYGEN DEFICIENCY

Mortality events are the most easily detectable changes in benthic communities. Under mass mortality one may understand "an unusual and rapid increase in mortality rate, of sufficient proportions to affect significantly the size of the population and to disturb, at least temporarily, the ecosystem of which the population is a part" (Sindermann & Swanson, 1979). Such events may be triggered by a wide range of phenomena (for a review, see Brongersma-Sanders, 1957), with oxygen deficiency often being cited as an immediate cause. Varying degrees of oxygen depletion may be distinguished. Thus, oxic or aerobic conditions refer to the normal state of oxygenation, with hypoxic (or dysaerobic) conditions denoting significantly reduced oxygen levels. Finally, the terms anoxic or anaerobic, applied strictly, indicate total lack of dissolved oxygen. Values may be expressed in units of pressure, volume, or weight, with the following conversion factors being applicable (after Rhoads & Morse, 1971) :

$$1 \text{ mm Hg} = 1.316 \text{ ml } O_2 \text{ l}^{-1}$$

$$1 \text{ g } O_2 \text{ l}^{-1} = 1.401 \times 10^3 \text{ ml } O_2 \text{ l}^{-1}$$

$$1 \text{ g } O_2 \text{ l}^{-1} = 1.065 \times 10^3 \text{ mm Hg}$$

Oxygen deficiency or hypoxia is indicated by concentrations below approximately 2mg O_2 l^{-1} : here benthic community structure (species, abundance, biomass) deteriorates abruptly (Rosenberg, 1980), although many species are affected at higher concentrations. The formation of H_2S may further reduce the tolerance of those species capable of surviving temporary anoxia.

Oxygen deficiency alone is insufficient as direct proof of eutrophication. The basin configuration of semi-enclosed shallow seas or geomorphological structures may prohibit water exchange, especially the exchange of deeper water layers, resulting in permanent or recurring oxygen depletions and faunal impoverishment. The Black Sea is an example of the former, sill formation in fjords an example of the latter. However, even in such stagnant basins, oxygen depletion and benthic mortalities may be promoted by organic enrichment associated with eutrophication. Recently, eutrophication has been implicated in several well-documented cases of oxygen depletion. These include mortality events in seas as biologically and hydrodynamically diverse as Tokyo Bay (Seki et al., 1974) and the Seto Inland Sea (Imabayashi, 1983) in Japan, the New York Bight (Swanson & Sindermann, 1979) and Chesapeake Bay (Officer et al., 1984) in the eastern Atlantic, Elefsis Bay (Zarkanellas, 1979) and the North Adriatic Sea (Fedra et al., 1976; Stefanon & Boldrin, 1982; Stachowitsch, 1984; Montanari et al., 1984; Faganeli et al., 1985) in the Mediterranean Sea, the German Bight (Rachor, 1980; Dethlefsen & Westernhagen, 1983) in the North Sea, and Scandinavian waters (Leppäkoski, 1969; Jørgensen, 1980; Rosenberg, 1986).

It should be stressed that only in rare cases is eutrophication alone considered to be the primary cause of oxygen deficiency and benthic mortalities. Typically, it is cited as a contributing or enhancing factor, which together with adverse meteorological and hydrodynamic conditions, increases the frequency or severity of such events. Additional criteria for citing eutrophication include increased frequency or area affected by oxygen deficiency, increased input of nutrients, increase in plankton blooms or coastal macroalgal vegetation, and decreased water transparency. Many of these developments have been registered in those areas more closely examined here (the German Bight, Scandinavian waters, the North Adriatic Sea, the New York Bight, and Chesapeake Bay). The following similar features and sequence or combination of events are of high predictive value in defining location, time, and effect on benthic communities of eutrophication-induced oxygen deficiencies and mass mortalities :

Depth and substrate

The five regions cited above may all be classified as sublittoral soft bottoms; such fine-grained sediments are particularly susceptible to organic enrichment and anaerobic conditions. The German Bight between Helgoland and the Elbe River is characterized by muddy bottoms at water depths between 20 and 30m. The average depth of the Kattegat is 23m (the adjacent Limfjorden a maximum of 15m), and that of the Gulf of Trieste does not exceed 25m (North Adriatic Sea 50m). The New York Bight may also be classified as a shallow sea (30-60m), while Chesapeake Bay does not exceed 45m.

Stratification

A second feature common to the selected mortality events is the stratification of the water column. This barrier isolates bottom waters and benthic communities from oxygenated water layers. When respiration exceeds production below the pycnocline (thermocline and/or halocline), oxygen depletion is unavoidable. This process is accelerated by the fact that the thickness of the lower water body is in most cases much smaller than the overlying layer - often only several meters. A thermocline at approximately 20m was reported for the German Bight in 1981 (Rachor & Albrecht, 1983) and at 15-20m in 1982 (Dethlefsen & Westernhagen, 1983). A strong thermocline with temperature differences of up to 10°C between surface and bottom waters is typical for the North Adriatic Sea (Stefanon & Boldrin, 1982); in the deeper part of the Gulf of Trieste it may last up to 9 months - with periodic mixing after storm events - and occurs at approximately 18m. Both the depth and strength of the pycnocline increases from spring to summer in the New York Bight (Staff & Steimle, 1979); strong pycnoclines were observed during mortalities in 1968 and 1976, being prolonged beyond the normal five months (April-August) in 1976 by two months due to early warming of the air and to early onset of spring river discharge (Armstrong, 1979). A halocline also develops in Chesapeake Bay in February/March and lasts until September or October (Officer et al., 1984). Finally, a marked halocline is present both in the Skagerrak and Kattegat, at a depth of 15m in the latter (Rosenberg, 1986).

Plankton blooms

Severe plankton blooms, a phenomenon often associated with eutrophication, may have a lethal effect on benthic communities either directly through production of toxic substances or indirectly through elevated oxygen consumption during their decomposition. The latter process typically takes place below the stratification, demonstrating that processes in the pelagic subsystem may be intimately related to oxygen depletion and mortalities in the benthic subsystem. A mass occurrence of the dinoflagellate *Ceratium furca* preceded the low oxygen situation in the German Bight in 1981 (Rachor & Albrecht, 1983) and 1982 (Dethlefsen & Westernhagen, 1983). The latter event was characterized by large amounts of cloudy detritus accumulated in ripples and small troughs on the bottom. The 1976 mass mortality event in the New York Bight was also accompanied by a major bloom of the dinoflagellate *Ceratium tripos*, with a series of phytoplankton blooms and suspended flocculent matter being reported in lesser mortality events in 1968 and 1971, respectively (Sindermann & Swanson, 1979). In early July, 1976, flocculent aggregates of decomposing phytoplankton several meters thick were observed at the thermocline and more dense accumulations about 1cm thick on the bottom (Mahoney, 1979). This material darkened progressively during decomposition over a period of one week. The author also reported occlusion of the gills of the mud shrimp *Axius serratus* by this material. This sequence corresponds to the presence of great amounts of suspended material, including giant mucus streamers up to several meters in length, in the Gulf of Trieste in 1983. This material covered the macroepifauna, killing sponges and entangling their associated fauna within two days (Stachowitsch, 1984). This loose material darkened within several days, leaving only the tips of elevated biogenic mounds free. Changes in timing, quality, and size of plankton blooms have also been reported in Chesapeake Bay (Officer et al., 1984), with organic matter produced in the preceding summer and fall, collecting in deep water in winter, being the major factor contributing to oxygen depletion (Taft et al., 1980). Although a causal relationship between eutrophication and plankton populations was not conclusively established, mass occurrences of dinoflagellates were registered in the Kattegat and Skagerrak in the early 1980s, the genus *Ceratium* contributing to mortalities through production of toxic substances in Laholm Bay in 1980 and *Gyrodinium* causing massive kills of fish, mussels, and bottom animals (Rosenberg, 1985, 1986).

Season and duration

In the northern hemisphere, periodic annual oxygen depletion is a phenomenon known to occur predominantly in late summer (Pearson & Rosenberg, 1978). This period also corresponds to the mortality events in the areas under consideration here, a feature of high diagnostic value allowing monitoring efforts in sensitive areas to focus on specified critical seasons. Thus, a late summer (August/September) decline in species number was typical for the inner German Bight in the late 1970s (Rachor, 1980). Lowest oxygen values and increased infauna organisms in dredge surveys were reported between August 25 and September 17 in 1981 (Rachor & Albrecht, 1983), in 1982 mortalities between August 10 and

August 18 (Dethlefsen & Westernhagen, 1983). Reoxygenation in the former case was achieved on September 21, in the latter at the end of August after two weeks of strong northeasterly winds. Mortality in the New York Bight, known to occur locally in the period August-October (for example, 1968, 1971, 1974), was first reported on July 4 in the major 1976 event (Sindermann & Swanson, 1979). Oxygen depletion persisted until October, when lower surface temperatures and mixing broke down the pycnocline. In the Gulf of Trieste, mortality of organisms began on September 12 1983 and was monitored for two weeks; most benthic organisms died in the first three days (Stachowitsch, 1984). The smaller regions of decaying organisms observed in 1974 (Fedra et al., 1976) also occurred in September, and the mortality event south of Venice in 1977 was first reported by fishermen in September and extended into November (Stefanon & Boldrin, 1982). Mortalities in late summer and autumn are also typical for Scandinavian waters (for example Laholm Bay, 1980; Limfjorden, 1975) (Rosenberg, 1986; Jørgensen, 1980).

SHORT-TERM EFFECTS ON BENTHIC COMMUNITIES

The first indications of benthic community stress due to oxygen deficiency are often provided by fishermen who report either dead or dying organisms in their nets, a conspicuous presence or absence of molluscs, crustaceans and fish, or who capture assemblages of species not normally caught together. It should be stressed that at this point community deterioration may be rather advanced. Only direct observation by SCUBA and/or underwater photography are capable of providing detailed information on the extent of damage to benthic communities. Thus, trawl surveys in the German Bight contained only few species and specimens of dead fish. At the same time, underwater TV cameras revealed several other species of dead fish and permitted quantification of dead and stressed bottom invertebrates such as the brittle star *Ophiura albida* and the bivalve *Venus striatula* (Dethlefsen & Westernhagen, 1983). In the New York Bight, SCUBA divers were the first to report unusual conditions on and around shipwrecks. In the Limfjorden (Jørgensen, 1980) and the Gulf of Trieste (Stachowitsch, 1984) only SCUBA observations were able to detect individual behaviour patterns and the sequence of mortality of benthic species due to oxygen deficiency.

Behavioural modifications and mortalities

Altered behaviour of benthic organisms provides an opportunity to detect critical oxygen deficiencies at an early stage; their specific sequence of mortality provides information on the duration and severity of such phenomena. The detailed in-situ observations in the Gulf of Trieste in 1983 (Stachowitsch, 1984) will be used as a basic framework for comparing data of benthic community deterioration in the seas characterized above. The animal groups chosen include :

Sponges

A characteristic feature in the Gulf of Trieste was a mucus layer covering sponges and other sessile macroepifauna organisms. Based on discoloration and the mortality of associated faunal elements, all sponges had died within the first two days after the onset of community deterioration. Sponges (35% of total biomass in the investigated community) are a major component of the multi-species clumps characterizing the deeper Gulf. The many smaller species associated with sponges - chiefly crustaceans - were therefore also affected immediately and lay entangled in these mucus strands. Large forms, such as the brittle star *Ophiothrix quinquemaculata*, abandoned the sponges. Sponges apparently are not a major structural feature in the other areas under consideration here, and no sponge mortalities were reported. The accumulation of cloudy detritus on the bottom in the German Bight (Dethlefsen & Westernhagen, 1983) and of a dark, dense flocculent organic material in the New York Bight is a strong indication of a negative effect not only on motile (Mahoney, 1979) but also large sessile species.

Fish

In the Gulf of Trieste, small benthic fish were also affected on the first day. Great numbers of dead gobiids *Cobius jozo* as well as juvenile Trachinidae and small flatfish were found dead on the sediment surface. As in the German Bight and in the New York Bight, larger benthic fish and pelagic species showed avoidance behaviour and were apparently able to flee oxygen deficient waters (Faganeli et al., 1985). In the 1977 mortality event these fish were concentrated at the leading edge of the affected area, resulting in increased catches of fish normally not caught together (Stefanon & Boldrin, 1982). Such avoidance behaviour and subsequent re-population was also observed by Azarovitz et al. (1979) in the New York Bight. Here, catches decreased and demersal fish such as the American sandlance (*Ammodytes americanus*) were taken in waters above the anoxic layer. Dead sandlance were also observed by Dethlefsen & Westernhagen (1983) using underwater TV. Summer flounder were also concentrated at the leading edge of anoxic waters in the surf zone and in inlets and bays in the New York Bight (Azarovitz et al., 1979). Studies on the behaviour of the larger bluefish (*Pomatomus saltatrix*) showed blockage of migratory patterns.

Crustaceans

In addition to the early mortality of small shrimp and the crabs *Pilumnus spinifer* and *Pisidia longicornis* associated with sponges in the Gulf of Trieste, a number of larger forms were affected both in the Gulf and in the other areas under consideration here. The burrowing shrimp *Upogebia tipica* left their burrows and were seen in great numbers on the sediment surface along with smaller numbers of *Jaxea nocturna* and *Axius stirhynchus*. Increased catches of the Norway lobster *Nephrops norvegicus* in the German Bight during oxygen depletion indicate that these animals left their burrows and were available to bottom trawls (Rachor & Albrecht, 1983). In the New York Bight, the first signs of unusual conditions were diver reports of lobster (*Homarus americanus*) leaving their shelters and aggregating on the highest parts of shipwrecks, a phenomenon paralleled by thousands of dead lobster outside their dens and aggregated on the highest parts of outcrops in the North Adriatic Sea (Stafanon & Boldrin, 1982). In addition to mortality, the response of lobster in the New York Bight included avoidance behaviour and disruption of seasonal migrations (Azarovitz et al., 1979). At the same time, smaller infauna forms such as the deep burrowing mud shrimp *Axius serratus* and the mantis shrimp *Platysquilla enodis* were on the sediment and could be captured by trawl and dredge. Drastic reductions in the populations of sand shrimp (*Crangon septemspinosus*) and rock crab (*Cancer irroratus*) were also reported (Steimle & Radosh, 1979). In the Gulf of Trieste, living, moribund, and dead *Squilla mantis* were on the sediment during the day and several individuals were observed swimming freely several meters above the bottom (Stachowitsch, 1984). Finally, the response of the blue crab *Callinectes sapidus* to oxygen deficiency has eliminated commercial deep water crabbing in Chesapeake Bay. The behavioural response of *Callinectes* includes crowding along the shore and even emergence onto land (Officer et al., 1984).

Echinoderms

Echinoderms, a major component of the macroepibenthos in the Gulf of Trieste, showed a variety a behavioural modifications before death in the 2-3 days after the first signs of stress. *Ophiothrix quinquemaculata* (28% of macroepifauna biomass) abandoned the multi-species clumps upon which they aggregate in large numbers and assumed a non-suspension feeding posture on the sediment surface. Death on the following day was indicated by overturned individuals with curled arm tips. *Ophiura texturata*, normally lying flat on or partially buried in the sediment, assumed a humped posture with elevated disc, a behaviour pattern also observed in the German Bight and induced by hypoxia in laboratory experiments (Dethlefsen & Westernhagen, 1983; Dries & Theede, 1974). On the second day, the sea star *Astropecten aurantiacus* was observed on mounds with greatly extended discs. This posture - a stress reaction characterized by a gas-filled stomach - was also observed in the Emilia Romagna region off Cesenatico, Italy (A. Rinaldi, pers. comm.), and was followed on the third day by overturning individuals. *Amphiura chiajei*, the echinoderm species to succumb last, was aggregated in large numbers on the top of mounds. All individuals of the epibenthic holothurian *Holothuria tubulosa* were found eviscerated on the first day, with death taking place on days 2 and 3. On day 1, the burrowing form *Thyone fusus* emerged from the sediment. Dead individuals of this genus were also collected by grab in the New York Bight (Steimle & Radosh, 1979). On the third day, the sea urchin *Schizaster canaliferus* emerged from the sediment in the Gulf. Community deterioration in the German Bight in 1981 was also indicated by unusually large numbers of echinoderms (*Ophiura*, *Echinocardium* and *Asterias*) in dredges (Rachor & Albrecht, 1983).

Polychaetes

Polychaetes, bivalves, and anemones appear to be the most resistant components of the benthic fauna. In the Gulf of Trieste the large polychaetes *Eunice aphroditois* and *Dasybranchus caducus* emerged on the second and third days after first signs of community stress; most individuals were dead on day 4. A similar emergence of moribund but still living *Nereis diversicolor, N. virens, Pectinaria koreni,* and *Heteromastus filiformis* was observed in Limfjorden, Denmark (Jørgensen, 1980). Smaller specimens emerged first. These polychaetes revived when taken to oxic waters but succumbed if oxygen depletion continued for an additional week. Entangled polychaetes in trawl nets is a symptom of anoxic bottom water in the fjord. Normally deep-burrowing polychaetes hanging dead from trawl net mesh in the New York Bight included *Sigalion arenicola* and *Nereis longosetosa* (Steimle & Radosh, 1979).

Bivalves

In the Gulf of Trieste the first signs of stress in bivalves was the emergence of *Cardium* sp. accompanied by extension of the siphons. A similar behaviour was registered in Limfjorden, where the siphons of *Cardium edule* and *Syndosmya alba* stretched a few cm above the sediment, those of *Mya arenaria* 10-20cm above the black mud (Jørgensen, 1980). This was followed by emergence of these species (the siphons of *Mya* extending 20-30cm above the bottom). These bivalves were considered to be able to survive for an additional week in this state, with emergence and reburial of larger clams apparently being possible. Substantial early losses of *Mytilus edulis* however, were reported in dense beds on the soft mud (extremely high respiration even under normal conditions. coupled with sensitivity to H_2S). The defense mechanisms of the oyster, a species of key economic importance in Chesapeake Bay, are also overcome relatively quickly by hypoxia (Officer et al., 1984). Finally, open living (gapers) and dead (clappers) bivalves were observed in the Gulf of Trieste (*Solecurtus sp.*), the German Bight (*Venus striatula*; Dethlefsen & Westernhagen, 1983), and in the New York Bight. In the latter area, high mortalities of surf clams (*Spisula solidissima*), ocean quahogs (*Arctica islandica*), and sea scallops (*Placopecten magellanicus*) led to an estimated long-term financial loss (surf clam industry) of $550 million (Ropes et al., 1979).

Anemones

Both in the Gulf of Trieste and in the Limfjorden, anemones were the most resistent to oxygen depletion. *Calliactis parasitica*, normally found attached to hermit crab shells in the Gulf, detached on days 3 and 4 and could be observed lying on the sediment with extended tentacles. Other species reacted by constrictions of the column, elevation of the tentacle crown above the substrate, and finally, in burrowing forms, by emergence, exposure of the pedal disc, and discharging of acontia. After one week, however, virtually all species, including the large *Cerianthus* sp., had died. In the New York Bight *Cerianthus americanus* was collected by trawl and observed dead by divers. In Limfjorden, anemones also loosened their attachment to shells and were found lying on the mud.

LONG-TERM EFFECT ON BENTHIC COMMUNITIES

Behavioural modifications and mass mortality represent only one aspect of eutrophication-promoted deterioration of benthic communities. A single, restricted mortality event alone is usually insufficient to permanently alter community structure; the long-term effect of repeated anoxia is a more serious threat to ecosystem stability. Recovery time depends on the frequency of disturbance, the area affected, and the type of community previously present as well as the method of population expansion of the component species (larval dispersal, brooding/immigration). Mature, stable communities, i.e., those with mechanisms dampening the effect of fluctuations of physical parameters (resistent species, K-strategists) may require several years to achieve their former state. Less highly developed communities, i.e., those conforming to external fluctuations with corresponding variation in species composition, diversity, or density (resilient species, r-strategists) may recover more rapidly. Thus, in the sublittoral soft bottom community in the Gulf of Trieste, which is characterized by perennial, large, slow-growing species, the former species are beginning to reappear only after three years (Stachowitsch, unpubl.). Total recovery in the New York Bight is expected to take several years due to the extensive dimensions of the affected area (Steimle & Radosh, 1979). Recolonization of the Bornholm Basin in the Baltic after the 1968 mortality event led, even after several years, to a community showing "very little if any resemblance to the original *Macoma baltica* community described earlier as being characteristic for the Basin" (Leppäkoski, 1971). In areas with annual mortalities due to oxygen depletion, the relatively brief recolonization period may prohibit recovery, allowing atypical or impoverished communities to evolve. Thus, a steady impoverishment trend was noted in the German Bight in the late 1970s (Rachor, 1980). Essentially an annual reestablishment of a transitory succession stage occurs in Chesapeake Bay, where the benthic fauna after summer mortalities is characterized by a dominance of autumn spawners (Officer et al., 1984). Due to the local or patchy nature of the affected area in Limfjorden, recolonization seems to take place largely within one year; the composition of the community, however, is regulated by the alternating sequences of extinction and recolonization (Jørgensen, 1980).

The species initially present after mass mortality events include first colonizers or pioneer forms as well as surviving organisms. Again, despite wide-ranging differences in the areas considered above, similarities in the composition of these transitory stages exist. Thus, not only the absence, but also the presence of specific species groups provides evidence of unfavourable conditions. Survivors of short-term anoxia or long-term hypoxia mainly include molluscs, anemones, and polychaetes. In the Hornholm and Kiel Bays, only adult individuals of the bivalve *Astarte* and old *Astarte, Mya,* and *Cyprina*, respectively, were found after prolonged stagnation (Leppäkoski, 1971; Rosenberg, 1980). This is in agreement with the emergence/reburial behaviour of 5-10 year old clams in Limfjorden and Lovns Broad (Jørgensen, 1980). Other resistent bivalves include *Corbula* (Rosenberg, 1980) and both *Nucula* and, to a lesser extent, *Abra* (Rachor, 1980). There is a lack of consensus as to whether polychaete species found after mortality events are tolerant to oxygen deficiency, i.e., whether they are survivors or pioneers. Both types, however, may be considered to be "indicator" species : forms whose presence indicates unfavourable environmental conditions - in this case oxygen deficiency, organic enrichment, presence of H_2S, repeated defaunation, and decreased competition. *Nepthys hombergii*, for example, survives the detrimental late summer in the German Bight. *Harmothoe* is the last survivor in Lubeck Bay (Schultz, 1968). Common pioneer forms (transitory opportunists, typically recolonization with planktonic stages) include capitellids (*Capitella*) and spionids (*Polydora, Pseudopolydora, Spiophanes*). The small tube-dwelling species *Arabellides oculata* was found in dense aggregations in the central area affected by oxygen depletion in the New York Bight after one year (Steimle & Radosh, 1979). Serpulids were dominant pioneer forms in the Gulf of Trieste (Stachowitsch, unpubl.). Transitory emigrants (recolonization by migration) in Northern European fjords and estuaries include the errant polychaete *Harmothoe* and *Ophiodromus* (Rosenberg, 1980). For a detailed review of tolerant species and macrobenthic succession see Pearson & Rosenberg (1978). Recolonization by emigration is of reduced significance after large scale mortalities. At the same time, barriers to larvel recruitment include the loss of structures on which to settle due to sediment mobility and the loss of microhabitats for larval survival. Finally, the loss of adults results both in reduced reproductive capability (less larvae) and inhibits settlement of those larvae settling preferentially on or near adult individuals.

Eutrophication-promoted oxygen deficiency and benthic mortalities result in great losses of benthic biomass, direct loss of commercially valuable species, loss of productivity, disruption of food chains, and therefore reduced food sources for demersal and pelagic fish (which also avoid such areas). These changes lead to significant alterations in the community structure of the most densely populated and diverse regions of the sea floor. The effect is a destabilization of the entire ecosystem. Much research must be done before we understand the complex processes leading to eutrophication-induced oxygen deficiency and mortalities. However, at the same time we must ask ourselves "whether we can afford to wait until we understand causes and effects in marine ecosystems more clearly or whether we should take precautionary measures to drastically reduce pollution loads of the area under consideration" (Dethlefsen & Westernhagen, 1983). The meteorological and hydrographic phenomena are beyond our control; it is however, within our power to reduce organic input and thus ameliorate the degree of eutrophication - a contributing factor in environmental catastrophes in vital coastal areas.

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EFFETS PATHOLOGIQUES DE L'EUTROPHISATION MARINE

par

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"Et toutes les eaux qui étaient dans la rivière s'étaient changées en sang. Et les poissons qui se trouvaient dans la rivière moururent. Et la rivière empestait, et les Egyptiens ne pouvaient pas boire l'eau de la rivière".

(Livre de l'Exode, 7, 20-24)

Comme en témoignent ces deux versets de la Bible, dès l'antiquité, les Egyptiens avaient constaté l'apparition des eaux rouges à caractère toxique.

Si Cook et Vancouver, lors de leur expédition sur la côte Nord-Ouest du Pacifique ont été les premiers à signaler la présence de telles substances toxiques pour l'homme où dans leurs relations de voyage ils ont en effet déploré "la maladie et la mort d'une partie de leur équipage, à la suite d'une consommation de moules et de palourdes empoisonnées". c'est seulement en 1832 que Darwin, lors de son expédition sur le "Beagle" rapporta l'apparition d'efflorescence d'algues rappelant celles des Dinoflagellés toxiques. Mais ce n'est en fait qu'à la fin du XIXe siècle que l'origine de ces "eaux rouges" (red tide des auteurs anglo-saxons) fut réellement attribuée à la multiplication explosive de certains micro-organismes marins susceptibles de libérer dans le milieu des éxotoxines et pouvant provoquer des réactions graves chez d'autres organismes marins ou chez l'homme qui les consomme.

1. LES EFFETS TOXIQUES DES DINOFLAGELLES

L'apparition des "eaux rouges" est un phénomène accidentel, saisonnier, très localisé, caractérisé par une coloration soudaine des eaux allant du jaune-rouge au marron. Le plus souvent elle est de courte durée : de quelques heures à quelques jours, exceptionnellement quelques semaines. Les colorations sont dues à la prolifération presque exclusive d'un micro-organisme planctonique (atteignant 2 à 6 millions de cellules par litre). Après quelques jours, le phénomène se dissipe assez brusquement. Durant la phase de pullulement des cellules dans les eaux rouges, on constate souvent non seulement une intoxication des animaux marins vivant dans ces eaux, avec mortalité en masse, mais on observe aussi dans bien des cas des manifestations pathologiques survenues chez les populations littorales consommatrices de mollusques, ou intoxiquées par les aérosols issus de ces eaux rouges, prenant alors le caractère d'une épidémie locale.

Les organismes planctoniques responsables des "eaux rouges" appartiennent aux ordres des : Dinoflagellés, Chloromonadines, Chrysomonades, qui envahissent certaines zones marines et certaines régions littorales. Ces flagellés, surtout abondants dans les mers chaudes commes les eaux du golfe de Floride, celles des côtes de Malabar dans l'Océan Indien, les côtes algériennes, ou encore celles de l'Adriatique, de la Côte d'Azur en Méditerranée, prédominent en surface du point de vue quantité pendant la saison chaude, tendant alors à remplacer les Diatomées qui souvent diminuent pendant cette période. Cependant, leur développement n'est pas l'apanage des eaux chaudes puisque depuis une dizaine d'années, des efflorescences ont été décrites en Espagne, au Portugal, (Côte Atlantique), en Irlande, en Suède, en Norvège, en France, (Golfe du Morbihan et Côte Normande 1982-1983). Dans le cycle du complexe marin leur économie générale est importante, car ils servent d'aliments à tous les planctontes hétérotrophes ou holozoides depuis les protistes jusqu'aux poissons pélagiques, anchois, sardines, aux animaux benthiques, mollusques et crustacés. On concoit donc que de telles efflorescences peuvent avoir des conséquences souvent graves sur les pêches et sur l'homme.

On a pu décrire et étudier expérimentalement la toxicité de certains Dinoflagellés comme: *Gymnodium, Exuviella baltica, Exuviella sp, Gonyaulax tamarensis, Gonyaulax polyedra, Dinophysis acuminata,* de Chloromonadines comme *Chattonella subsala,* de Chrysomonades comme *Prymnesium parvum,* de *Gymnodinium breve, Prorocentrum micans.* Ces planctontes, existant à l'état endémique, c'est leur pullulation à certaines périodes et suivant certaines circonstances biologiques et physiques (direction et force des vents, température, courants, apport nutritif) qui leur confère leur agressivité vénéneuse. Il semble donc qu'il faille atteindre une concentration minima pour les rendre pathogènes.

Si la nature elle-même de la toxine, son mécanisme d'action et ses effets varient avec les organismes responsables, cependant les travaux de ces dernières décennies, soit des auteurs américains (Woodcock), des Anglo-saxons (Abott & Ballantine, Ingle & Davis), soit des Portugais (E. de Souza e Silva) ou encore dès Israéliens (Yariv & Hestrin), des Japonais et des Francais (Pierre M.J. & Lassus P.) ont permis de clarifier un peu cette question.

Avant d'aborder la nature chimique de la ou des substances toxiques responsables, nous résumerons quelques observations caractéristiques, chez l'homme et dans la faune marine.

C'est ainsi qu'à Venice, sur la côte de Floride, en juillet, époque à laquelle une épidémie mortelle décimant le poisson de cette région coincida avec l'apparition d'eaux rouges, la population riveraine manifesta des symptômes typiques d'irritation respitatoire : toux sèche, persistante, sensation de brûlure au niveau de tout le système respiratoire : nez, arrière-gorge, larynx, trachée et même poumons. Or, il se produisit à cette date un coup de vent venant du large, chargeant l'air atmosphérique de gouttelettes d'eau de mer riche en Dinoflagellés : l'agent responsable identifié s'est trouvé être un *Gymnodinium*. C'est alors que Woodcock réalisa expérimentalement les mêmes symptomes : certains sujets furent soumis à des aérosols d'eau de mer artificiellement chargée de gouttelettes d'eau de mer contenant une forte concentration de *Gymnodinium* (56 x 10 par litre, soit la concentration constatée lors du coup de vent); après quelques minutes, les patients présentaient les mêmes symptômes décrits plus haut. Toux sèche, irritation de la gorge et du nez et sensation de brûlure : en revanche, des aérosols d'eau relativement claire ne produisirent aucun effet nocif : de même, si au préalable, l'eau chargée de *Gymnodinium* était filtrée sur un coton très serré de deux centimètres au moins d'épaisseur, les aérosols restaient sans effet irritant.

Abott et Ballantine ont remarqué au cours de leurs expériences faites avec *Gymnodinium* que l'agitation des cultures dégageait immédiatement une vapeur irritante et fortement désagréable pour l'appareil respiratoire; à ce sujet, il est intéressant de noter que l'administration préalable d'anti-histaminique, de type phénergan, semble minimiser les réactions allergiques.

Plus récemment Shigekatsu Sato et Coll. ont relaté l'apparition d'une maladie dans la région de Récife au Brésil: ils l'attribuent à la présence d'aérosols d'eau de mer chargés de *Trichodesmium erytraeum*, micro-algue appartenant au groupe des Cyanophycées, responsables d'apparition "d'Eaux Rouges" concomitantes.

Ils résument ainsi ces faits: "La maladie humaine qui est localement nommée "Tingui", et le nom provisoirement suggéré par Barbosa (1946) de Tamandaré Fever, est ici caractérisée comme la fièvre à *Trichodesmium* principalement parce que la maladie peut provenir d'aérosols contenant des *Trichodesmium* (entiers ou fragmentés) comme dans le cas du *Gymnodinium* rapporté par Woodcock (1948). La maladie a été observée presque annuellement, généralement en février ou mars, dans la Baie de Tamandaré, mais elle peut apparaître également sur la côte Nord-Est du Brésil".

Elle se caractérise par des symptômes respiratoires accompagnés d'asthme, d'élévation de température, de douleurs articulaires et périorbitales, parfois d'éruption sur le thorax et les bras. La durée de cette symptomatologie est en moyenne de 3 jours.

Par ailleurs, on sait que l'ingestion de certains Mollusques occasionne chez l'homme des manifestations toxiques extrêmement graves qui peuvent entraîner la mort. Il semble bien dans ces cas que le facteur responsable soit "une toxine" et non des facteurs exogènes comme la présence du cuivre ou de matières polluées dans le milieu marin. Ces planctontes, nourriture des Mollusques infestent alors l'animal qui devient toxique pour l'homme qui le consomme.

Sur ce sujet Abott & Ballantine ont réalisé les expérimentations suivantes:

Des séries d'animaux depuis les Echinodermes, les Mollusques ainsi que les Crustacés, jusqu'aux animaux plus différenciés comme les Poissons, ont été immergés dans de l'eau de mer à laquelle on avait ajouté des cultures de *Gymnodinium* en concentrations croissantes. On a pu observer le comportement de ces animaux et l'évolution de leurs symptômes. Après immersion, le poisson s'agite et fait des efforts pour sortir de l'eau, il nage de facon désordonnée; cette phase de défense, où les symptômes sont encore réversibles, dure quelques minutes, puis apparaissent les troubles respiratoires, avec ralentissement du rythme; le poisson ne nage plus, il flotte soit sur le côté, soit sur le dos : cette seconde phase s'accompagne de spasmes violents avec troubles de la sensibilité et abolition des réflexes: cette deuxième phase est irréversible. Enfin, à plus ou moins bref délai suivant les animaux, la mort survient avec blocage du système nerveux.

D'après ces expériences les réactions des différentes espèces aux cultures de *Gymnodinium* peuvent se résumer de la manière suivante : seuls les Annélides sont épargnés; les Mollusques (2-3 jours) ainsi que les Echinodermes (3 jours) et certains Crustacés (*Calanus finmarchicus*), 1-2 jours, etc... résistent assez longtemps aux cultures toxiques; par contre, les poissons plus différenciés, comme les Gobies ou les Blennies, meurent beaucoup plus rapidement (en 20 ou 40 minutes).

D'autre part, les études faites par E de Souza e Silva sont particulièrement intéressantes : alerté par de fréquents accident d'intoxication alimentaire par ingestion de coques, cueillies à la lagune d'Obidos (Portugal), se manifestant le plus souvent par des paralysies et des paresthésies, cet auteur a été conduit à en rechercher l'étiologie dans la flore et la faune planctonique de cette lagune. Des études corrélatives entre la toxicité des bivalves récoltés et l'apparition des "eaux rouges" d'une part, et les conditions hydrologiques d'autre part, ont mis en évidence que la toxicité des coques (*Cardium edule*) est fonction de l'apparition de certaines formes planctoniques appartenant aux Dinoflagellés, colorant en brun rougeâtre la zone marine étudiée.

En effet, lors du développement prodigieux d'*Exuviella baltica* (80,000,000 de cellules/litre), puis de *Gonyaulax tamarensis* (3,000,000 de cellules/litre) et de *Peridinium stenei* (1,000,000 de cellules/litre), la toxicité des coques a été de 7.680 unités souris*; puis suivit une

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*L'unité souris est la quantité de poison qui produit, par l'injection intrapéritonéale, la mort de souris ayant des poids entre 18 et 22 g. dans un temps moyen de 15 à 20 minutes.

période où le nombre des Dinoflagellés diminua considérablement (722,000 exemplaires de *Gonyaulax tamarensis*/litre, 2,000 exemplaires d'*Exuviella baltica* et pratiquement plus de *Peridinium stenei*), période pendant laquelle la toxicité des coques fut de 5,840 unités.

En février 1959, lors d'une nouvelle apparition d'eaux rouges, alors que la densité de *Gonyaulax tamarensis* s'élevait à 4,700,000 cellules/litre, on constate que la toxicité de *Cardium edule* était de 26,560 unités souris, cette période d'efflorescence ne dura que quelques jours et fut suivie de l'apparition de Tintinnides et de Diatomées, si bien que la toxicité de *Cardium* a diminué progressivement puis disparu complètement.

En novembre 1960, se manifesta encore un développement intense de *Glenodinium foliaceum* (1,700,000 cellules/litre) qui dura 2 mois, accompagné d'une grande quantité de *Gyrodinium sp*, la toxicité des bivalves se montait alors à 15,500 unités souris.

Des observations analogues ont été faites aux U.S.A. dans la baie de Kingston Harbour, où l'appartition d'eaux rouges coincidait avec l'efflorescence d'*Exuviella*, qui entrait pour 95% dans la masse de phytoplancton.

Par ailleurs, Yariv & Hestrin (Israël) ayant constaté une mortalité en masse dans la faune de certaines eaux saumâtres lors des efflorescences d'un flagellé particulier, *Prymnesium parvum*, se sont particulièrement attachés à en rechercher les facteurs responsables, leurs mécanismes d'action et leur nature chimique.

Mais des manifestations d'eaux rouges également dues à certains flagellés ont été signalées à plusieurs reprise en Méditérranée non seulement dans sa partie africaine, mais aussi comme nous l'avons signalé plus haut, sur le littoral francais.

Nous rappellerons à ce sujet la prolifération d'une Cloromonadine *Chattonella subsala* (Biecheler), dont les effets toxiques ont été bien décrits par Subrahmamyan (1954), décimant Poissons, Mollusques et Crustacés. Cette observation, rapportée par Hollande et Enjumet, concerne les eaux du port d'Alger où, en 1956, les eaux devinrent couleur brun-rouille très caractérisque; l'examen plus appronfondi montrait une prédominance très nette de *Chattonella subsala* (Biecheler) puisque les auteurs comptaient de 1 à 2,000,000 d'individus par litre.

Depuis une décennie, ces explosions sont de plus en plus fréquentes et se manifestent un peu partout dans le monde (U.S.A., Japon), mais aussi dans les mers de l'Europe (Hollande, Irlande, Angleterre, France, Portugal), infestant les parcs coquilliers et par voie de conséquence responsables de maladie à caractére épidémique.

Parmi celles recencées, les effets de l'efflorescence d'un Dinoflagellé au cours de l'été 1983 en Bretagne et en Normandie méritent d'être décrits : Début juin apparaissait en Baie de vilaine des eaux colorées de grande ampleur, dans lesquelles étaient détectée la présence presque exclusive d'un Dinoflagellé reconnu toxique : *Dinophysis acuminata*;

dès la fin du mois celui-ci était retrouvé dans les contenus stomacaux des moules, alors que les services sanitaires signalaient des cas de gastro-entérites, et interdisaient la vente des coquillages (interdit qui ne fut levé définitivement que le 31 octobre).

L'Extension du phénomène d'eaux rouges se propagea en Bretagne Sud sur près de 400 km de côtes, tandis que sur le littoral normand se manifestaient également des eaux colorées et des cas d'intoxications digestives, nécessitant un arrêté d'interdiction de ramassage et de vente de coquillage. C'est ainsi qu'en Bretagne l'enquête épidémiologique selon la D.D.A.S. a répertorié 3,394 cas de gastro-entérites attribuables à la consommation de coquillages au cours de l'été alors que sur la côte normande les services d'hygiène enregistraient 125 cas.

La maladie est caractérisée, au point de vue clinique, principalement par des troubles diarréhiques accompagnés de malaises, d'élévation de la température, de céphalées. parfois de signes cardio-vasculaires, neurologiques et cutanés. Au cours de ces épidémies, des tests de toxicité ont été réalisés selon la méthode de test-souris (Yasumuto, 1980), voisin de celui proposé par E de Souza : à partir de 10 g d'hépatopancréas de coquillages contaminés est preparé un extrait testé sur la souris; trente minutes après l'injection intra-péritonéale chez la souris, les troubles apparaissent puis la mort survient par apnée après un temps plus ou moins long suivant le niveau de toxicité de l'extrait. Malgré ses imperfections ce test permet de détecter la toxicité des coquillages et ainsi d'assurer un contrôle de la qualité sanitaire des organismes marins.

Nous-mêmes. au cours de l'été 1983, sur le littoral des Alpes-Maritimes en même temps qu'apparaissait une efflorescence de Dinoflagellés (*Gonyaulax polyedra*) et de *Gyrodinium* nous avons pu constater que des manifestations pathologiques sont apparues chez nombre de baigneurs fréquentant ces eaux.

Celles-ci consistaient en éruptions cutanées accompagnées de prurit et d'élévation de température nécessitant parfois une hospitalisation plus ou moins brève.

2. LES TOXINES

Nombre de Dinoflagellés présents dans les zones d'eutrophisation à hauts risques sont capables d'élaborer et d'excréter des toxines dans le milieu. Pour certains d'entre-eux la toxine a pu être isolée, et souvent identifiée. Parmi les mieux connues nous citerons la Sacitoxine isolée de *Gonyaulax catanella*, la Gonyautoxine isolée de *Gonyaulax tamarensis* dont les formules chimiques nous sont fournies par les travaux de Shimizu et coll. 1977.

Nous citerons notamment la Prymnésine, isolée d'une Chrysophycée *Prymnesium parvum* dont l'activité hémolytique et cytotoxique a été démontrée par Paster : c'est un glycolipide d'un poids moléculaire d'environ 23,000.

Dans le même ordre d'idée, il est intéressant de signaler que la ciguatoxine et la maîtotoxine, isolées de la chair de certains poissons responsables de la ciguatera, maladie répandue dans le Pacifique et due à l'ingestion de ces poissons, ont récemment été extraites d'un Dinoflagellé, les poissons ne devenant toxiques qu'après ingestion de celui-ci.

Enfin, selon les travaux rapportés par Marcaillou et coll., Murata et coll. auraient extrait à partir de moule, la fraction toxique de la toxine de *Dinophysis acuminata* qu'ils ont appelé Dinophysitoxine I (D.T.X.I.). Il s'agirait de l'acide 35 S méthyl okadaîque (C45, H70, O13).

Dans la plupart des cas il s'agit bien d'exotoxines qui, sécrétées dans le milieu, agissent comme des télémédiateurs; chez certaines espèces il peut cependant s'agir d'endotoxines, qui sont néanmoins libérées dans le fluide marin au moment de la lyse cellulaire (souvent favorisée par les bactéries lytiques) et qui peuvent également être considérées comme des médiateurs toxiques.

Ces faits sont confirmés par les expériences d'Aldrich et Coll. (1967) faites avec des cultures de *Gonyaulax monilata*, espèce dans laquelle le maximum de toxicité est atteint un mois après le début du déclin de la culture.

Selon Shilo (1967) "il est également important d'étudier le rôle des facteurs physiologiques et environnementaux dans la biosynthèse des toxines algales, et de comprendre les étapes conduisant à l'accumulation extracellulaire de la toxine dans le milieu aquatique. Ceux-ci comprennent les facteurs qui affectent l'excrétion et la stabilité de la toxine. ou qui augmentent ou inhibent l'activité de la toxine extracellulaire".

Ce rappel bibliographique des conséquences pathologiques liées à l'eutrophisation de zones marines met en évidence l'etendue et l'ampleur de ces phénomènes dystrophiques qui peuvent aussi bien porter atteinte au capital nutritionnel marin qu'à l'état sanitaire des populations qui peuvent être infestées par voie digestive, respiratoire ou cutanée. De ce fait leur impact sur l'économie de toute une région est certain. Il impose que soient définies les mesures de détection et de prévention pour faire face à ces risques.

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THEORIE GENERALE DE L'EUTROPHISATION

par

M. Aubert

Resumé

Les apports telluriques vers le milieu marin comportent une importante fraction en matière organique composée essentiellement d'azote, de phosphore et de carbone. Ces substances minéralisées par les processus bactériens sont à la disposition de la flore phytoplanctonique. Il faut que dans des conditions énergétiques convenables (températures et éclairement) existe un stock de nutriles nécessaire et suffisant pour la croissance phytoplanctonique, mais il n'y a pas de parallélisme entre les taux d'azote ou de phosphore dans l'eau et les taux de productivité de ces espèces.

A l'état naturel, la répartition des espèces composant la flore phytoplanctonique comprend une majorité de diatomées avec, à d'autres moments, des poussées intéressant les dinoflagellés. La répartition de ces principales espèces se fait selon un rythme qui peut être expliqué, à partir des expérimentations faites au C.E.R.B.O.M., par les processus biochimiques suivants :

Au départ, nous voyons croître la population des diatomées à partir de l'azote et du phosphore d'origine tellurique. Cette croissance est stimulée par de médiateurs d'origine bactérienne : Vitamine B12, phytohormones. Cette prolifération phytoplanctonique entraîne une diminution progressive des taux d'azote et de phosphore. L'étude biochimique des eaux montre que les diatomées sécrètent dans le milieu certaines substances dont le spectre est caractérisé par un pic voisin de 245nm. L'action de cette substance est antagoniste de la prolifération des dinoflagellés (médiateur planctonostatique).

Les diatomées ayant consommé l'azote et le phosphore se mettent à décroître par dénutrition.

Le nombre des diatomées ayant fortement diminué, les dinoflagellés ne sont plus soumis aux médiateurs antagonistes et peuvent alors se développer, mais le stock d'azote et de phosphore consommé antérieurement par les diatomées n'étant pas encore remis en circulation, la croissance des dinoflagellés, organismes autotrophes et hétérotrophes, peut s'effectuer à partir du carbonne resté disponible. Les dinoflagellés, de plus en plus nombreux dans le milieu émettent à leur tour des médiateurs antagonistes qui ont une double action : la première empêche la prolifération des diatomées, la deuxième est une auto-inhibition des dinoflagellés eux-mêmes. Le spectre de ces sécrétions est caractérisé par un pic voisin de 230nm.

Les dinoflagellés, d'une part ayant épuisé les stocks nutritifs, et d'autre part ayant subi l'influence du médiateur auto-inhibiteur, commencent à disparaître.

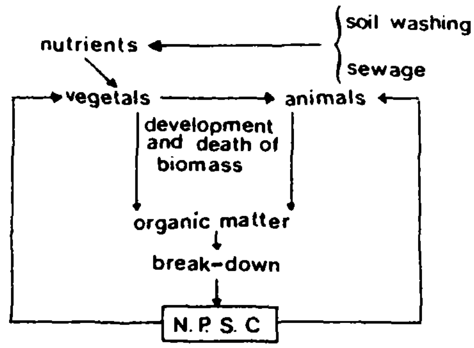
Cette disparition lève l'obstacle à la prolifération des diatomées qui, à partir d'un stock d'azote et de phosphore reconstitué par les apports constants telluriques, peuvent reprendre leur processus de croissance.

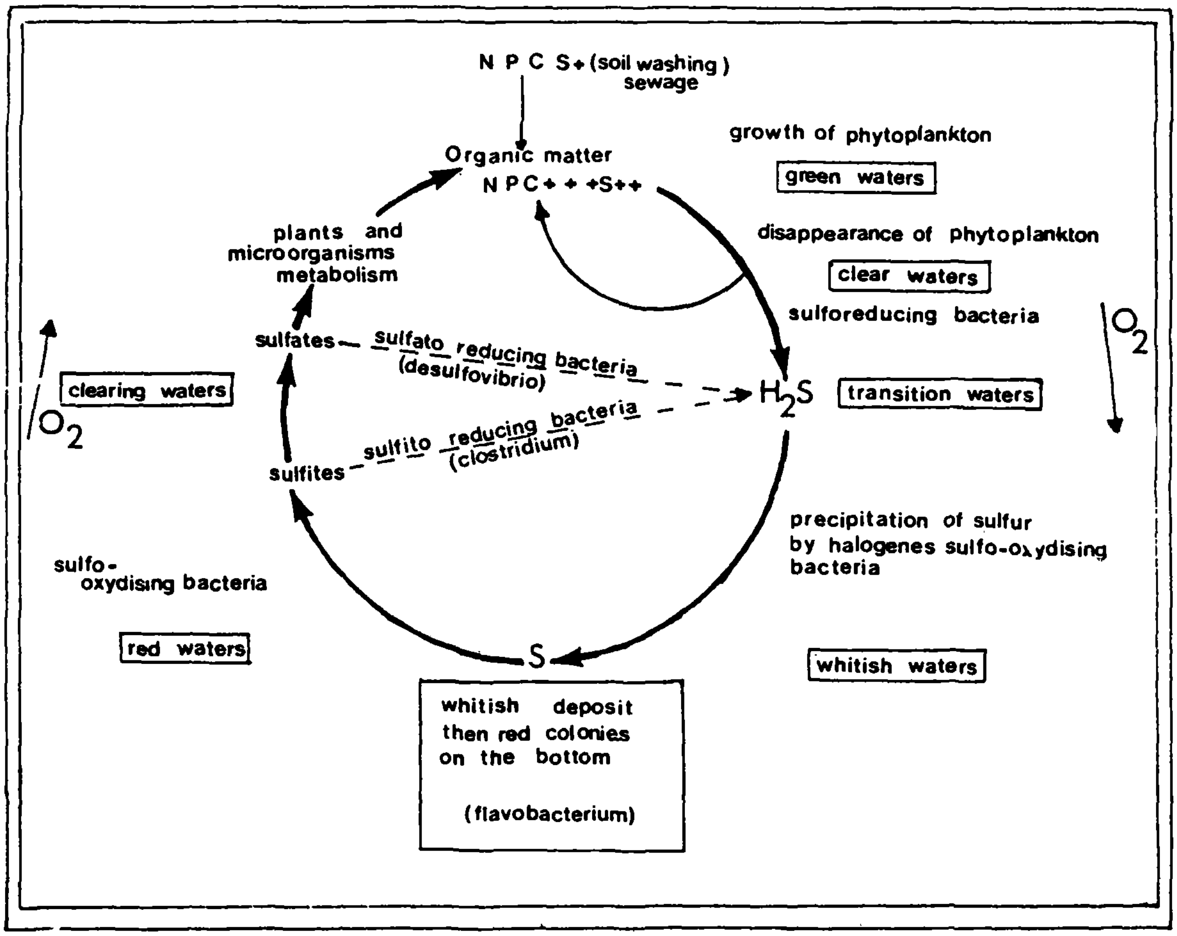
Cette évolution cyclique est celle que l'on rencontre habituellement dans les eaux de mer littorales soumises aux apports telluriques.

Mais en certaines zones marines et avec une fréquence accrue, on voit se développer des proliférations de dinoflagellés qui atteignment des taux élevés avec une extension importante et relativement durable, entraînant des phénomènes toxiques. L'exploration du milieu ayant montré qu'il n'y a pas de relation directe entre les taux de phosphates et de nitrates et al prolifération phytoplanctonique, la cause de ces proliférations anormales apparaît liée à la détérioration des médiateurs par des pollutants rejetés en mer. Des médiateurs inhibiteurs sont en effet déteriorés par certains polluants (pesticides, hydrocarbures, détergents, métaux lourds). Il n'y a donc plus de frein à la croissance des dinoflagellés. Le phénomène ne peut s'interrompre que par épuisement des nutriles et par brassage des eaux lié à des perturbations hydrodynamiques ou météorologiques qui viennent modifier leur composition biochemique.

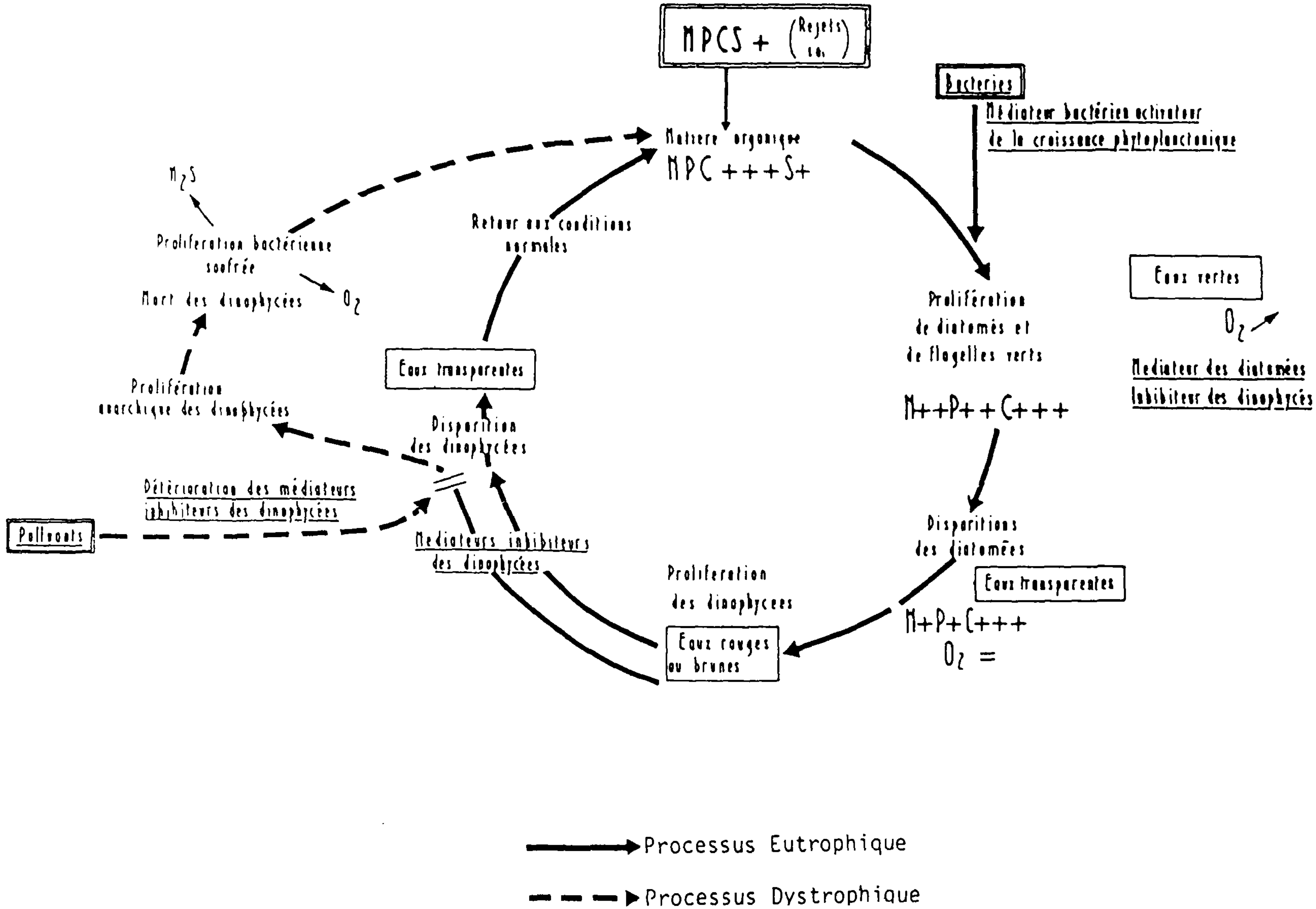
APPLICATIONS PRATIQUES EVENTUELLES :

L'isolement et la mise en évidence de la nature chimique de ces médiateurs planctonostatiques devrait permettre d'en faire la synthèse, de les produire industriellement et de les répandre dans les zones cloisonnées de conchyliculture dès l'apparition de phénomènes eutrophiques arrêtant ainsi la prolifération des espèces planctoniques toxiques.





Schematic Presentation of Bacterial Cycles in Eutrophied Systems.
(From M. & J. Aubert, 1986, R.I.O.M. 83-84)



Schematic Presentation of the Phytoplankton
Cycle in Eutrophied Systems

SYSTEMS ANALYSIS AND ECOLOGICAL MODELLING FOR ASSESSMENT AND CONTROL OF MARINE EUTROPHICATION

by

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AN INTRODUCTION TO THE PROBLEM

Eutrophication is a well known, although still somewhat controversial theme in limnology (Hutchinson, 1969, 1973). In lakes, eutrophication is generally understood to describe their natural aging process; cultural eutrophication refers to the man-made acceleration of this process, triggered by excessive nutrient loads to water bodies from industrial, agricultural and domestic sources. The marine manifestation of eutrophication is what in limnological systems is referred to as cultural eutrophication, or simply man-made overfertilization of aquatic systems. It has to be understood as a specific form of pollution, and, from the viewpoint of the catastrophic changes it can trigger, as a stress factor (Pearson, 1981).

From a socio-political perspective, eutrophication becomes a concern as soon as it starts to endanger the value (in ethical, aesthetic or monetary terms) of an important part of our environment. For all practical purposes therefore, a simple pragmatic definition has been adopted that holds eutrophication to be a form of (nutrient) pollution that degrades and endangers a natural resource, in this particular case, coastal marine systems.

Marine eutrophication is by and large a coastal phenomenon, that requires the coincidence of two important factors :

- a relatively shallow and sheltered basin with reduced water exchange, often subject to thermal or density stratification;
- a massive source of nutrient inflow, usually a river or the fallout from urban or industrial waste water systems; agricultural (non-point) runoff as a rule contributes indirectly through a major drainage system, i.e. a river.

The Mediterranean Sea as a whole, although well enclosed, with a water area of about 2.5 million km^2 and a drainage area of 1.8 million km^2, excluding the Nile basin (with 2.7 million km^2), with a population (of the 18 Mediterranean states) above 300 million, is rarely acutely endangered. Several areas, however, and the North Adriatic Sea, the Gulf of Tunis, and the Gulf of Saronikos (Athens) as probably the most obvious examples, are subject to severe impacts and accelerating degradation. Direct and indirect effects on tourism, fisheries, and the richness and variety of the marine environment in general are being attributed to marine eutrophication. A special issue of Ambio (Volume VI, 6, 1977) testifies to these problems that go far beyond eutrophication.

THE ROLE OF SYSTEMS ANALYSIS AND MODELLING

The central approach of systems analysis involves looking at a given system from the perspective of the next higher system, which defines boundary conditions and driving forces, and at the set of the component sub-systems that define the function.

In the case of marine eutrophication this means viewing the coastal marine environment from the perspective of the entire marine system as well as its terrestrial catchment, and looking at the ecological processes from the level of the socio-economic and political system causing the excess nutrient input on the one hand, and utilizing the endangered resource on the other hand.

In terms of the components, it means looking at transport processes, energy flow and oxygen dynamics, trophic relationships and related questions at the level of individual species and communities.

The systems analytical approach and modelling as its central tool can make several important contributions :

- it can integrate and synthesize available information;
- it can identify gaps in our knowledge and understanding of important phenomena;
- and finally, it can be used as a decision-support tool, providing information on alternative courses of action, priorities, sensitivities, and trade-offs.

While there exists a large volume of information on tbe biology and ecology of marine systems (for a pollution-oriented example of an excellent compilation of information see Rat der Sachverstandigen fur Umweltfragen, 1980) and the Mediterranean in particular, scientific information is rarely compiled with one specific management purpose in mind. Putting together the pieces of the puzzle can be greatly assisted by a comprehensive framework such as an ecosystems model. A successful example of the use of modelling also as a vehicle for data synthesis is, for example, described in Kremer & Nixon (1978).

Interactive data bases, graphical display of data under interactive user control, and processing of these data with statistical methods and finally simulation models provide extremely powerful tools for the synthesis of fragmented data and information (e.g. Fedra & Loucks, 1985).

Most of the ecological relationships and dependencies relevant to marine eutrophication are qualitative hypotheses at best (e.g. Barnes & Mann, 1980; Canale, 1976; Cushings & Walsh, 1976; Goldberg et al., 1977; Parsons et al., 1977; Longhurst, 1981). Too many variables interact to identify any clear and direct relationships through the noise and uncertainty of most observations. While the general trends and qualitative relationships are obvious. any more detailed and quantitative relationships (other than in the form of an empirical description of a specific event at a specific site) are lacking. Formulating such hypotheses as models amenable to simulation and testing them against the usually sketchy evidence can help to greatly improve our understanding of ecological processes (Fedra, 1981).

The ecological level is only one of the levels of conceptualization. At the next bigger frame of reference, marine eutrophication is transformed from an ecological phenomenon into a socio-economic and political problem.

While modelling can help understand the processes and dependencies involved, and can help to explain (in terms of their inner workings) the phenomena, it does not improve them. Corrective action is only possible at the political and socio-economic level. Here modelling can be used to :

- estimate nutrient loads from secondary data (e.g. on population, industrial production volumes and technologies) and rank the sources contributing to the problem;

- address what-if questions, i.e. evaluate possible corrective actions and estimate their cost effectiveness.

To design and evaluate alternative development policies in terms of the governing socio-economic activities, objectives, and constraints, the primary information requirements for decision support include :

- Background information on the *status quo* and likely developments, including straightforward extrapolations of the current trends;

- Design and analysis of feasible development policies and action plans (optimization of individual activities such as sanitation measures or regulatory options), including :

- Economic analysis (input/output), cost/benefit, for the regional economy and industrial activities or technology alternatives, infrastructure measures, or regulatory options, and their environmental impacts and effectiveness, respectively);

- Resource requirements and allocation (e.g. capital, technology);

- Environmental impact analysis, i.e. the simulation of the environmental consequences of any of these possible actions or developments including the effects of no corrective action. or the extrapolation of current trends;

- Comparative evaluation of alternatives in terms of economic and environmental criteria (policy analysis).

Obviously, the volume and complexity of the information involved requires the use of modern computer and information technology.

MODELLING THE PROBLEM'S COMPONENTS

To provide a comprehensive representation of the marine eutrophication phenomenon, any description will have to include :

- a description of the sources of nutrients, i.e., the socio-economic and technological activities in the catchment area;

- a description of the transportation processes, from the river systems to the coastal circulation patterns to the transport mechanism in the overall Mediterranean basin;

- a description of the ecological and physiological processes triggered by the excessive nutrient loading and the consequent environmental degradation phenomena;

- a description of the resulting feedback mechanisms, e.g. on tourism and fisheries.

Modelling the catchment of the entire Mediterranean is a complicated, but conceptually relatively simple task. The three major types of sources are industrial waste water, domestic waste water, and non-point runoff, largely from agricultural areas.

For all these three categories of pollution sources, more or less well tested estimation procedures and models do exist, including, for example on water pollution and pollution control comprising treatment technologies in general, Clark (1977), James (1978), Horvath (1984), Cheremisinoff & Young (1975); on nonpoint sources Reckhow et al, 1980; Overcash & Davidson (1981), Novotny & Chester (1983); Rast & Lee (1978); and on industrial point sources Lund (1971); Bridgewater & Mumford (1979); Sell (1981); Overcash (1986).

These techniques allow an estimation of nutrient release from various forms of land use, industrial production,and urban waste water systems and treatment plants using an array of methods from simple areal or per capita export coefficients to complex process-oriented simulation models; many of them also include economic estimates. Such model-based estimation techniques certainly include considerable uncertainties: these uncertainties. however, have to be seen *vis a vis* the uncertainties and measurement errors in traditional sampling and measurement techniques and extrapolation from such data. A successful example of using such estimation techniques at the watershed level, together with a detailed ecological water quality model, is given in Fedra (1985).

The transportation of nutrients involves two distinct phases: transportation in river systems (e.g. Shen, 1979; Orlob, 1983;) and transport in the marine system (e.g. Cooper & Pearce, 1977; Castellano & Dinelli, 1975; Holland, 1977). In both cases, the description of the physical transport phenomena is complicated by the biochemical transformations that run parallel (e.g. Canale, 1976).

In the coastal marine environment itself, models describe primary production (e.g. Steemann Nielsen 1975; Nihoul 1975), trophic relationships from phytoplankton to zooplankton (Steele & Frost, 1977; Steele & Mullin, 1977) and fish (Andersen & Ursin, 1977), and the benthos as an important element in the nutrient and associated oxygen cycle (e.g. Ott & Fedra, 1975; Olscher & Fedra, 1977; Fedra, 1977). Numerous models to describe these ecological and ecophysiological relationships do exist. Few of them, however, provide for a satisfactory coupling of physical transport phenomena and the biological processes or economic criteria (for a study attempting such an integration see Ikeda, 1985).

Finally. the tools of system dynamics (Forrester, 1968), and more recently, also of symbolic and approximate simulation (e.g. Gupta et al., 1985) allow for the description of the feedback mechanisms connecting the environmental system back to the socio-economic watershed based on empirical evidence or on expert opinion.

In summary, a large assortment of tools for modelling the marine eutrophication process in a comprehensive framework does exist. While all these tools certainly have their shortcomings, they provide the challenging possibility of integrating the large amount of available information into a coherent framework for numerical experimentation and decision support.

PUTTING THE TOOLS TO WORK

Applied systems analysis is action oriented: its central claim is to be a useful decision support tool beyond the management level of operations research, at the strategic planning and policy level (Loucks et al., 1985; Fedra & Loucks, 1985).

The coordinated development of a multi-national catchment aimed at a reduction of the pollution load to the Mediterranean system as a whole and a number of priority regions in particular, requires the simultaneous consideration of numerous inter-relationships and impacts, e.g., the processes in the physical and biological system, economic and industrial development, resource .requirements for technological change and infrastructure development, and socio-economic effects. Plans and policies for a rational and coordinated development and action plan need a large amount of background information from various domains such as economics, industrial and sanitary engineering, and environmental sciences, in a readily available format, directly usable by the planner and decision maker. However, the vast amount of complex and largely technical information and the confounding multitude of possible consequences and actions taken on the one hand, and the complexity of the available scientific methodology for dealing with these problems on the other hand, pose major obstacles to the effective use of technical information and scientific methodology by decision makers.

One aim of applied systems analysis is to develop tools to make the scientific basis for planning and management directly available to planners and policy and decision makers. Using concepts of artificial intelligence coupled with more traditional methods of applied systems analysis and operations research, these tools are designed to provide easy and direct access to scientific evidence, and allow the efficient use of formal methods of analysis and information management by non-technical users as well.

Integrating available information, and providing a problem representation that is directly meaningful and understandable for a non-technical user of such decision support tools, allows the gap to be bridged between the level of detail and complexity of scientific data and methods, and the information requirements at a strategic planning and policy level.

The abundance of increasingly affordable computing power lends itself to such new and demanding applications (Fedra & Loucks, 1985). In the case of marine eutrophication with its multi-sectoral and international framework, providing decision support to planners and policy makers is certainly an ambitious task. At a planning and policy-making level, problems are characterized by their multi- and interdisciplinary nature, as well as the often dominating importance of political, judgemental elements as opposed to purely technical, scientific problems.

As a consequence, the classical formal approaches to technical problem solving are not strictly applicable, and the people involved are not necessarily technically trained experts only but will include elected representatives, interest groups, and the general public. Therefore, new methods of problem solving, or applied systems analysis, and new means of communicating scientific and technical information have to be developed.

The basic problem is one of man-machine communication, that is combining the largely numerical domain of scientific evidence and formal models with the necessarily subjective and largely judgemental domain of perception and evaluation in an interactive, attractive, and educational format. A friendly user-interface with emphasis on symbolic and pictorial representation of information, using natural language and colour graphics, can provide access to otherwise difficult-to-use formal methods (Fedra, 1985).

In advocating and building computer-based information and decision support systems, we clearly imply that informed and structured decisions are "better" decisions. The problem is one of providing information of a kind and in a format that is directly relevant to the problem at hand, so that it really can support the decision-making process in practice. This requires, on the one hand, a high degree of flexibility in problem representation, calling for a pluralistic approach combining descriptive, consultative, and normative models, and on the other hand, communication and display formats that are immediately understandable, such as well-designed graphics. The design of a model-based decision support system also requires close attention to the questions of interaction, communication, and of course, institutional structures. It also requires a different approach to problem representation. Instead of getting the problem to - somehow - fit a preconceived methodology, we need a larger and more flexible array of tools to choose from.

This new paradigm for modelling and systems analysis envisions an integrated man-machine system, where, instead of learning to fly an aircraft or to control a nuclear power plant the user learns to manage coastal marine systems and their terrestrial catchment with the help of an appropriate simulator or trainer. The difference between what is proposed here to the more traditional off-line approaches seems worthwhile reiterating. Instead of delivering "the optimal" solution or a set of solutions to choose from, what is delivered is a customized set of tools and techniques, that will allow the user to generate and evaluate solutions to his problems. No longer is the client required to specify all his objectives and quantify his criteria *a priori*: he can explore the problem at leisure, and develop his objectives and criteria as part of the ongoing learning process. The methods of analysis are now made part of the decision-making process at the strategic planning and policy level.

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CASE STUDY

EUTROPHICATION IN THE GOLFE DU LION

by

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INTRODUCTION

It is very well known that oceanic primary production is essentially occuring in coastal areas, and that the related zones represent a small part of the whole oceanic area.

In the western Mediterranean sea. the available data in the Golfe du Lion are a good illustration of this general statement.

Eutrophication in superficial waters in coastal areas. results from several phenomena

- winter vertical mixing of waters
- coastal upwellings of deep waters
- discharges of effluents (rivers, sewages, industrial effluents).
- natural terrestrial runoff.

The Golfe du Lion which is affected by different sources of eutrophication is one of the most productive areas in the Mediterranean (except, of course, the Adriatic sea).

LOCAL CONDITIONS

In the western Mediterranean sea, the Golfe du Lion (Fig. 1) is characterized by a large continental shelf. It stretches in a semi circular plan down to 200 m depth between Cap Creux and Cap Croisette (Marseille). Its mean depth is 90 m, its area is about 11000 km^2. The southern edge is cut by canyons which are privileged exchange routes between oceanic deep waters and superficial ones.

The main features of the weather in this region are : low rainfall (600 $mm.yr^{-1}$), predominance of dry, cold and buffeting northern or northwestern winds. The wind strength and its frequency have a great influence on the vertical and horizontal water circulations, including important modifications in the marine ecosystems.

The Golfe du Lion is washed by the oligotrophic cyclonic liguroprovencal stream which originates in the Atlantic (Fig. 2). In summer, it is temporarily invaded with deep water (oriental intermediate water) rich in nutrients. In winter, the area consists of vertically mixed waters originating from great depths (Fieux, 1972; Gascard, 1974).

The extension of the Rhone river waters at the surface of the sea in the Golfe du Lion (Fig. 3) depends on the season, the flow of the river (Tournier, 1969), the strength and the direction of the wind. The Rhone river with a mean flow of 1600 m^{3-1} provides 93% of very eutrophic fresh waters flowing into the Golfe du Lion.

SOURCES OF EUTROPHICATION

Four sources can be distinguished :

1) <u>The winter vertical mixed waters</u> : (Gostan & Nival, 1963 ; Gascard, 1974, 1978) are one of the most important sources of nutrient enrichment of the surface coastal water and also of the open sea. These waters may spread throughout the Golfe du Lion. The origin and evolution of these vertical mixed waters are well documented (Medoc Group, 1970; Minas, 1968; Minas & Blanc, 1970; Costa et al., 1972).

2) <u>The coastal "upwellings"</u> : Upwellings of deep waters are generated by northern and northwestern winds, they result in temporary nutrient enrichment of the surface water (Millot & Wald, 1980, 1981). The impact of such upwellings on the primary production is not yet well known.

3) Impact of the River Rhone : Eutrophication by inputs of the Rhone river has been investigated (Blanc et al, 1969; Blanc & Leveau, 1970; Coste, 1971, 1975). Concentrations of various nutrients in the waters of the Rhone have been compared to those in deep Mediterranean water; nitrates are found to be 8-10 times higher, and phosphates 3-10 times higher.

4) Urban and industrial effluents : Estimation of their importance is difficult; nevertheless some estimations have been made : in the maritime zone II (defined in the Med Pol Program : Golfe de Fos, the Spanish sector to the Balearic islands and the French-Italian coast to the islands of Tuscany and Corsica) nutrients brought by coastal effluents constitute only 10% of the river inputs (Rapport PNUE 1977 no. 32, 1984).

Natural runoff of drainage basin

Mediterranean rainfalls are stormy and wash fertilized farmland. If the main part of these waters is collected by sewage, the remaining run off discharges directly to the sea diffusely along the shore.

QUALITY OF THE DIFFERENT INPUTS OF WATER

Quality of the Rhone river waters : This has been monitored by monthly surveys during a 3 year period, August 1966 - July 1969 (Coste, 1971, 1975). A new survey (R.N.O.) resumed in 1980 and is still in progress after an interruption in 1982 (Leveau & Coste, in press).

Quality of the Golfe du Lion waters, impact of the Rhone river : Many cruises have been dedicated to this problem with different strategies : a network of stations and multiparametric measurements in the surface waters provides a spatio-temporal distribution of nutrients in different water layers. The seasonal aspects (Figs. 4, 5, 6b and e) have been also considered (Blanc & Leveau, 1973; Freije, 1985).

The impact of the Rhone river waters on the very oligotrophic sea waters induces a dense but localized phytoplankton bloom, the intensity and limits of which have been studied.

The phytoplankton blooms quickly utilize the available nutrients and, depending on the weather conditions (Fig. 6c, f), they can sediment *in situ* after death or they can be scattered and mineralized elsewhere, sometimes in the open sea (Freije, 1985).

EVALUATION OF STUDIES AND DATA

Evaluation of Rhone input : The Rhone river represents a drainage basin of about 95000 km^2 with a mean flow of 1600 m$^{3-1}$ (51 x 109 m$^{3-1}$). The mean flows of suspended solids, nitrogen, phosphorus are respectively : 5

millions $T.yr^{-1}$ for suspended solids, 150000 $T.yr^{-1}$ for nitrogen and 7000 $T.yr^{-1}$ for phosphorus (Leveau & Coste, in press).

Turbid and eutrophic Rhone river waters run across the oligotrophic Liguro-provencal stream, with few suspended solids, moving from east to west.

Fate of Rhone river waters in the sea : The low-density water spreads at the surface of the sea, and the dilution sheet moves southwest or west, driven by the liguro-provencal stream. It covers the whole of the Golfe du Lion, the direction and extension being determined by weather conditions.

The thickness of the dilution sheet is variable, from a few cm to several meters.

The "thermic patches" corresponding to Rhone river waters were studied by remote sensing. The temperature of the Rhone river waters presents large variations depending on the season. The difference in temperature between the Rhone river water and that of the sea is sufficient to distinguish the development of the Rhone river plume from the "thermic patches". Variations of the "thermic patches" can be monitored by remote sensing pictures at short time intervals (Fig. 7) to correlate the extension, variation and progression of the plume with changes of the atmospheric conditions (Demarcq & Wald, 1984).

Impact of the Rhone input - Suspended solids. The amount of suspended solids varies with flow and periods of flood. When they reach the sea, material sediments near the mouth (Monaco, 1980). At the surface, turbidity remains important defining 3 concentric zones characterized by the size of the material (Fig. 8). (Loeillet, 1984, Loeillet & Leveau, 1985).

The suspended solids reduce the light penetration necessary for photosynthesis; they also behave as vectors by adsorption of chemical pollutants.

Impact of eutrophication : Nutrients introduced in the field cause important eutrophication of part of the Golfe du Lion waters. A combination of de-salting of water and eutrophication induces development of an unstructured, undiversified, immature, planktonic system with a great abundance of small size species (Blanc & Leveau, 1970, 1973; Jacques, 1970). The high chlorophyll *a* content corresponds to a large phytoplankton biomass.

The development of "thermic patches" with time and space has been monitored by remote sensing (CZCS) under favourable weather conditions. Measurements of chlorophyll *a* and primary productivity carried out simultaneously provided good correlations.

The highest productivity is estimated as 460 mg $C.m^{-3}$. d^{-1} (Demarcq, 1985; Freije, 1985).

When the hydroclimatic conditions are favourable (Peres et al., 1986), i.e. stability of waters, high temperature, and high level of nutrients, red tides (Dinoflagelates) are regularly observed near the mouth of Rhone river.

TECHNICAL CONTROL OF EUTROPHICATION

Measurements in the Rhone river : The river is regularly sampled, in parallel with flow measurements.

Measurements of different parameters in water : A national network of measurements (Reseau national de mesures - RNO) is operating in different zones of the Golfe du Lion.

National and international programs : Several programs on eutrophication are conducted in the Golfe du Lion.

PROSPECTS

The main parameters, input, water quality, nutrient content, hydrodynamics in the Golfe du Lion, are well characterized. It is necessary, now, to study the dynamics of the system and the correlations between its different parameters.

- Quantification at different scales of time and space of the suspended solid flux in relation with allochthonous or autochthonous origin; measurements of the transfer to open sea (sedimentation, velocity, transport, accumulation, determination of the affected benthic zone).

- Spatio-temporal fluctuations of planktonic communities

  . fluctuation of the primary productivity
  . development of zooplanktonic communities, importance of grazing, detritus production

- Bacterial production and re-mineralisation cycle.

- Study of benthic communities, correlations with suspended solids sedimentation and planktonic productivity.

  . definition of benthic communities
  . study of trophic groups and interrelations with particulate matter

- Ichtyological enrichment connected with primary and secondary planktonic productivities; displacement of fish shoals with patches of high productivity.

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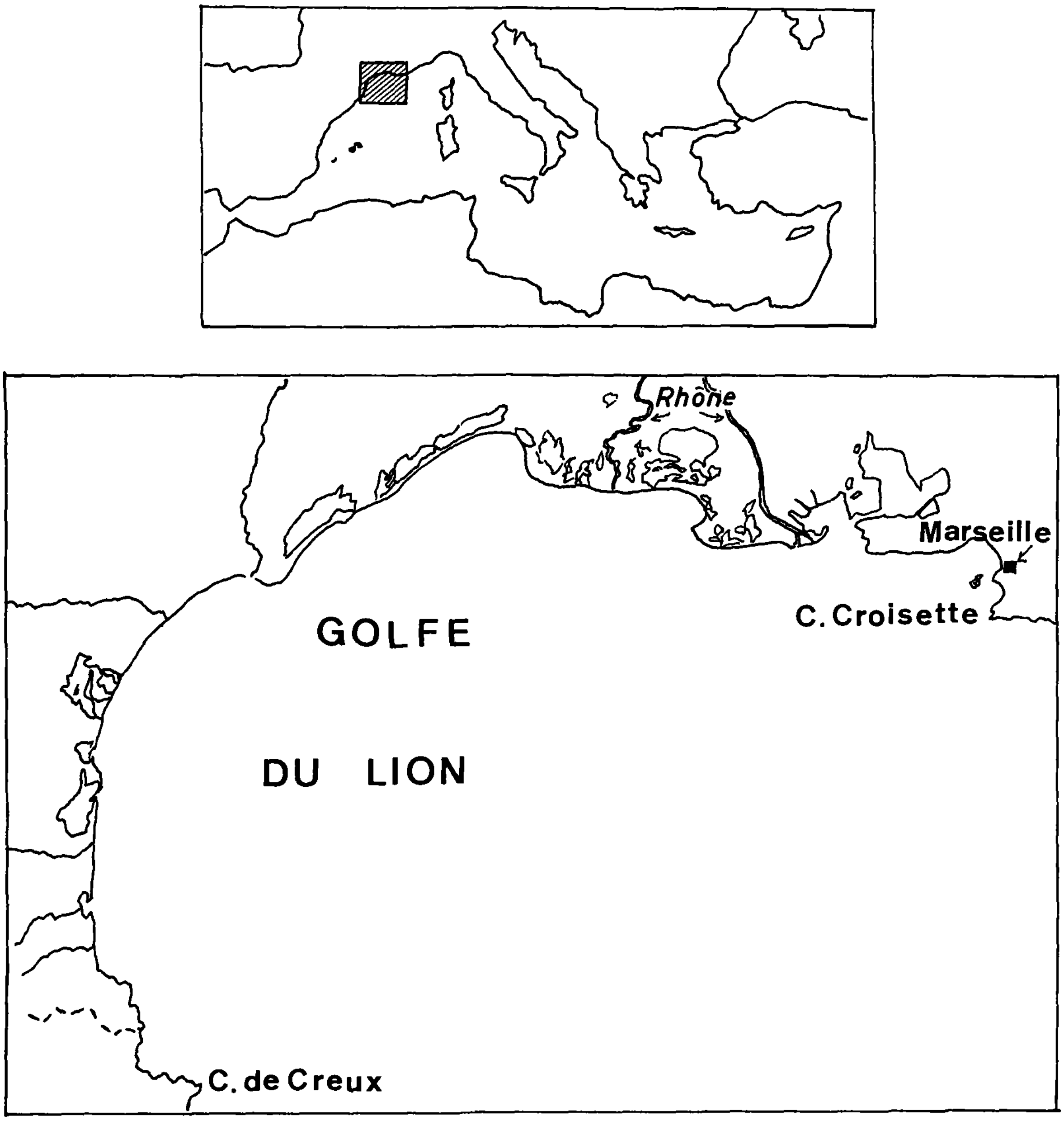

Figure 1 : Golfe du Lion

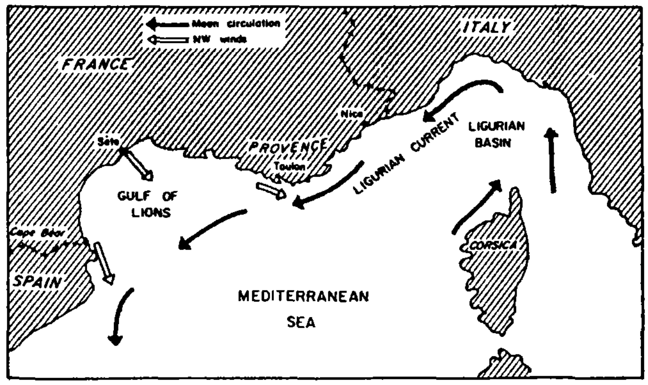

Figure 2 : The general oceanic circulation is influenced by the N - NW winds near the coasts of Provence (from Millot & Wald, 1980)

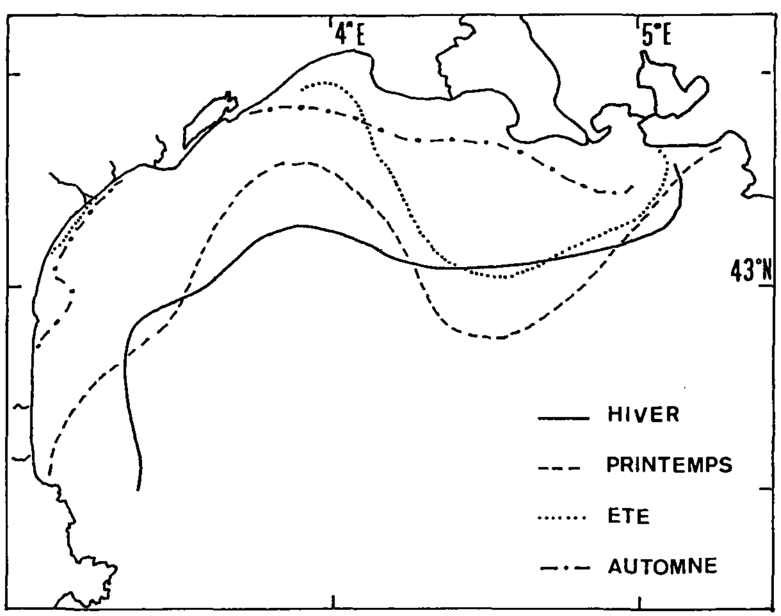

Figure 3 : Changes in seasonal surface water for 37% isohaline (from Tournier, .1969)

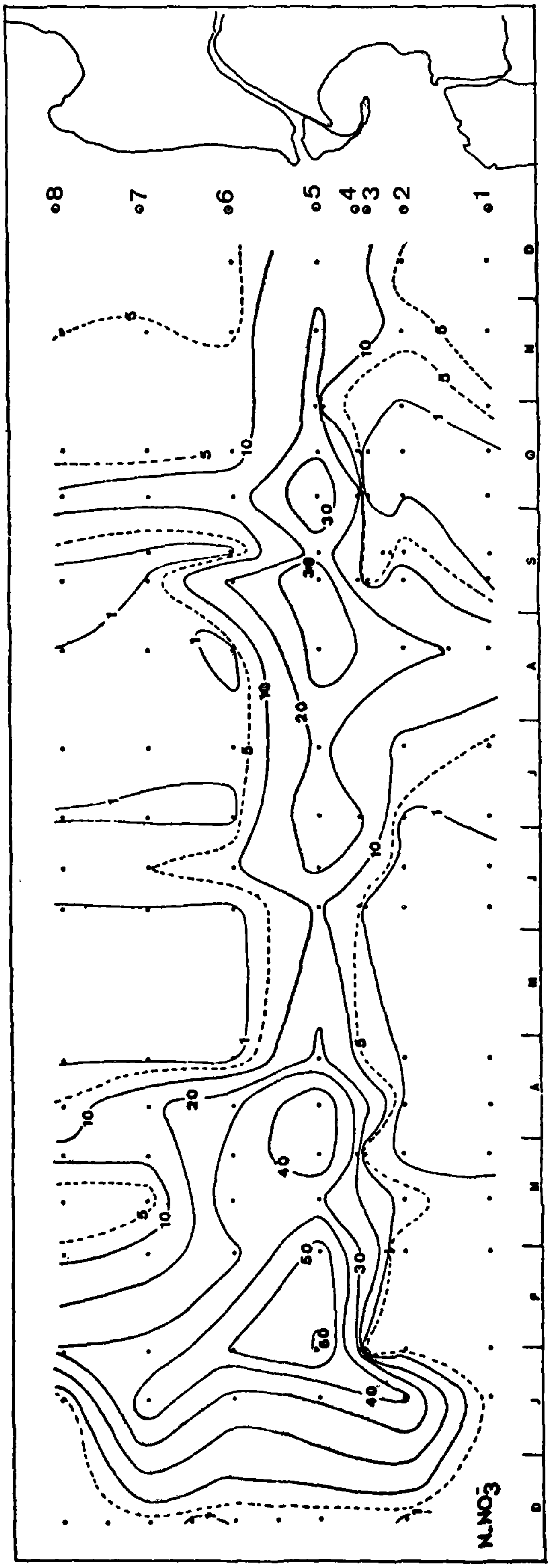

Figure 4 : Monthly surveys of nitrogen concentrations ($N - NO_3$ ug at. l^{-1}) in surface coastal waters along a transect near the mouth of the Rhône river

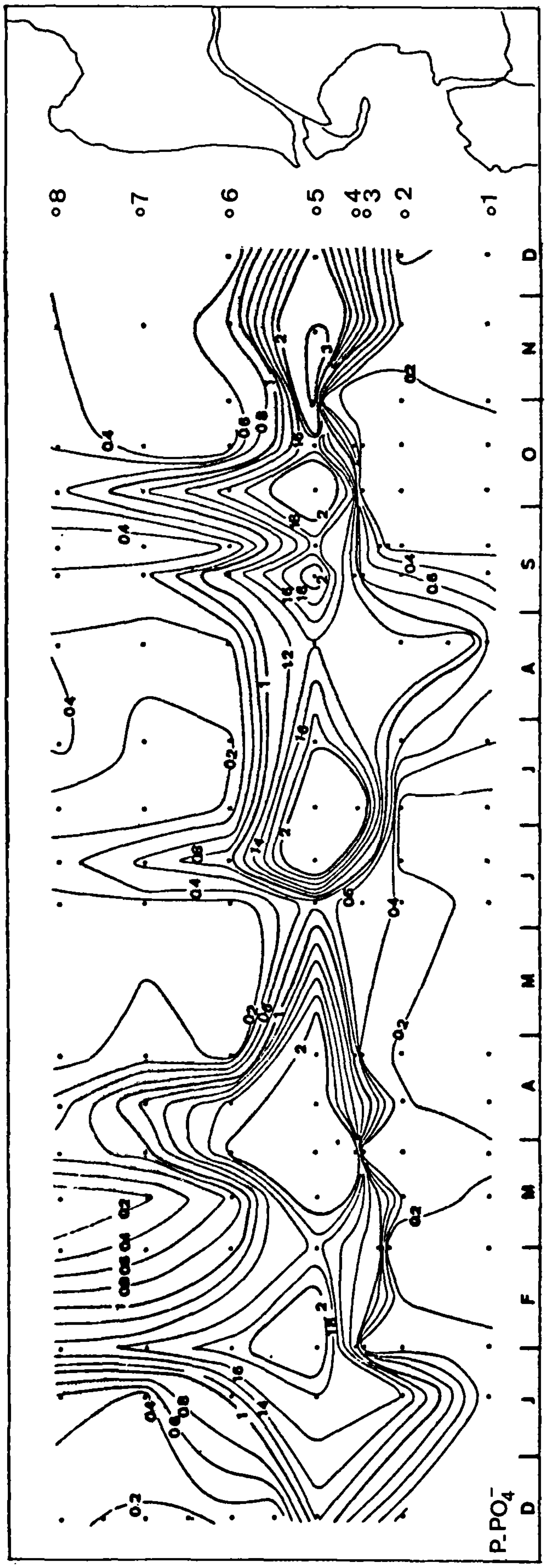

Figure 5 : Monthly surveys of phosphorus concentrations ($P - PO_4$ ug at. l^{-1}) in surface coastal waters along a transect near the mouth of the Rhône river.

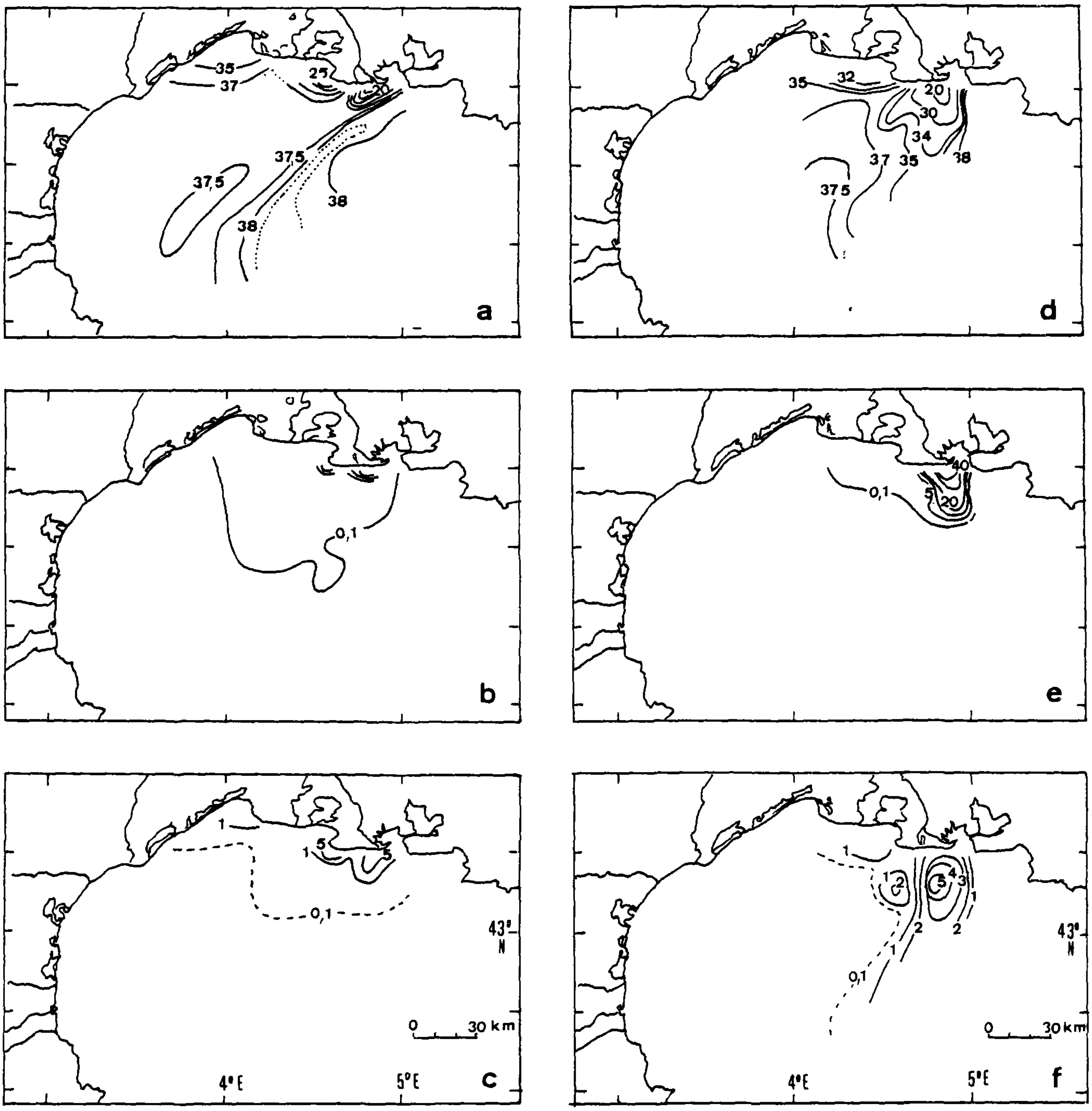

Figure 6 : Spatial distribution of three parameters (salinity, nitrate-nitrogen and chlorophyll *a*) measured under two meteorological conditions during Eurhogli cruises. Period with wind a, b, c; period without wind d, e, f. Salinity a, d; NO_3 - N (ug at. l^{-1}) b, e; chlorophyll *a* (ug. l^{-1}) c, f.

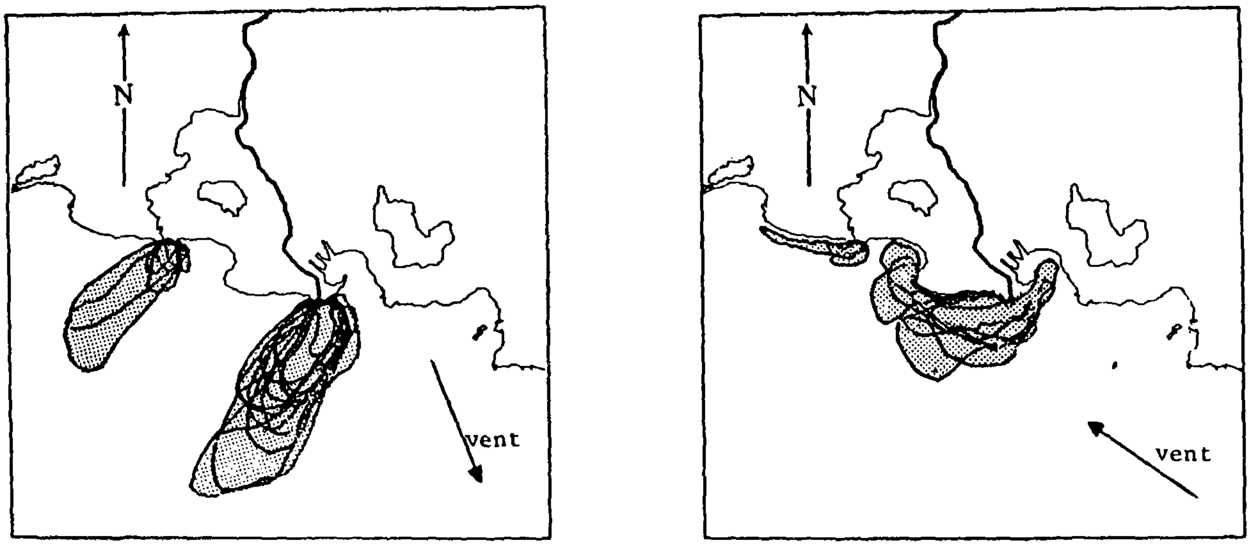

Figure 7 : Superposition of plume contours obtained at different dates for wind blowing from N - NW and from E to SE (from Demarcq & Wald, 1984)

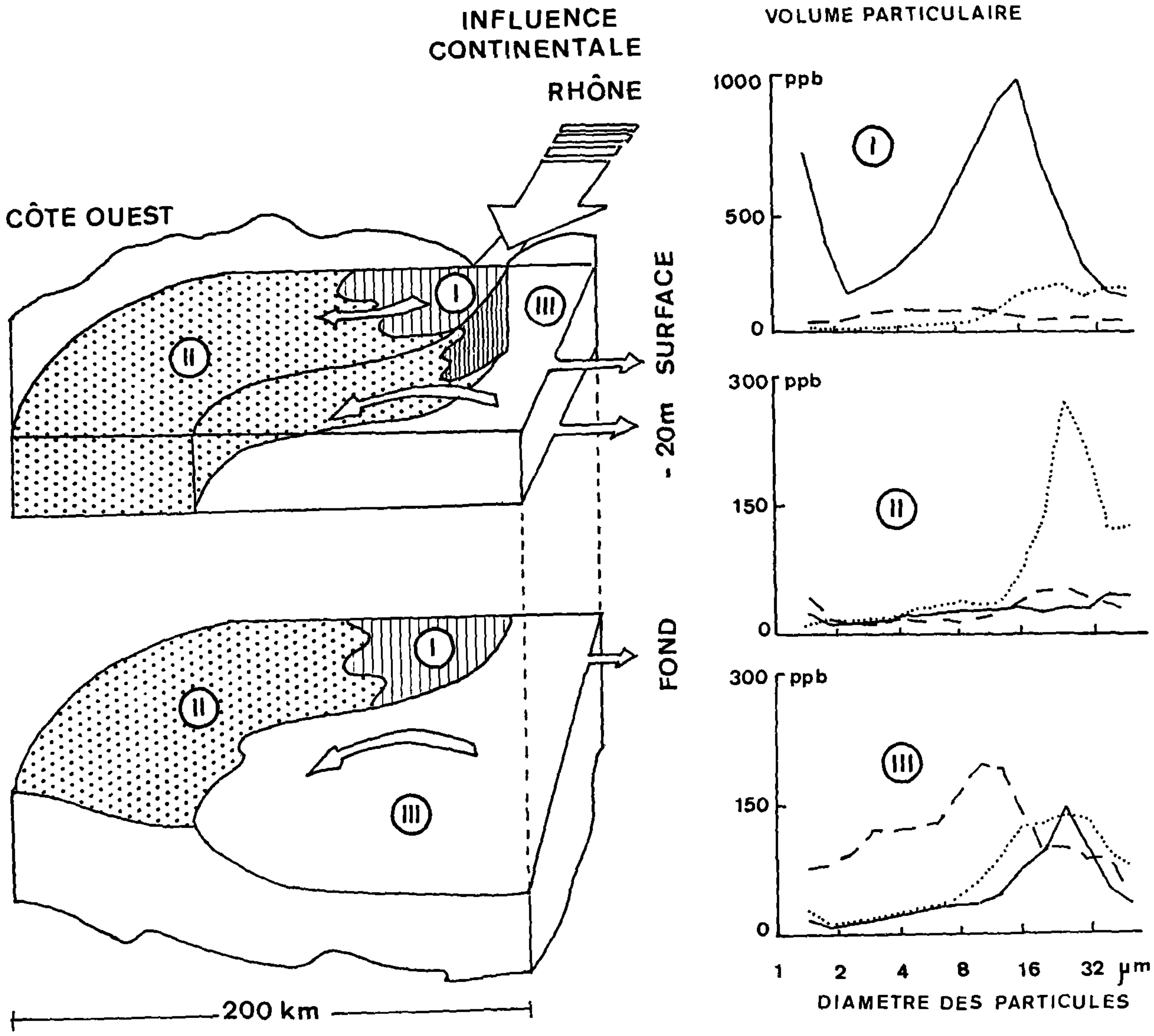

Figure 8 : Schematic presentation of the Golfe du Lion derived from data collected during Eurhogli cruise. Specific distribution of particulate matter within the three zones of the scheme : primary area of dilution (I); continental shelf (II); non affected area (III). Particle size distribution in each zone (surface :——— intermediate levels (- 20m) :········, bottom :-------)

ADDENDUM : L'ETANG DE BERRE

This is a much more extreme example of eutrophication. It is a shallow (9m) semi-enclosed environment, which is, together with the gulf of Fos, an extension of the Golfe du Lion. It receives a strong irregular input of fresh water in the north part, although the south part is linked with the sea. A strong almost permanent stratification of water is induced by the spread of fresh water at the surface, over the sea water trapped at the bottom, in the south. A persistent halocline does not permit any exchange between the 2 water masses. The surface water are rich in nutrients, and regularly present a high density of phytoplankton (10^6 - 10^9 l^{-1}). After the death of these organisms, their sedimentation in the deepest layers of the pond induce a very strong oxygen depletion, and at the halocline an oxycline is superimposed, separating a deep layer of anoxic saline water and an upper layer of oxygenated less saline water. This system is only disturbed by hydrodynamic movements induced by the winds. The succession of these periods of strong eutrophication with their consequences on the deeper layers, have caused the almost total disappearance of the benthos, which does not have time to re-establish during the short periods of normal situation.

CASE STUDY

EUTROPHICATION OF THE SARONIKOS BAY

by

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INTRODUCTION

It is most often the availability of nutrients such as nitrogen and phosphorus that controls the rate of organic production by marine phytoplankton. (Dugdale, 1967; Ryther & Dunstan, 1971). In the Eastern Mediterranean Sea, the low influx of nutrients from land drainage and the characteristic circulation pattern normally result in a small phytoplankton crop and a low rate of primary production (Becacos-Kontos, 1968; Dugdale & Hopkins, 1978). However, in some localities, nutrient enrichment of this otherwise nutritionally poor sea induces exceptionally dense phytoplankton crops. The Saronikos Gulf represents in many ways an excellent case for the investigation of the effects of urban waste disposal into an oligotrophic marine environment.

The Saronikos Gulf, which, for centuries, has accommodated the marine activities of men, has only in the last two decades been exposed to severe ecosystem modification as a result of the heavy and poorly dispersed waste disposal from the Athens - Piraeus - Elefsis areas.

A multidisciplinary international effort has evolved to study the problem out of both Greek and foreign interest. Major organizational contributions have come from the Greek Government, the World Health Organization, the United Nations Development Program, the United Nations Educational Scientific and Cultural Organization, the University of Washington and the NATO Subcommittee on Oceanographic Research. The research is unusual in that it will cover nearly all aspects of the marine waste disposal problem, that is,

a. the exploratory oceanographic observations (the program began in November 1972),

b. the definition of dominant rates and processes,

c. the general pollutant dispersion characteristics of the present outfall,

d. the design criteria and location for a new outfall, including the prediction of changes to occur between now and the time the new outfall comes into use (5-10 years), and

e. the comparison between ecosystem prediction and monitoring after the new outfall has been in use.

EXISTING DATA

Information on eutrophication of the Saronikos Gulf has come from numerous surveys performed since 1964. Fig. 1 shows the area and the location of stations, and Table I, the parameters measured and their annual range.

Hydrographic Characteristics

The Saronikos Gulf, typical of many semi-enclosed seas in the Mediterranean, presents two sections, the eastern and the western ones, separated by Aegina Islands (Fig. 1). The eastern section, with the metropolitan area its head, has a relatively uniform bottom topography, with a depth of 200 m to the south-east of Aegina to 90m between Aegina and Vouliagmeni. The main body of the eastern basin has depths between 70 and 90m. The Western part of the Saronikos is deeper. From the west of Salamis the basin is 130m deep and connects to the south with a 400m depression in the west of the Methanon peninsula. At the north end of the Gulf lies Elefsis Bay with depths of about 30m. The bay is joined to the gulf by two narrow and shallow channels.

The upper Saronikos Gulf is polluted mainly from the sewage outfall, which introduces untreated sewage from the Athens metropolitan area into the sea. Some of the characteristics of the sewage are shown in Table II. Significant amounts of nutrients are also introduced in the form of industrial effluents directly into Elefsis Bay (Friligos, 1979).

The circulation is wind driven (Coachman et al., 1976). Most of the year, it is cyclonic, driven by north or southeast winds. The remainder (about one third of the year), it is anticyclonic (due to southwesterly winds). Renewal of the water in the gulf has been estimated to occur about once every one or two months (Hopkins & Coachman, 1975).

Chemical and Biological Characteristics

The Saronikos Gulf has no run-off rivers so that the Athens effluents located at the north of the gulf provide a very large single source of chemical contaminants to the gulf. Thus, the upper Saronikos Gulf and Elefsis Bay are influenced by domestic waste discharges and industrial effluents, so that the conditions in these areas (eutrophic system) are so different from those found in the lower Saronikos Gulf (oligotrophic system) that they must be considered separately.

The Outer Gulf Water

The Outer Gulf water, which is the source water to the Saronikos Gulf lies to the south east, on the continental shelf separating Athens from the open Aegean, from where it derives its oligotrophic (Table I) biochemical structure (Friligos, 1984a). A well-defined annual phytoplankton cycle, with maxima in spring and autumn, was recorded in the Outer Saronikos Gulf (Ignatiades, 1969). Annual phytoplankton production is 64g $C.m^{-2}yr^{-1}$ (Becacos-Kontos, 1968). Production increases slightly over shelf areas, due to terrestrial influence and benthic production.

The Outfall Area

The present sewage plume rises to the surface from a depth of 30m approximately 100m offshore; it is usually mixed within the near field (0 - 2 km). Circulation in the vicinity of the outfall is quite restricted, particularly since the construction of a new harbour breakwater pier. The best dispersive conditions occur with winds from the northern quadrant, in which case the plume stretches out to the south, where it is exposed to deeper wave mixing and larger scale mean circulation. Winds from other directions, particularly from the south to southwest, cause the plume to accumulate next to the coast (Hopkins & Coachman, 1975; Friligos 1981b, 1982c). In the near field area, the benthic community has been decimated, with the exception of a polychaete species (Zarkanellas & Bogdanis, 1977). In this area, coliform bacteria have concentrations of 10^2 - 10^4/ml (Sotiracopoulus et al., 1984). Plankton production is depressed despite high nutrient concentrations (Friligos, 1974, 1981d; Hopkins et al., 1974) and D.D.T. concentrations of 1.5 ppm have been found in the sediments (Pavlou, 1973). Toxic trace chemical uptake by the edible benthic and pelagic forms is a matter of great concern (Satsmadjis & Gabrielides, 1977; Taliadouri - Voutsinou, 1980). Comparison of the As and Hg concentrated in the edible fish (*Pagellus erythrinus*) taken from this area and Rhodes showed up to 2.5 times the As in the outfall fish, but no significant increase in the Hg concentration, reflecting the relative exposure to sewage (Papadopoulou et al., 1973).

The Inner Gulf Water

In the intermediate field (2 - 10 km), active diatom and dinoflagellate blooms are observed, with production rates over an order of magnitude greater than the oligotrophic background (Dugdale & MacIsaak, 1975; Gudenberg, 1976). Nutrient values are high and, to the extent that they are conservative, provide good tracers of the circulation patterns (Coachman et al., 1976; Friligos, 1976b; 1981c). Nevertheless the results must be treated with circumspection as nutrients are hardly conservative, being taken up by phytoplankton, which results in a biological redistribution (Friligos 1982b; 1984b; 1985b,c). Inverse relations between silicate concentrations and diatom biomass, and direct correlations between dinoflagellates and ammonia concentrations were observed (Gudenberg, 1980). It should be noted that the appearance of red tide coincides with fish kills. (Satsmadjis & Friligos, 1983). Zooplankton diversity is reduced with some serious consequences to the local fishery (Yannopoulous et al., 1974; Yannopoulos & Yannopoulos, 1976).

The Western Saronikos Gulf

The Western Saronikos being farther from the open Aegean has a longer flushing time than the Eastern Saronikos (Coachman et al., 1976). The age of the water, estimated from nutrient budget calculations, is between one and eight years (Friligos, 1985a). Here the surface waters stay warmer longer in autumn and warm up faster in spring, but the deep water is slightly cooler (14^{o}C) than that at corresponding depths outside the Saronikos (Friligos, 1986). In the western half, a basin (420 m deep, with an 80 m sill) appears to accumulate portions of the effluent to such a degree that present oxygen values at the bottom are around 2 ml/l and nitrate and silicate are around 10 and 20 μM respectively, more than ten times background (Friligos 1976a; 1983c; 1986). However, for most of the year, the deep water gains oxygen and nutrients through the weak process of vertical diffusion (Dugdale & MacIsaak, 1975; Friligos, 1986). With an increased organic load from the Athens outfall, it is only a matter of time before the deep basin becomes anoxic, with very serious consequences to the surrounding fishery.

Elefsis Bay

Elefsis Bay, in the north, is separated from the sewage outfall by a channel, but receives locally significant industrial and domestic effluents. (Dugdale & MacIsaac 1975; Griggs & Hopkins, 1976; Friligos, 1979). Because of its shallowness and restricted access to the rest of the gulf, this bay is undergoing rapid alteration (Hopkins & Coachman, 1975). During winter and early spring, convection results in an isothermal water column and very small salinity, density and oxygen gradients. A thermocline starts to develop below the surface in May and reaches its deepest position in the summer months. For the last ten years, the annual organic input to Elefsis Bay exceeded its capability to accommodate it, resulting in anoxic conditions in the lower layer during the warm half of the year (Friligos, 1982a; 1983b). Benthic organisms as well as benthic and pelagic fish kills occur during summer (Zarkanellas, 1979). Other problems associated with marine anoxic conditions will become increasingly acute (Friligos, 1981a). In winter, convective overturn maintains oxygenation at near saturation levels, despite very high nutrient levels (Friligos, 1983a). In Elefsis Bay and in the upper Saronikos Gulf, the eutrophication conditions affect the periodicity of phytoplankton (irregular pattern of blooms), the species composition, succession and diversity (Tett & Ignatiades, 1976; Igantiades & Mimikos, 1976; 1977). Also, the species diversity of zooplankton was greatly reduced, with the copepod *Acartia clausi* contributing 99% (Yannopoulos & Yannopoulos, 1976). Both inorganic and organic nutrient supply may be linked to blooms of jellyfish (Wilkerson & Dugdale, 1984).

CONCLUSIONS

In conclusion in areas such as the Saronikos Gulf, where the surrounding waters are naturally unproductive and where the bottom shelves rapidly, primary treatment may be preferable to secondary treatment. In such unproductive areas, the adverse effect of sewage discharge into the sea on the phytoplankton community apparently can be made insignificant if the outfall is properly designed. Using a model, Brooks (1983) made the following recommendations :

1. Primary treatment is essential. The separation of domestic wastes from industrial effluents should be done to facilitate biological treatment.

2. Partial biological treatment is a desirable step before committing to full biological treatment.

3. The removal of nutrients is the only way to improve far field water clarity, but to the detriment of fisheries. The removal of nitrogen would be very costly and is not usual for major sea discharges.

4. A 2000m long outfall diffuser at a depth of 60m or more is needed for either primary or secondary effluent to take advantagees of stratification.

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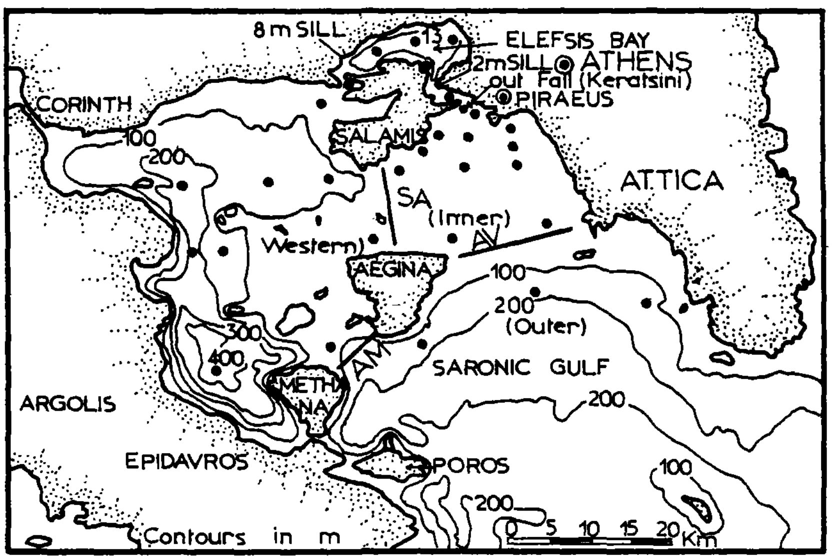

Fig. 1. Location of the stations, Oceanographic subregions and bathymetry of the Saronikos Gulf. Main passages designated as follows :

SA, Salamis-Aegina;
AV, Aegina-Vouliagmeni;
AM, Aegina-Methana.

TABLE 1

Annual range of hydrographic parameters at surface waters of Saronikos Gulf and Elefsis Bay

Parameter		Saronikos Gulf			Elefsis Bay
		Outer	Inner	Western	
Temperature	(^{o}C)	13.2-24.6	13.4-25.1	13.3-25.0	12.0-24.8
Salinity	(^{o}/oo)	37.9-39.0	37.3-38.8	37.8-39.0	35.0-39.0
Oxygen	($ml.l^{-1}$)	5.0- 5.5	4.8-6.0	4.9-5.6	3.0- 5.0
Ext. coeff.	(m^{-1})	0.15-0.05	0.48-0.11	-	0.68-0.19
Chlor.a	($mg.m^{-3}$)	0.02-0.10	0.2-1.0	-	0.5-1.0
Phytoplankton	(cells l^{-1})	$7x10^3$-$1x10^6$	$3x10^5$-$3x10^7$	-	$6x10^3$-$4x10^6$
Zooplankton	($ind.l^{-1}$)	$4x10^2$-$3x10^3$	-	-	-
PO_4-P	(μM)	0.05-0.10	0.10-0.50	0.08-0.30	0.10-0.80
NO_3-N	(μM)	0.10-1.00	0.50-2.00	0.50-1.00	0.10-5.00
NO_2-N	(μM)	0.10-0.20	0.10-0.50	0.10-0.40	0.10-1.00
NH_3-N	(μM)	0.10-0.20	0.50-2.00	0.10-1.00	1.00-15.00
SiO_2-Si	(μM)	0.80-1.00	0.90-3.00	0.80-2.80	1.00-5.00
Petr.hydr.	($mg.l^{-1}$)	-	-	-	14.9-21.8

TABLE II

Concentration of chemical parameters in a composite sewage sample August 1982 (the composite sample was made up of 24 hourly samplings.

Ammonium (NH_3-N)	1580	μM
Nitrite (NO_2-N)	75	μM
Nitrate (NO_3-N)	136	μM
Phosphate (PO_4-P)	187	μM
Silicate (SiO_2-Si)	332	μM
Suspended matter	730	$mg.l^{-1}$
BOD_5	360	$mg.l^{-1}$
COD	820	$mg.l^{-1}$

CASE STUDY

RED TIDES IN THE NORTHWEST ADRIATIC

by

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HISTORICAL RECORD

Red tides, or more generally, algal blooms in the Adriatic Sea have been well known since the last century. Among the first records in the scientific literature are the blooms observed in June and July of 1872, 1880 and 1889 (Syrsky, 1872; Castracane 1873, 1881, 1891) on the coast between Ravenna and Ancona (Fig. 1). In this century there have been several cases of algal blooms in various zones of the Adriatic, most frequently in the northern part (Ravenna, Venezia and Trieste) but also in the central and southern coastal waters (Marche, Abruzzo and Puglia) (Forti, 1906; Cori, 1906; Issel, 1992; Schreiber 1928; Zanon, 1931; Marchesoni, 1954).

More recently Piccinetti & Manfrin (1969) have reported an intensive algal bloom in May that lasted one week, 8 kilometers wide along the coast of Emilia Romagna, in which a great number of species of fish and molluscs died. In this bloom, *Peridiniales* species were predominant in the phytoplankton, chiefly *Peridinium depressum*. In some samples this species represented up to 95% of the algal population. together with *Peridinium pellucidum* and several species of *Ceratium (C. candelabrum, C. furca, C. pentagonum, C. fusus, C. tripos)*. Piccinetti & Manfrin (1969) ascribe the death of fish and molluscs to the bloom of *Peridinium depressum*, as a consequence of the lack of oxygen due to algal biomass decomposition. They conclude that there was no evidence for an effect of algal toxins upon the organisms mortality.

THE TREND DURING 1970-1980

Until the red tide of 1969, algal blooms in Adriatic sea were episodic and not site-specific. Starting with 1975, algal blooms became more and more frequent in the waters along the Emilia Romagna coast. These blooms, mainly consisting of Diatoms and Dinoflagellates, are extensive enough to have adverse effects on the marine ecosystems and cause serious problems for tourism and considerable damage to fisheries. This zone has the highest density of tourists between June 15th and September 15th in the whole of Italy, with as many as 40 million of "attendances" (this term corresponds to the number of tourists multiplied by the number of days of stay) along the 100km of the Emilia Romagna coast.

The first astonishing event occurred on September 7th 1975, when thousands of tons of dead benthic molluscs and fish were collected along the coastal area near Ravenna (from Milano Marittima to Cesenatico), as a consequence of a very impressive algal bloom (Mancini et al., 1980). Since then blooms of Diatoms and red tides have appeared regularly with varying severity in different years, extending along ever wider coastal areas of the Northwest Adriatic, south of the mouth of the River Po. In contrast, the occurrence of red tides along the coast of the Veneto and Friuli regions (north of the Po) has been highly irregular.

The spread of eutrophication phenomena in recent years can be exemplified by the red tide that occurred during the second half of October 1984, extending along the entire coastal area between the Po River mouth and the Conero Promontory (Fig. 2). This bloom consisted entirely of *Gymnodinium corii*, with a maximum of 850 mg m^{-3} of total chlorophyll near the Po mouth and 200 mg m^{-3} in the southern part (Ancona). The area involved was 200km in length and several kilometers wide.

ALGAL SPECIES RESPONSIBLE FOR BLOOMS

The algal species of Diatoms responsible for blooms are mainly *Skeletonema costatum* and to a lesser extent *Rizosolenia hebetata*, *Asterionella japonica*, *Chaetoceros laciniosus*, *C. curvisetus*, *C. lorentianus*, *Coscinodiscus sp.*, *Melosira sp.*, *Cyclotella sp.* and *Thalassiosira sp.*

The Dinoflagellates found are *Gonyaulax poliedra*, *Gymnodinium corii*, *Prorocentrum micans*, as the main species. Some others are less important and found less frequently *(Prorocentrum minimum*, *Peridinium pellucidum*, *Glenodinium spp)*.

In the last years the dominance of these species during blooms has been :

1978 - In March, the bloom consisted of *Skeletonema*, with more than 100.10^6 cells l^{-1}. Dinoflagellates appeared in July and August *(Gonyaulax)* and October *(Gymnodinium)*, creating isolated patches of different extent along the coast of the Region.

1979 - At the end of winter, *Skeletonema* has reached a maximum of 30.10^6 cells l^{-1}. During the summer, *Gonyaulax* was the dominant species and *Gymnodinium* became noticeable in November and December, instead of in October.

1980 - After the spring bloom of *Skeletonema*, this year was characterized by a series of limited episodes in both summer and autumn, related to the particular meteorological conditions of that year (low rainfall).

1981 - In February, *Skeletonema* had reached 25.10^6 cells l^{-1}. In March *Glenodinium lenticula* prevailed among the Dinoflagellates with 30.10^6 cells l^{-1} in contrast to other years.

The next most abundant species was *Massartia rotundata*, with 10.10^6 cells l^{-1} in June. Starting at the end of August, several blooms of *Gymnodinium* occurred in the central part of the Emilia Romagna coast, with a maximum cell density of 25.10^6 cells l^{-1} and chlorophyll concentrations up to 1 mgl^{-1}. These blooms persisted also for the next months.

1982 - In March, there were *Skeletonema* blooms in the entire area, which were replaced in May by *Glenodinium lenticula*. The summer season was characterized by red tides of *Gonyaulax polyedra* and the appearance of a new species of Dinoflagellate, very similar to *G. tamarensis* but not yet fully classified. This species reached 10.10^6 cells l^{-1}. In August, the area with a low oxygen condition (less than 1 mgl^{-1}) extended north-to-south for about 100 km over an area of 900 km^2 (Fig. 3).

1983 - During the first three months there was an extensive bloom of *Skeletonema*, followed by a general increase in Dinoflagellates (*Prorocentrum*, *Gonyaulax* and *Peridinium trochoideum*). *Skeletonema* reappeared in July-August and then *Gymnodinium* until mid November.

1984 - The diatom *Skeletonema* was present in March and April. This alga was replaced in June by *Prorocentrum micans*, spreading more than 3 km from the shore. At the end of August and during September there were blooms of *Gonyaulax*, *Gymnodinium* and *Massartia*. In October, the massive bloom of *Gymnodinium corii* already mentioned occurred and spread throughout the coastal waters for a length of 200 km.

1985 - Together with *Skeletonema* in February, there was an enhanced growth of such diatoms as *Nitzschia* and *Thalassiosira*. In April and May, there were mixed blooms of Diatoms and *Prorocentrum* that persisted (though with decreased intensity) into the summer when productivity was very low, as in 1980. There were impressive blooms in October, this time dominated by *Gonyaulax*.

1986 - During this last year there was an extremely large growth of *Skeletonema* from January to May, with the appearance of some other species of Diatoms and, at the end of May, of *Prorocentrum* and *Chaetoceros*. The phytoplankton composition in June and July was quite different from that of the other years because of the persistence of the large population of Diatoms. About the end of August there was a recurrent small bloom, mainly due to *Peridinium trochoideum*.

On the basis of the patterns of these last ten years, described in detail in several reports of the Emilia Romagna Region (Chiaudani et al., 1980b; Marchetti, 1984; Montanari & Rinaldi, 1984) a general trend can be seen as follows :

- Blooms of diatoms develop at the end of winter or the start of spring in both coastal and open waters, with densities of tens of millions of cells l^{-1}. These cell blooms can last until summer.

- Generally, Dinoflagellate blooms have maximum algal density between August and October. These algae develop mainly in coastal water and, less frequently, farther out.

The long series of records collected during the last decade allow us to recognize the general conditions under which red tides most frequently occur. Algal blooms are supported by anticyclonic meteorological conditions in which there is a stratified water column, without transport of water masses. These conditions are likely to occur after widespread and heavy rain over inland regions, so that the water flow of the river Po and other coastal rivers is considerably increased. Specifically, it has been observed that the largest algal blooms in the central part of the Emilia Romagna Region have taken place 6-9 days after the start of widespread rain, particularly when the wind has blown from the east (1-3 m sec^{-1}) and wave motion was between 0.1 and 0.5m (Lenzi et al., 1984).

Meteorological depression, rough and destratified sea, heavy northeast winds able to create rapid water overturn, lack of rain or moderate and localized rain, all create unfavourable conditions for red tide occurrence.

TROPHIC CONDITIONS

Emilia Romagna coastal waters which have the most frequent red tides of the entire Adriatic, are generally rich in nutrients. The areal distribution of phosphorus, nitrogen and silica salts is inversely related to salinity. During periods of high flow in the River Po, such as in spring and in autumn, salinity can be less than 10% at the river mouth and up to 34-36% (close to the maximum of 38% in the Adriatic sea) in the southern part of the Emilia Romagna coast. Consequently there is a decreasing gradient of nutrients from north to south and from the shore to the open sea. Phosphorus was found to be the limiting factor in 87% of 6038 samples collected during 1978-80 and 1982-84, with nitrogen limiting in 9%, and the elements were balanced in only 4% of the samples. The role of phosphorus is thus clear. However, examining the pattern of the N/P ratio over the year, nitrogen limitation occurred most frequently during the summer. In spite of that, phosphorus remains the element of major concern from the point of view of trophic conditions (Marchetti et al., in press). The influence of phosphorus on algal growth has been shown also in laboratory experiments with natural phytoplankton populations, mainly *Prorocentrum sp.* and *Gymnodinium sp.*. It has been observed (Chiaudani et al., 1980a, 1980b) that algal cultures living in media deficient in phosphorus did not grow better than the controls, but they did in media deficient in nitrogen. There was no significant differences between cultures with and without vitamins.

CONCLUSIONS

On the basis of this evidence, red tides and algal blooms have occurred in the Adriatic Sea for at least a century. They have occurred with regular frequency in the coastal waters of Emilia Romagna for a decade and sporadically north and south of that Region. The fact that algal blooms frequently occur after heavy rains and along the coast near the mouth of the largest Italian river (River Po) and many other watercourses indicates a relationship of eutrophication phenomena since 1975 with an increase in the nutrient load carried into the Adriatic by these watercourses. It is possible to draw this conclusion because of the collection of data for orthophosphate phosphorus and nitrate nitrogen concentrations in the River Po by many investigators over several years (Fossato, 1971, 1973; Provini et al, 1980, 1982; Zanoni & Merighi, 1981; Zanoni, 1985, personal communication). These data show that the nitrogen concentration has doubled and phosphorus has increased 2.4 times between 1968 and 1984 (Marchetti et al, 1985).

As has already been pointed out (Marchetti, 1984), it appears that nutrients transported by the River Po can favour a generalized water enrichment and consequently fast growth of Diatoms and Dinoflagellates. The growth of these last organisms can also be positively influenced by nutrient salts and organic substances coming from the many small rivers located along the coast.

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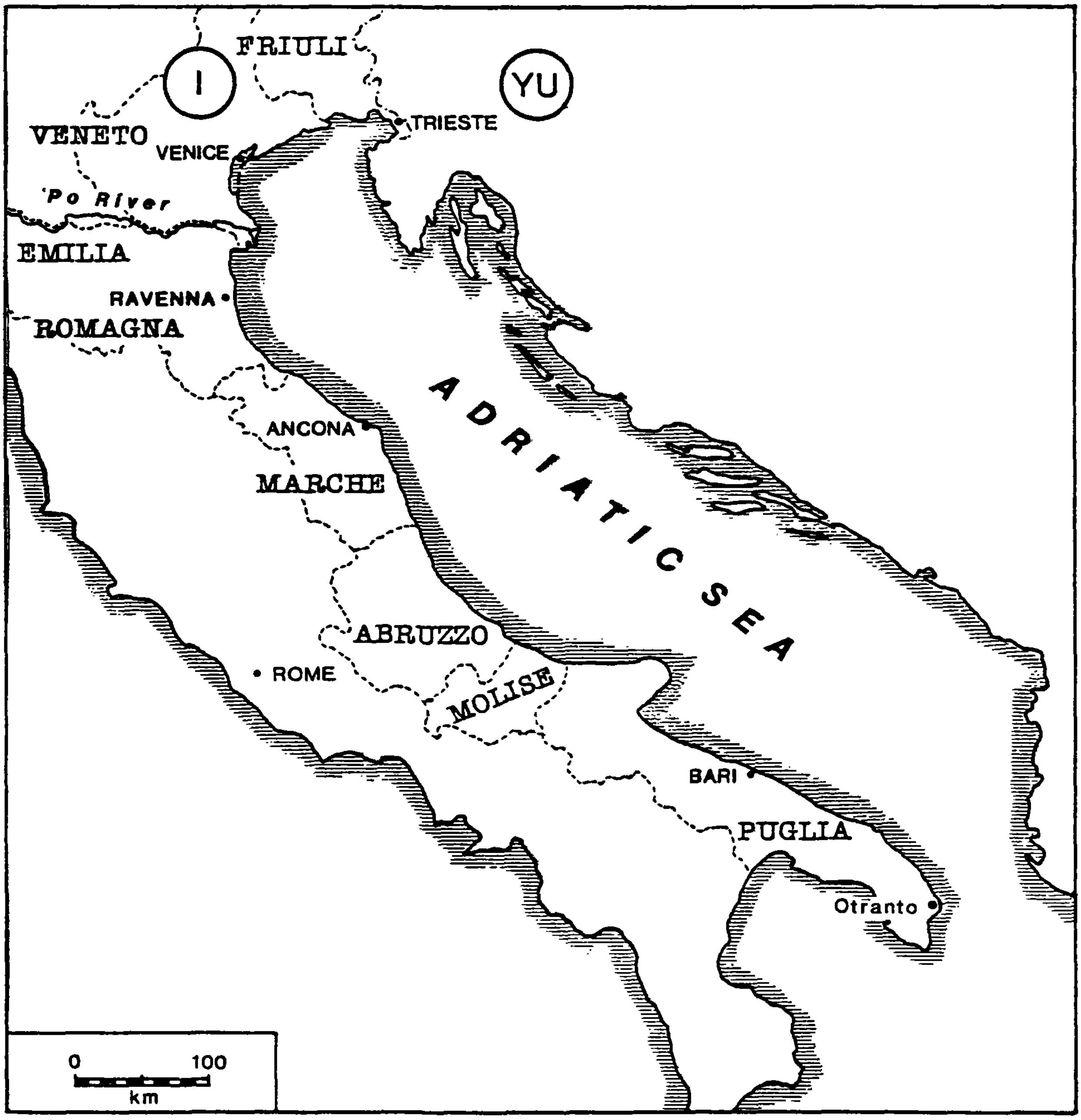

Fig. 1 - The Adriatic Sea : sites of the Italian coast cited in the text

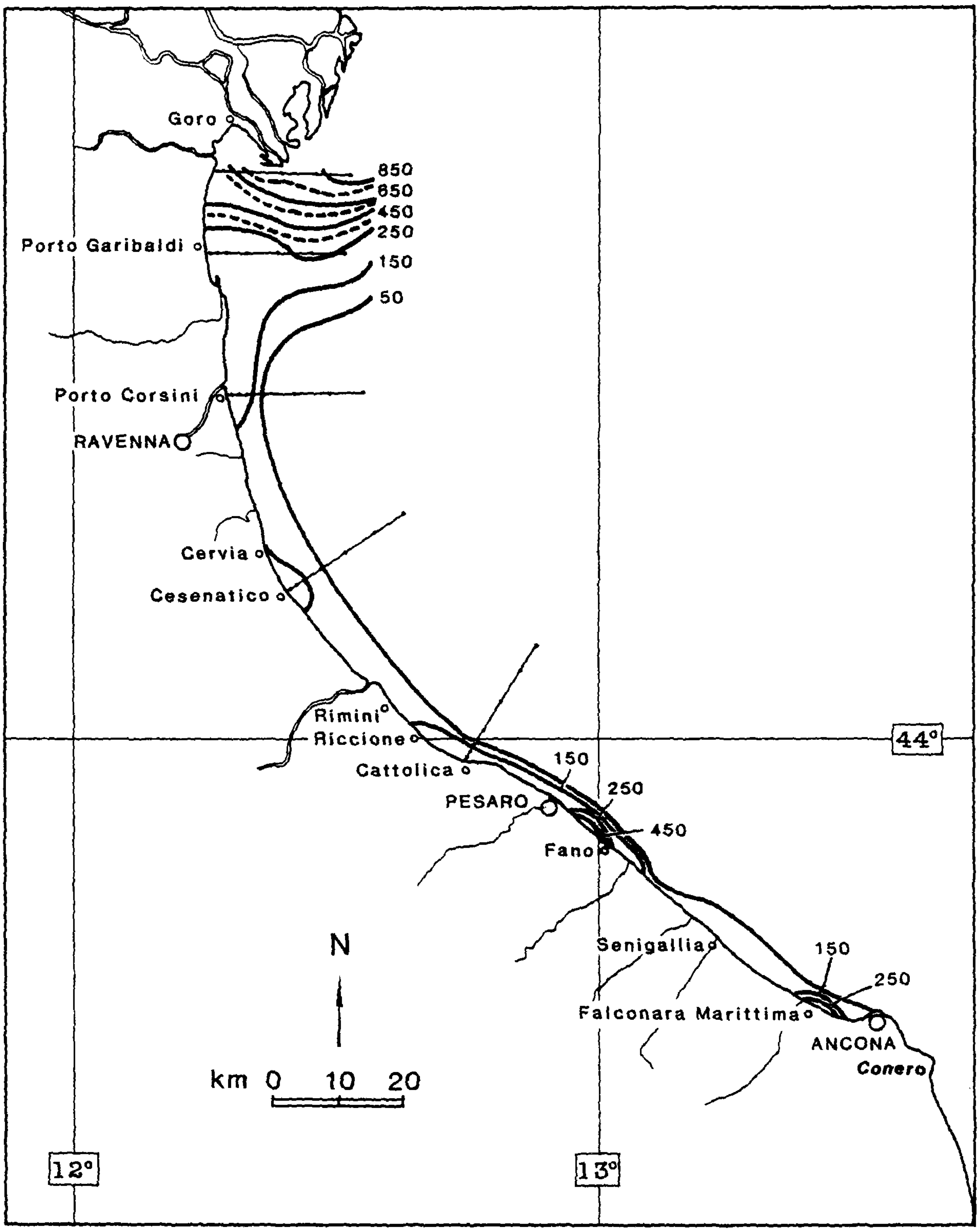

Fig. 2 - Surface chlorophyll values measured on October 22-27 in coastal waters of Emilia Romagna and Marche. Values are expressed in mg m^{-3} of chlorophyll a.

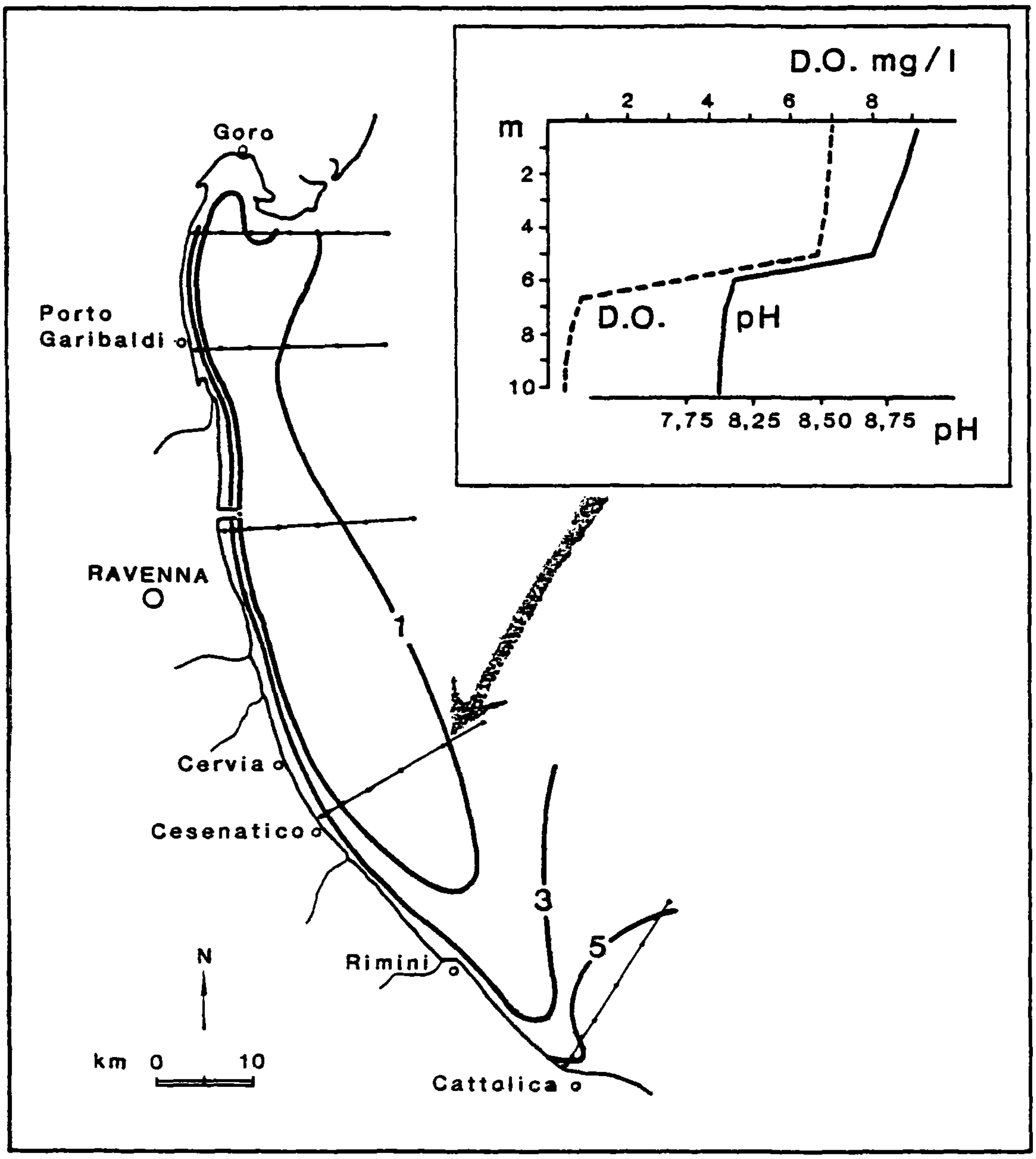

Fig. 3 - Dissolved oxygen values measured in deep coastal waters of Emilia Romagna during August 1982

CASE STUDY

EUTROPHICATION IN THE COASTAL AREA OF THE REGIONE EMILIA ROMAGNA

by

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INTRODUCTION

In the last decade the attention of the international scientific community and of central and local authorities has been increasingly focussed on the ecological degradation of the Upper Adriatic.

Recurrent spring and autumn algal blooms appear widespread at the water surface, from Istria to the Po delta, to Ancona and sometimes further south to the Manfredonia Gulf. This situation seriously affects both the aquatic life with the death of different species of fish, and the tourist activity of the entire coast, where summer resorts usually accommodate millions of tourists.

A great deal of resources have been invested in water treatment activities through law *n.650 of 1979*, through *the financial* laws of the last four years, through the Investment and Employment Fund and through contributions of local authorities. In addition a number of laws were passed in order to limit the present status of eutrophication, such as the recent law that reduces the phosphorus content in detergents.

Unfortunately, despite all the efforts at different levels, the effective management of the water quality in the upper Adriatic is still an unresolved problem. In particular the interventions were not always planned with a uniform idea of the essential objectives; sometimes even the reduction of nutrients flowing into the Adriatic sea was not among the objectives.

At present the contamination of inland waters that flow into the Adriatic sea is still increasing and, as a consequence, algal blooms become more and more frequent and widespread.

In parallel with the political activity, an important scientific activity, including research and data collection, was carried out by the National Council of Research (CNR) and by the Regione Emilia Romagna, whose coasts are the most seriously affected in the upper Adriatic area.

The scientific research has been more analytical than synthetic, and after several years of work, has not yet provided identification of the most important factors affecting the eutrophication phenomena in the Upper Adriatic sea. The studies have been deep and interesting, analyzing in detail many of the single phenomena that contribute to the overall eutrophication mechanism, such as the hydrodynamic circulation, the sediment dynamics, the biological evolution, etc. Unfortunately each single phenomenon was regarded as "the important" phenomenon by the scientists and no attempt made to establish priorities of importance of the different phenomena, or to establish a good balance in the spatial or temporal description of the different phenomena.

At this point in time it was felt necessary to overcome the limits of the traditionally segmented research, which is generally carried out by areas of competence or disciplines, and to propose a multidisciplinary research program.

The starting point of this research program was planned as a four week workshop, organized in Bologna from August 27 to September 22, 1985, by the Istituto per i beni artistici, culturali e naturali of the Regione Emilia Romagna and sponsored by UNESCO, UNEP and by the International Commission for Water Resources Systems of IAHS.

During the workshop, after gathering the available data and studies, a breakdown of the eutrophication problem into its major components was attempted by accounting for all the factors that may influence the eutrophication phenomena and by exploring the possibilities of their mathematical representation.

By the end of the four weeks study a simplified model of the Emilia Romagna coastal area was set up which can reproduce some of the specific characteristics of the eutrophication phenomenon in the area. In addition the analysis of data and the results of all the mathematical models developed has indicated the main research lines which should be further investigated, and the mathematical models which should be implemented in order to provide the National and Regional authorities with an operational management tool.

DEFINITION OF THE CASE STUDY

Pollution sources and environmental conditions

The quality of waters of the Adriatic sea may be considered satisfactory in broad terms. In fact the extensive exchange of waters in the autumn and winter periods still allow, generally, for good quality conditions, comparable at least to those of the Mediterranean sea. Under particular local conditions and in areas close to the shoreline, though, eutrophic conditions are present with frequent algal blooms.

The environmental conditions of the North Adriatic are in fact particularly suited for algal blooms. The depth of sea north of Ancona ranges from 50 to 70m, and reduces to 20m in large areas close to the shoreline. The hydrodynamic circulation, anti-clockwise during the autumn-winter period, becomes practically non-existent from the beginning of summer.

The climatic conditions in the June-October period are also particularly suited for the development of algae and in addition all the rivers and the sewer systems discharge thousands of tons of nutrients into the Adriatic.

The low salinity of the polluted waters coming from the River Po and from the other streams, encourages the stratification of waters with high concentrations of nutrients in the surface waters, thereby favouring the development of different species of algae, in particular diatoms and dinoflagellates.

By the end of summer the red algal blooms (Dinoflagellates) jeopardize the tourist activity of the Emilia Romagna summer resorts, giving rise to anoxic conditions with stinking waters and death of fish.

According to the Istituto di Ricerca Sulle Acque (IRSA) of the CNR, a wide area close to the coast of Veneto, Emilia Romagna and Marche should be considered as eutrophied up to 60 km from the shoreline, due to the high concentration of chlorophyll *a* and nutrients. A moderately eutrophied neighbouring area can then be identified from Istria to Ancona, while further south, one can identify mesotrophic and oligotrophic conditions (see figure 1).

These stress conditions are mainly caused by the significant flow of nutrients discharged by major rivers such as the Po, the other rivers of Friuli, Veneto, Emilia Romagna and Marche and the sewer systems of the coastal resorts, together with the unfavourable hydrodynamic conditions that prevent their transport from the coastal area.

The distributed pollution sources are spread over a very wide tributary catchment (the River Po catchment by itself covers most of Northern Italy for more than 70,000km^2) and are mainly due to municipal sewers (circa 25 million inhabitants), to industrial wastes (even more than the municipal load), to zootechnical wastes (Northern Italy accommodates more than 6 million cows and 6.5 million pigs) and to the washout of fertilizers due to rain.

The transport of the nutrient loads to the sea is then a function of the hydrological conditions of the different rivers. The Alpine rivers contribute with a more or less constant flow of nutrients, while the Appennine rivers provide peaks of concentrations during flood events.

The diffusion of pollutants along the coast is then a function of the meteorological and hydrodynamic conditions of the coastal area; favourable conditions with strong North-South current and intense mixing due to wave motion, alternate with unfavourable conditions characterized by total lack of wave motion and water exchange, which locally enhances the concentration of nutrients and determine the most favourable conditions for the development of algal blooms.

THE AIMS OF THE WORKSHOP

The principal objective of the workshop was the analysis of components that contribute to the eutrophication of the Upper Adriatic sea, at different levels of aggregation, in order to reach a comprehensive picture of the phenomenon. This should lead to the development of a model to be used within a decisional framework (see figure 2).

With reference to figure 2, one can notice the variety of different phenomena involved, each of which may be known (interpretation scheme and available data) or mathematically represented different levels of sophistication.

Given the final goal of setting up a model of the eutrophication phenomenon that allows for the simulation of the system under different scenarios and intervention hypotheses, the focus of the workshop was the identification of the macroscopically dominant factors.

The kernel of the system was then introduced as an extremely simplified ecological model under boundary conditions represented by the inflows from the mainland and by the general circulation of the Adriatic sea.

The other phenomena, whose relevance was considered to be less in the overall scheme, were not considered in this study to avoid losing the required degree of aggregation.

DEVELOPMENT OF THE WORKSHOP

The study began with a detailed analysis of the area on the basis of observed phenomena, previous research and available data.

The analysis of the environmental system led to the disaggregation of the problem into its basic components described in figure 2 and to the definition of the ecological model of the algal dynamics to be used as the kernel of the entire system.

The analysis of previous research showed that some of the components of the phenomenon were already studied in great detail and mathematical models were already available. Unfortunately the models were not developed as part of a higher aggregation level system, but as final objectives, and therefore could not be used as tools of the final system model.

For instance the *two-dimentional* hydrodynamic model of the North Adriatic circulation integrating the partial differential equations using a time step of a few minutes is a fine model if one requires such accuracy. However, for analysis of the overall eutrophication phenomenon a much simpler model can be used, which can be integrated for more than one year with time steps larger than one day and which can give results of the same order of accuracy as the available hydrological and water quality data.

The analysis of data for the selected period (1983-1984) showed that water quality measurements were available along the Emilia-Romagna coast and at the mouth of most of the inflowing streams. It also showed lack of information in terms of the point and non-point pollution sources and of their transport to the sea.

Other meteorological data were also not readily available, such as wind direction and velocity or solar radiation, and a great effort was made to gather and to computerize all the available information.

Four working groups were then established; the first one dealing with data collection and data analysis; the second one reconstructing the hydrology of the tributary catchments and the calibration of water quality/water quantity curves; the third one dealing with the mathematical representation of the different biological and ecological processes and the fourth group trying to reproduce the hydrodynamic behaviour of the area using an integrated finite difference model approach.

The first group gathered the water quality data from the Emilia-Romagna reports, from previous studies and all available sources. In addition the hydrological data were obtained with the collaboration of the Hydrographic Offices of Bologna, Parma and Venice.

After computerization, the data were corrected from punching errors then statistical and graphical analyses were performed.

The second working group applied multiple regressions to the calibration of water quality/water quantity models in order to extend to the entire period the scattered water quality measurements.

The third group analysed two different ecological models; the first one, which was called ONEBOX, since it considered the entire coastal area as a unique box, represented the overall phytoplankton and zooplankton dynamics without distinguishing between different algal species (see figure 3). The second model, called Big Box represented the differing behaviour of the diatoms and dinoflagellates (see Figure 4).

Both models were set up by integrating the partial differential equations using a Runge-Kutta variable step integrator.

Due to the limited timeframe of the workshop, only ONEBOX was used in the case study. The model was thus calibrated in order to reproduce the available data.

The fourth group investigated the hydrodynamic circulation of the area under study, as part of the general Upper Adriatic circulation, and a parabolic model based upon the integrated finite differences approach was set up and calibrated using the water density data measured along the coast and at large.

As can be seen from figure 5 the model is composed of a number of boxes. This is consistent with the ecological box approach, and the extention to a multiple box ecological model is thus straightforward.

ANALYSIS OF RESULTS AND CONCLUSIONS

As one can see from figure 5, showing the flow situation during the month of September, there is practically no exchange of waters along the coast. The residence time increases in August and September from the average 3-5 days to more than one month.

The result is consistent with the water quality data, showing a peak of phytoplankton in late summer-beginning of autumn, and can only be reproduced by ONEBOX, if one introduces the larger values of the residence time estimated by using the simplified hydrodynamic model (see figure 6).

From this preliminary result, from the detailed analysis of data performed during the workshop and from the experience gained, a number of conclusions were drawn.

These conclusions will constitute the main lines of the research and implementation activity to be carried on in order to develop an integrated model of the ecosystem, useful to the decision makers.

- First of all a data base oriented to modelling should be established and the data should be freely available to researchers and scientists. The data base should also include all the available information not only in terms of water quality, but also in terms of hydrometeorological data available in the tributary catchments.

- A study of the pollution sources should be established and models of their transport to the sea should be implemented: this is an important aspects, since the interventions can only be applied at this level.

- A multibox ecological model of the coastal waters, integrated into a simplified hydrodynamic model, should be implemented in order to simulate, together with the nutrient production and transport model. the effectiveness of the management policies. The ecological model in the final version, should include the distinction of the different species of algae (Diatoms and Dinoflagellates) due to the presence of the different species in the area showing different blooms in time and space.

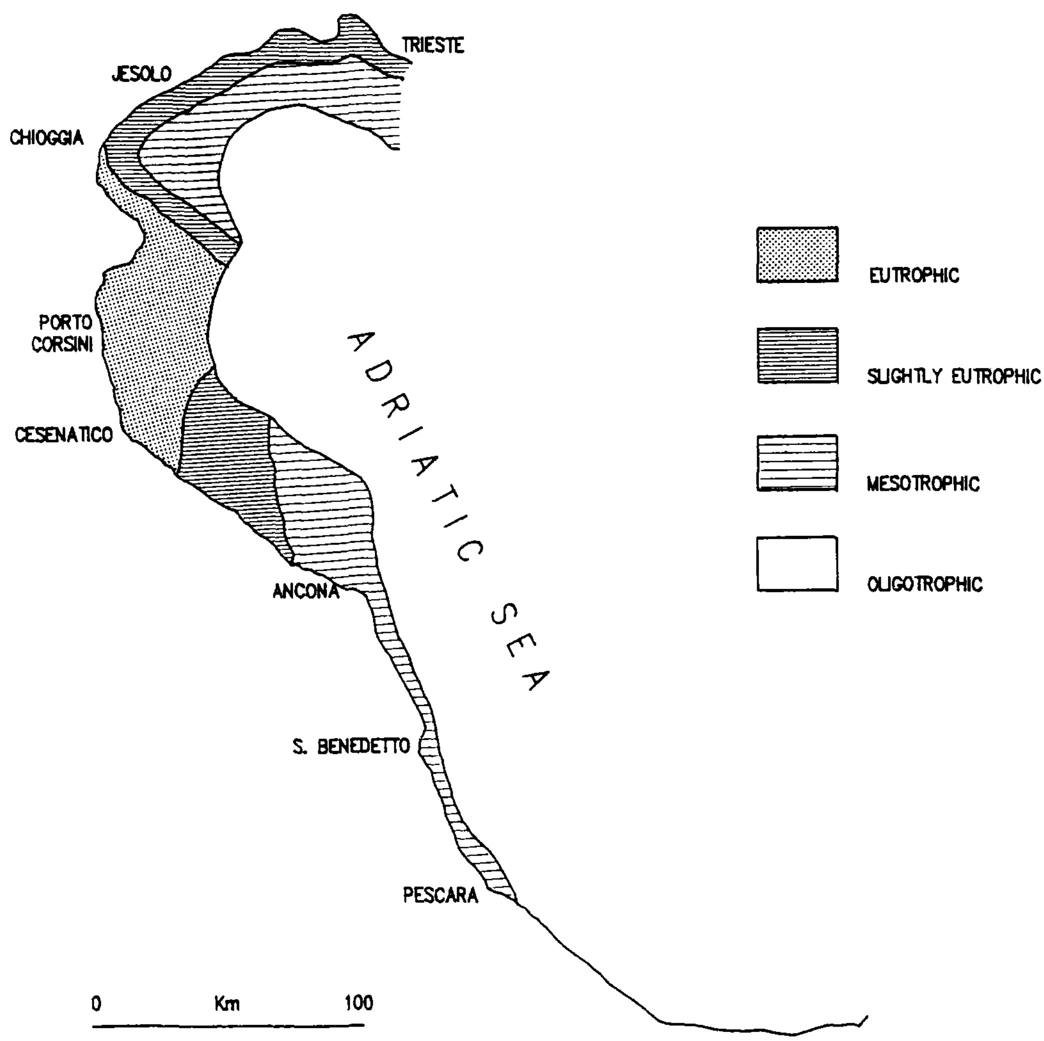

Figure 1 Scheme of trophic conditions in the coastal zone of the Adriatic sea, according to IRSA

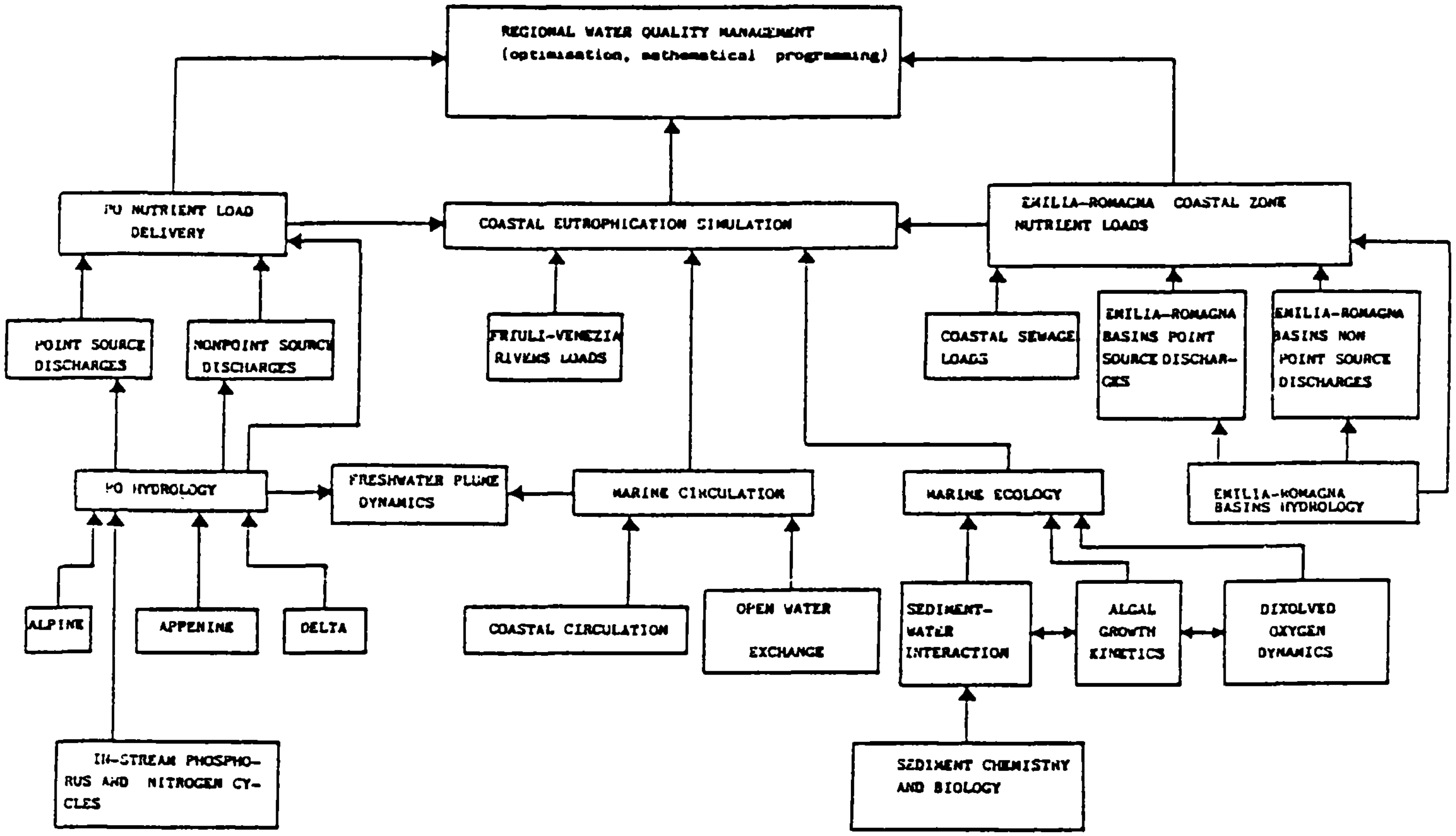

Figure 2 - Overall hierarchical decomposition of the coastal eutrophication problem

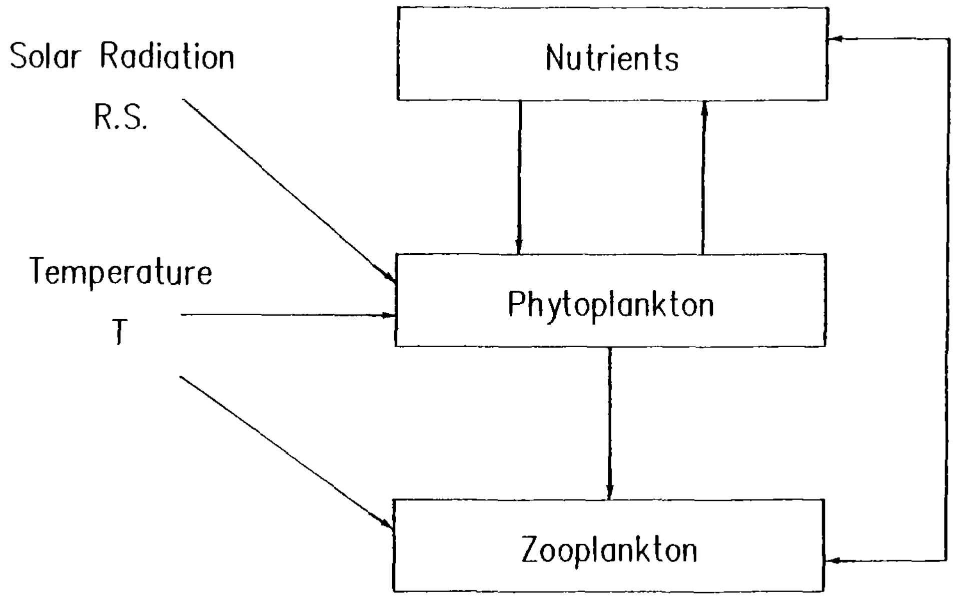

Figure 3 The biological scheme of ONE BOX

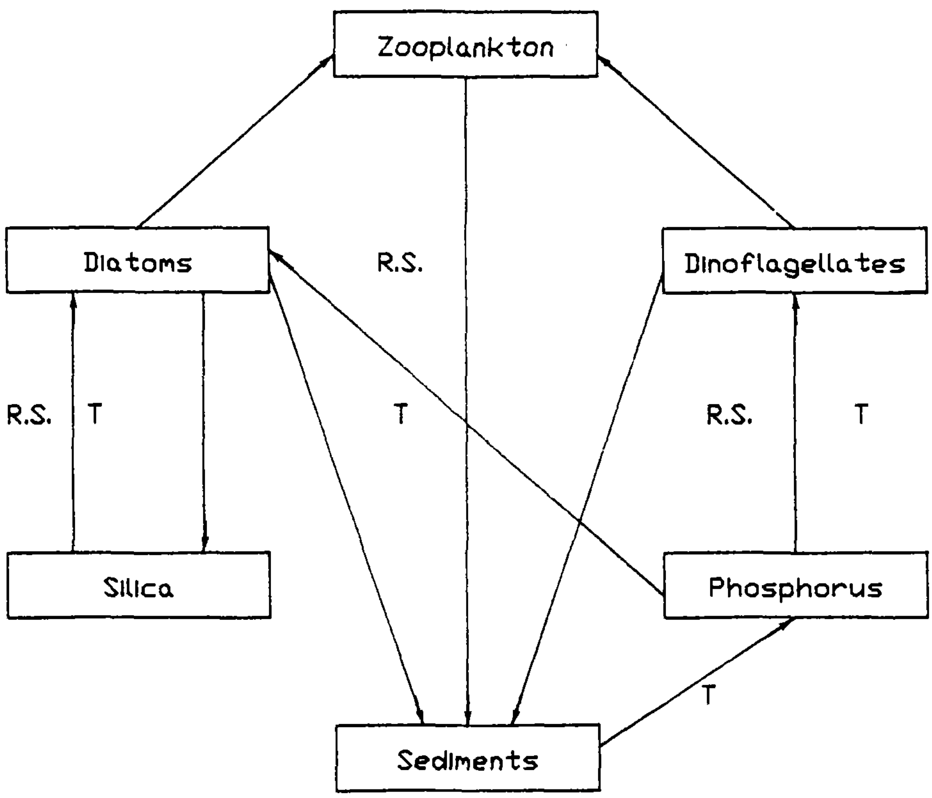

Figure 4 The biological scheme of BIG BOX

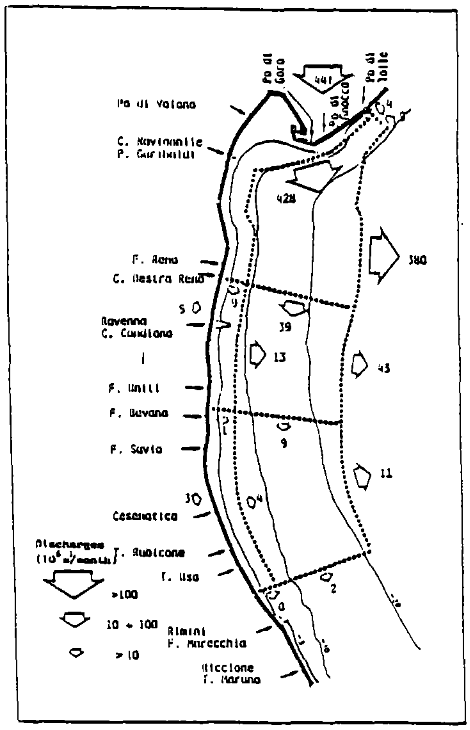

Figure 5 Water circulation in the coastal zone during the month of September according to the simplified zone

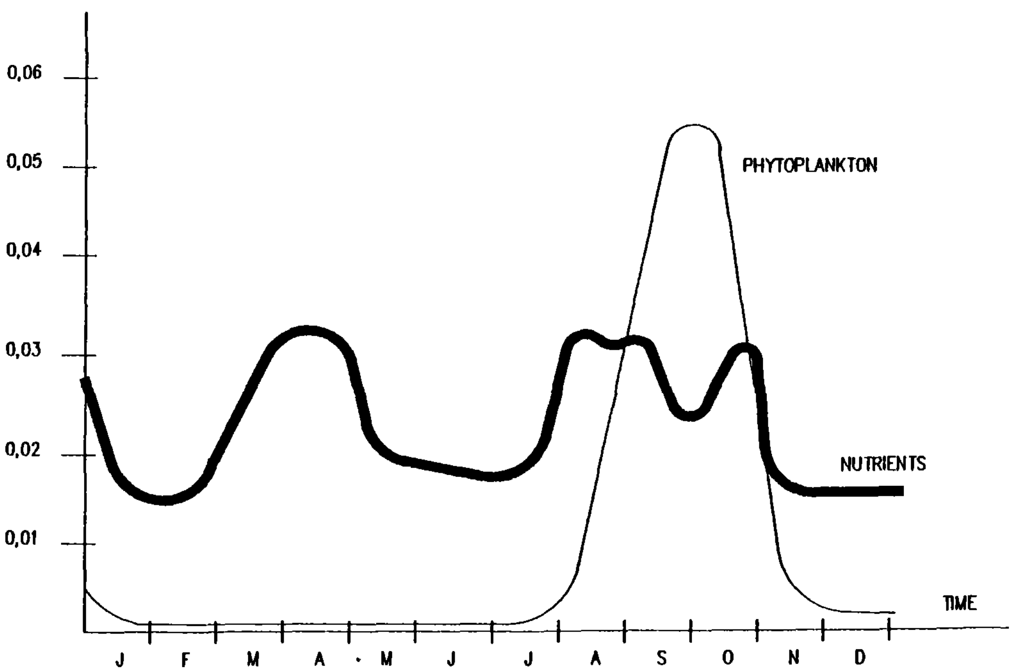

Figure 6 Phytoplankton behaviour when using ONE BOX with residence time estimated in the Cesenatico area

A SIMPLE MODEL OF EUTROPHICATION ON THE ADRIATIC COAST - WITH A FIELD EXPERIMENT TO DISPROVE THE MODEL

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INTRODUCTION

The ONEBOX eutrophication model presented in this report is based on the model of di Toro et al. (1971) and on modifications made by Verhagen (1974). Seasonal variations in the concentration of plankton and nutrient in a single well-mixed box are modelled as they respond to changes in ambient climate and nutrient loading.

Kremer & Nixon (1978) provide a critique of some of the assumptions which are made and discussed in the original work of di Toro et al. (1971). ONEBOX is a useful starting point for developing a sequence of models of the eutrophication of the Adriatic coast to the south of the Po delta.

THE ONEBOX MODEL

The equations of the model in vector matrix notation are

$$dX/dt = A.X - D.M. + N \qquad (1)$$

where X(t) is the state vector of the system at time t. namely X(t) = [P(t), Z(t), N(t)] and P, Z, and N are phytoplankton, zooplankton and nutrient respectively, measured as concentrations. In the following formulation, the units of both phytoplankton and zooplankton are assumed to be the same, but the unit of mass for nutrient may be different.

The non-linear dynamics of the system are contained in the A(X,t) matrix as follows

$$A = \begin{bmatrix} (Gp - Dp - Qo/V & 0 & 0 \\ 0 & (Gz - Dz - Qo/V) & 0 \\ Anp.(Dp - Gp) & Anp.(Dz - Gz) & -Qo/V \end{bmatrix} \qquad (2)$$

In this matrix all elements have the units 1/time. Gp. Dp. Gz and Dz are the specific or fractional growth rates per unit time of phytoplankton and zooplankton respectively. The conversion factor Anp is the mass of nutrient per unit of plankton. It couples the nutrient dynamics to the plankton and is the same for both phytoplankton and zooplankton.

The term -Qo/V is the inverse of the residence time for a box of volume V through which water flows at a rate Qo. It represents the fractional rate at which P, Z and N are washed out of the box by Qo on the assumption that it is well-mixed. Since this acts on P, Z, and N, it appears on the diagonal of A.

We also assume that

$$Qo = Qr + Qa \tag{3}$$

Qo is the sum of the river inflow rate Qr and an exchange flow rate Qa with the outer coastal waters. The identification of Qa from salinity data is explained later.

The vector D.M is the term-by-term product of the vectors

$$D = \begin{bmatrix} Qa/V \\ Qa/V \\ Qa/V \end{bmatrix} \qquad M = \begin{bmatrix} Pa \\ Za \\ Na \end{bmatrix} \tag{4}$$

where Pa, Za and Na are prescribed concentrations of phytoplankton, zooplankton and nutrient in the outer coastal waters beyond the region being modelled by ONEBOX. Multiplying Pa, Za, and Na by Qa/V gives the contributions from this source to the rates of change dP/dt, dZ/dt and dN/dt.

The final vector N is

$$N = \begin{bmatrix} 0 \\ 0 \\ Wn/V \end{bmatrix} \tag{5}$$

which contains the loading or input rate of nutrient Wn as mass per unit time. Note that the river inflow rate Qr does not appear in either D or N. The river loading rate must therefore be included in Wn since it is partially controllable.

THE TERMS OF THE A MATRIX

The terms of the A matrix are defined as follows.

The specific growth rate Gp of phytoplankton is a function of the phytoplankton and nutrient concentrations and of exogenous functions of time t such as temperature, solar radiation and photoperiod. We define

$$Gp(P,N,t) = (k2 + k1.T) \ . \ Ll(P,t) \ . \ Ln(N) \tag{6}$$

where T is the temperature and (k2 + k1.T) is the corresponding optimal specific growth rate of phytoplankton under optimal conditions of light and nutrient availability. The linear dependence on temperature holds approximately for a mixed population of phytoplankton species. It is not the appropriate form for individual species.

When optimal conditions are not present, this rate is reduced by limitation terms Ll and Ln, for light and nutrient respectively. These terms are taken from Verhagen (1974) as

$$Ll = \frac{e.f(t)}{[Ke + ep.P].\ H} \cdot \left[\ exp(-b).\ Io(b) - exp(-a).\ Io(a)\ \right] \quad (7)$$

where

$$b = a.exp\{-[Ke + ep.P].H\}$$
$$a = Ih(t)/[f(t).Is]$$
$$e = 2.71828\ .....$$

f(t) is the photoperiod. It takes its average value of 1/2 at the equinoxes. The maximum occurs at the summer solstice and is a function of latitude. H is the average depth of the box. Light is reduced by extinction in the water column and by the phytoplankton shading themselves. The parameters Ke and ep control these two light attenuation mechanisms.

The term a contains the daily solar radiation Ih(t), the photo-period f(t) and the optimum or saturating light intensity Is for the phytoplankton population being modelled.

Io is the modified Bessel function of order zero. It arises from the integration of the Steele function for light limitation

$$F(I) = (I/Is).\ exp(1 - I/Is) \quad (8)$$

over the depth of the box H and over the day. Within the photoperiod of the day, the solar radiation is assumed to have a cosine variation. The details of this integration may be found in Verhagen (1974).

The nutrient limitation term is

$$Ln(N) = N/(N + Kn) \quad (9)$$

where Kn is the half-value constant. When N = Kn, Ln = 1/2.

The specific death rate of phytoplankton is

$$Dp(z,t) = (k4 + k3.T) + Cg.Z \quad (10)$$

where

$$Cg = k7.T \quad (11)$$

The first part of Dp represents the 'endogenous respiration' of the phytoplankton and depends only on temperature T. The second part depends on the specific rate of filtration Cg.Z of the phytoplankton by the zooplankton. The coefficient of grazing Cg is assumed to be temperature dependent and has the units: volume of water filtered per day per unit of zooplankton. The death rate due to sinking and parasitism is ignored as a first approximation.

The specific growth rate of zooplankton is taken to be

$$Gz(P,t) = Cg.P.Azp. [Kmp + P)] \qquad (12)$$

The rate of ingestion of phytoplankton by zooplankton is Cg.P.Z. This is converted to a zooplankton growth rate by multiplying by a utilization efficiency or yield coefficient Azp which converts phytoplankton biomass ingested to zooplankton biomass produced, giving Azp.Cg.P.Z.

The efficiency with which zooplankton assimilate the ingested phytoplankton, has a maximum value Azp at negligible concentrations of P. As P increases this efficiency declines at a rate which is controlled by the half-value constant Kmp. When P = Kmp, the efficiency is halved. Andersen (1985) argues that the rate limitation should be applied to the grazing coefficient Cg instead.

The mass of phytoplankton which is not assimilated, is excreted directly to the nutrient pool. If both P and Z are measured in the same units, this nutrient flow rate can be expressed most simply as the difference between the rate of ingestion and the rate of growth :

$$Anp.(Cg.Z.P - Gz.\ Z) \qquad (13)$$

where Anp is the mass of nutrient per unit of phytoplankton or of zooplankton. Anp is the nutrient-in-plankton ratio.

The specific death rate of zooplankton is also temperature dependent and is taken to be

$$Dz(t) = k6 + k5.T \qquad (14)$$

The last row of the A matrix represents the differential equation for the limiting nutrient N without the terms containing Na or Wn, namely

$$dN/dt = Anp.[Dz.Z + (k4+k3.T).P + (Cg.Z.P-Gz.Z) - Gp.P] - (Qo/V).N \qquad (15)$$

The four terms multiplied by the nutrient-in-plankton ratio Anp, represent the mass flow rates due to (1) the death of zooplankton, (2) enodgenous respiration of phytoplankton, (3) zooplankton excretion and (4) photosynthesis by the phytoplankton. The last term represents the rate at which N is washed out of the box by the through-flow Qo. Note that there is no term in equation (15) for the exchange of nutrient with the surface sediments on the bottom of the box.

This treatment of the nutrient equation differs in one important respect from that in di Toro et al. (1971) and in Verhagen (1974). They define and use incorrectly a nutrient-in-zooplankton ratio. For our purposes, it is sufficient to define a single nutrient-in-plankton ratio which is the same for both phytoplankton and zooplankton.

Using definition (10), equation (15) can also be written as

$$dN/dt = Anp.(Dp-Gp).P + Anp.(Dz-Gz).Z - (Qo/V).N \qquad (16)$$

from which we find the last row of A

$$\begin{aligned} A(3,1) &= Anp.(Dp-Gp) \\ A(3,2) &= Anp.(Dz-Gz) \\ A(3,3) &= -Qo/V \end{aligned} \qquad (17)$$

The remaining terms in A are zero.

FINDING THE EXCHANGE FLOW Qa

The exchange flow Qa is found from salinity data. We begin by writing a mass balance equation for the salinity of a box containing a constant volume of water V,

$$V.dS/dt = Qr.Sr + Qa.Sa - Qa.S - Qr.S \qquad (18)$$

where Sr and Sa are the salinities of Qr (river) and Qa (Adriatic inflow) respectively. Since there is no change in the volume V, the outflow rate is Qr + Qa. Salinity is lost from the box at a rate (Qa + Qr).S on the assumption that it is well-mixed. Assuming Sr = 0, equation (18) becomes

$$V.dS/dt = Qa.(Sa - S) - Qr.S \qquad (19)$$

Since Qa multiplies the difference in concentration between the box and the outer coastal waters, Qa can also be called an Austausch or exchange coefficient.

We now solve for Qa in terms of measured salinities inside and outside the box

$$Qa(t) = [V.dS/dt + Qr.S]/[Sa - S] \qquad (20)$$

The average salinity of the box S(t) must be differentiated numerically in order to provide dS/dt. This procedure amplifies any errors in the data. Uncertainties in the denominator [Sa - S] are a further source of numerical instability. In particular, $S > Sa$ yields a negative value of Qa, which is meaningless. An ad-hoc resolution of this dilemma when it occurs, is to set Qa = 0.

Clearly, this approach can only be regarded as a first approximation to a combined dynamic model of both circulation and plankton in the coastal waters of the Adriatic which lie immediately to the south of the Po delta.

TESTING THE MODEL

The vector differential equation (1) was integrated with a variable step Runge-Kutta procedure and was tested as follows.

We begin by considering the box as a closed batch reactor with no inflows or outflows. D.M. and N are both zero and Qo vanishes on the diagonal of A. If Anp, the nutrient-in-plankton ratio, is also taken to be one, we find

$$d(P+Z+N)/dt = 0 \qquad (21)$$

when we add the rows of A, which correspond to dP/dt, dZ/dt and dN/dt. This implies that

$$P(t) + Z(t) + N(t) = P(0) + Z(0) + N(0) \qquad (22)$$

for all values of t. The non-linear dynamics in the A matrix continuously divide the initial mass of nutrient between the three compartments of the model ecosystem. This case is well worth studying before any exchange with the outer coastal waters, adjacent boxes or surface sediments is considered.

A second test can be made by turning off the plankton growth rates by setting P(0) = Z(0) = 0. If we now take Wn/V = 1 in the vector N, we find the trivial solution P(t) = Z(t) = 0 and N(t) = t, for all values of t.

A third and more complex test has been made by Verhagen (1974). He shows how a linearisation of the A matrix about average values of P and Z can be used to find the period and attenuation of prey-predator oscillations between the phytoplankton and zooplankton. These can then be checked against the non-linear numerical solution. Such oscillations were made to occur in the present model, but the test itself was not completed.

We now open the box. Let Qo exist, and keep M = 0. We find P(t) = Z(t) = 0 as before, when P(0) = Z(0) = 0. The differential equation for N is

$$dN/dt = -(Qo/V).N + Wn/V \qquad (23)$$

The solution for an initial value of N(0) = 0 is

$$N(t) = (Wn/Qo).[1-\exp\{-(Qo/V).\ t\}] \qquad (24)$$

Wn/Qo is that value of N which balances wash-out and loading. This balance occurs within a time equal to three times the residence time V/Qo, when starting from any initial condition.

APPLICATION OF THE MODEL

Phosphate was chosen as the limiting nutrient, on the basis of published values of the common nutrient ratios for the coastal waters being studied.

All forcing functions were available except daily solar radiation. This was taken from Andersen (1985) for Villefranche-sur-Mer which is approximately at the same latitude as the Po delta. Other parameter values were taken from di Toro (1971) for the Sacramento-San Joaquin delta in California, and failing that, from Verhagen (1974).

The box to which the model was applied, consists of a very shallow coastal strip 78 km long, south of the Po delta, and which extends roughly 5 km offshore. Qr was taken as the sum of all the coastal rivers entering the box plus 40% of the discharge of the Po which enters the top of the box through the southern branches of its delta. The corresponding phosphate loads plus the sewage load equals Wn. Other definitions of the model box are possible and remain to be explored.

First, the exchange flow rate Qa with the outer Adriatic was set to zero. In this case, the model predicted a gradual increase in phytoplankton to a peak in June followed by a slow decline into Winter. A judicious choice of parameter values also produced prey-predator oscillations which were mirrored in the phosphate concentration. Two or three model blooms can be made to occur between April and August. These typical response modes are not observed in the field data for the box in 1978.

Hence we were led to repeat the question posed by Malanotte Rizzoli & Bergamasco (1983) :

> "Why [do] the eutrophication phenomena occur only in summer [typically September to October] and do not start in late winter-early spring as soon as the light intensity in the water mass becomes sufficient for biological activity [?]" Page 1110.

Their study does not answer this question, but examines instead a related question : "Where does the Po water go ?", since the Po carries a large phosphate load.

The exchange flow Qa was then calculated from salinity data and the model run again. The results showed a sharp peak in phytoplankton in the period September to October, no peaks at other times of the year and no zooplankton grazing. This is in qualitative agreement with the observations for 1978. The reservations expressed above, concerning the exchange flow Qa, do not allow a stronger claim than this. See Figure 6 (Todini & Bizzarri this workshop).

The model residence time V/Qo is the key to this result. During the peak, the residence time is roughly 35 days, which allows the phytoplankton to grow. At other times, the residence time is roughly 5 days and the phytoplankton are washed out of the box before they can 'bloom'. The model zooplankton do not grow fast enough to take advantage of the transient build-up of the phytoplankton during September and October. This is our answer to the above question.

CONCLUSION AND RECOMMENDATIONS

The conclusion from this brief modelling exercise is best stated as a hypothesis :

Blooms occur when the water circulation stagnates

An obvious field experiment can be designed to test this hypothesis. The residence time of coastal waters can be locally increased by enclosure in large translucent bags or tanks. We fail to reject the hypothesis when blooms occur within the bags but not in waters which surround them.

Appropriate replication and randomisation of the timing and location of the experiment should be used to test the hypothesis.

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EUTROPHICATION IN THE MEDITERRANEAN SEA

Scientific Background for the Preparation of Guidelines on the Assessment of Receiving Capacity for Eutrophying Substances

by

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INTRODUCTION

Following the initiative of UNEP Coordinating Unit for the Mediterranean Action Plan, UNESCO/I.O.C. has been asked to organize a workshop in order to provide guidelines* for the assessment of receiving capacity for eutrophying substances and for the monitoring of long-term trends of eutrophication. The author was invited to prepare a working paper covering the following aspects:

- the concepts of eutrophication,
- the causes of eutrophication,
- quality of waters entering the receiving waters.
- estimating the nutrient input,
- evaluating the quality in water-bodies,
- eutrophication control techniques.
- designing a monitoring programme,
- monitoring after execution of remedial measures and
- assessing a typical situation

Recognizing the large variety and even contradictory opinions among Mediterranean scientists, engineers and decision-makers relating to eutrophication problems, and the obvious need for an interdisciplinary approach, a group of outstanding scientists has been invited to prepare specific papers, considering the following specific aspects of eutrophication:

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* From the relevant correspondence between the agencies it is evident that UNEP is looking for "practical" guidelines which makes the task even more difficult.

- Ecological processes and ecosystem modifications in
  - the pelagic environment and
  - the benthos.

EUTROPHICATION - A FORM OF MARINE POLLUTION ?

Although eutrophication has long been recognized as one of the most threatening forms, or rather consequences of pollution in fresh-waters and estuaries, considering the true marine environment this still presents a contentious subject. Two relevant examples may be mentioned here; the Baltic is well known for its "eutrophication reputation", and the Gulf of Trieste from which eutrophication phenomena are mentioned in the ecological section of this paper and detailed in the workshop paper by Stachowitsch and Avčin.

Considering the Baltic first, the majority of authors report its increasing eutrophication and anoxia as a consequence of the increasing rates of enrichment mainly by sewage. We read in GESAMP (1982): "Pollution problems in the Baltic stem from sewage discharges... Observations for the period 1961 to 1974 suggest that primary productivity is increasing... long-term oceanographic changes, coupled with inputs by man, have led to an oxygen decrease... The area with H_2S is estimated to have increased from zero in 1929 to 26.10^3 in 1959 and 84.10^3 km^2 in 1975". This contrasts with the opinion of Steemann Nielsen (1971), undoubtedly an authority in the field of primary productivity; "From various quarters it has been asserted that this sea is on the way to being completely spoiled, i.a. due to eutrophication.... In fact it is by no means certain that man has had much influence on the nutrient conditions in the Baltic during recent years.... In the Kattegat... (biweekly measurements of the rate of primary production during 1954-69)... it has been impossible to observe any increase in the rate of production during these 17 years... We may suggest that the eutrophication here if anything, may have increased the rate of fish production".

The second example, the Gulf of Trieste in which the ecosystem is assumed to be in the process of increasing eutrophication, has been considered by Olivotti, Faganeli & Malej (1985), who are very familiar with this area, both in its Italian and Yugoslav parts, as "not affected by eutrophication, rather the major part of eastern waters appear to be essentially oligotrophic". Along with such a statement the authors report measured data* which alone characterize this environment, in comparison with typical conditions in the Mediterranean, as highly eutrophic, and at a global scale about as productive as shelf-waters, e.g. of the boreal Atlantic.

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* Example: Station 27 in the centre of the Bay, 10 km offshore; means of 1-5 yrs data: Secchi 8 m (min.2, max 16), chlorophyll 1.26 $\mu g.dm^{-3}$ (mean max. 3.7), NH_4-N 3.3, NO_3-N 2.5 and P-PO_4 0.15 $\mu mol.\ dm^{-3}$

Such contradictions are indeed quite understandable for it is extremely difficult, though not impossible, to distinguish naturally occuring eutrophic condtions from man-made eutrophication, e.g. in coastal areas which are influenced by river discharges. In most cases, however, the controversies originate from different terminology and definitions or from misunderstandings. Again, the example quoted above illustrates this case. Olivotti et al (1985) stated that, according to the OECD definition, they consider "eutrophication as an undesirable degradation of the (marine) environment (caused by an excessive algal biomass) resulting in a deteorioration of water quality which interferes with most of the beneficial uses of water; it is causing, in many cases, significant economic losses; in other words, as a form of pollution". Obviously, by this definition the Gulf of Trieste can be classified as eutrophic even for an oligotrophic environment.

In order to avoid such misunderstandings it seems appropriate to repeat the GESAMP definition which has been accepted also by UNEP Mediterranean Action Plan as follows:

> "Introduction by man, directly or indirectly, of substances or energy into the marine environment (including estuaries) resulting in such deleterious effects as cause harm to living resources, hazards to human health, hindrance to marine activities including fishing, impairing of quality for use of sea-water and reduction of amenities".

The same authority stated further (GESAMP 1982) that a study of the health of the oceans requires consideration of many contaminants and potentially toxic substances, however the following being at present particularly relevant to man's impingement on the oceans because of their distribution, quantity or impact: sewage, some synthetic organics. petroleum, "trace metals" and radionuclides. Concerning effluents which may potentially at least contribute to eutrophication processes the following statements from the above source are also relevant:

> "Major chronic inshore marine pollution problems can often be attributed to the discharge of large volumes of wastes that have a local impact. These include materials which are partially biodegradable, such as raw sewage, sewage sludge, food and beverage processing wastes, pulp and paper mill effluents, woollen and cotton mill wastes, and sugar refinery effluents. Solid wastes such as mine tailings and dredge soils are also in this category.
>
> For sewage, problem areas are local rather than global, and coastal rather than oceanic. Sewage does present a direct risk of infections to humans on some beaches, especially during recreational seasons. Discharge on or near shellfish beds presents a greater risk to human health through the consumption of contaminated seafood.
>
> Nutrient increase is often associated with sewage, and the impact of this has been perceptible in many coastal regions. The effects of nitrogenous wastes are usually most obvious, but phosphate may adversely alter the species composition of regional phytoplankton".

Taking into account the above, internationally accepted statements and "borrowing" some justifications, based upon facts which are shown in documents prepared for this workshop, it appears that the following statements may adequately define the real meaning of the phenomena we are considering:

> Eutrophication is not a form but a consequence of pollution; in the case of man-made eutrophication, pollution is the discharge of any substance which promotes eutrophication

Recently, some authors tend to specify various degrees of marine eutrophication by using additional terms like mesotrophic, dystrophic and hypertrophic. It is the opinion of this author that the use of these terms creates confusion; the term dystrophic is certainly misused, as it was originally introduced to characterize lakes of low trophic level due to high concentrations of humic acids.

These definitions then serve as the starting point for the discussion of the workshop.

CHANGING EUTROPHICATION CONCEPTS

It seems that the first person who introduced the term "eutrophic"*, i.e. literally well-nourished, was Weber (1907) in relation to his studies of nutrient conditions in soils of German bogs. Naumann (1917) transferred the term into limnology, and was the first to perceive relationship between nutrients and primary productivity of lakes that led him to develop a classification scheme for lakes (1919, 1927), based on the trophic state in euphotic layers. At the same time Thienemann (1918, 1925) developed a parallel scheme but based on the oxygen content of the hypolimnetic layers, and the recognition that indicator species of chironomid larve reflect the trophic level of euphotic layers. Although there was some simplification in the early works by Naumann and Thienemann, they not only laid the foundation for the current lake classification, but also developed the classic concept of the eutrophication. This concept refers, of course, to the natural aging of lakes in successions of steadily increasing trophic levels due to natural inputs of nutrients, internal cycling, sedimentation etc., i.e. a process which has no comparable "counterpart" in the marine environment; exceptionally one can consider successional stages of some tropical lagoons as a similar process of natural aging. However, if we eliminate the aging component, there are a number of vast marine provinces where naturally induced eutrophication** occurs in the sense of the above concept. Obvious examples are the Black Sea with its river-borne nutrients and the Northern Indian Ocean with upwelling nutrient inputs etc.

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* As well as the terms "mesotrophic" and "oligotrophic".

** The term "eutrophic" has been introduced into biological oceanography relatively early to characterize highly productive waters, such as those in upwelling zones. Probably Gilson (1937) was the first to use the term in this context.

The Baltic, too, fits into the same scheme, although its nutrients are significantly enriched by man-made sources, i.e. in the combined process of natural and cultural eutrophication.

Although there are a number of historic, even antique, accounts of eutrophication cases in which man-made effluents contributed to some extent (e.g. the Lake of Tunis) the concept of cultural eutrophication is of recent origin, becoming a real problem along with booming urbanization and industry after the 2nd world war. First, there were an increasing number of lakes that were badly affected by cultural eutrophication, in addition to their natural aging. Expansions of human settlements along the shores, often to keep pace with the growth in tourism, with consequent sewage discharges (including detergent phosphorus), massive use of agricultural fertilizers, air-borne pollutants (including acid rain) are obvious causes of overfertilization and related ecosystem modifications. Cultural eutrophication went on to affect lowland rivers, drinking water reservoirs and indirectly groundwaters as well. In parallel, cultural eutrophication extended to marine environments, first in estuaries, lagoons, ports and embayments, followed by larger areas of coastal waters being affected worldwide and in the Mediterranean*, as will be shown later on in the case studies presented to this Workshop.

Considering now the conceptual views on natural versus cultural eutrophication, one can logically conclude that since there is no significant difference between the final effects of both processes, thus the concept should be about the same. However, even elementary ecological thinking shows a dramatic difference which is essentially related to time-controlled developments:

- <u>Natural eutrophication is a long-lasting process (time scale 10^3-10^4 years) that allows evolutionary ecosystem adaptations to elevated trophic conditions**</u>

- <u>Cultural eutrophication introduces sudden changes (time scale 10 years or less) and hence un-compensated ecosystem disequilibria, a stress environment and possibly substantial harm to living resources</u>.

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* First scientific and technical reports on the cases of cultural eutrophication were published in the fifties for the Baltic and coastal zones of USA (Long Island, San Francisco Bay). For the Mediterranean, Heldt (1929) was the first scientific paper describing a clear eutrophication case (the Lake of Tunis) though it did not apply a eutrophication concept. Probably the first papers using this approach were descriptions of man-made eutrophication and anoxia in the Port of Marseilles (Gilet, 1960) and in the Bay of Koper, Adriatic (Stirn, 1965)

** Even cases of massive, natural enrichment such as that induced by upwelling phenomena produce stress-environments and "immature" ecosystems (Margalef, 1978).

MAN-MADE EXOGENOUS FACTORS OF CULTURAL EUTROPHICATION

The purpose of the guidelines this workshop is producing is to assist Mediterranean countries in their efforts to control, or rather to reduce, the rates of cultural eutrophication in their coastal water, lagoons and estuaries. It seems appropriate therefore to restrict the discussion to those factors which society is in principle able to control, at least indirectly. Therefore the natural factors* of marine bioproductivity and related processes are not considered here, although these processes are primarily controlled by natural components: light, temperature, stability and dynamics of water masses, autochthonous nutrient pools and deposition and/or recycling conditions, structure and efficiency of trophic chains etc. Since the practical target of eutrophication control is reduction of excessive primary production, priority is given, rather pragmatically, to consideration of the relevant factors.

Factors Enhancing Algal Growth and Production

1. Nutrients

Unlike terrestrial (and to some extent fresh-water plants), which may experience growth limitation because of the short supply of any of the essential elements (C, H, O, N, S, Si, P, Mg, K and Ca), marine algae are normally exposed to an adequate supply all except N, P and Si compounds, i.e. the nutrients in sensu stricto. The supply of these nutrients is particularly deficient in many tropical marine environments and in the Mediterranean which is the only large subtropical sea that is, generally, very oligotrophic. A weak exchange of water masses with the Atlantic and the Black Sea, a narrow continental shelf and great mean depth, lack of strong vertical circulations and extraordinarily poor nutrient reserves in deep waters, limit an efficient replenishment of nutrients in euphotic layers. The major nutrient supplies originate from the Atlantic influx, rivers and recently from pollution, therefore the areas of enhanced productivity are located exclusively within the reach of the above sources.

Limiting Nutrient

Although the rigid application of Liebig's "law of the minimum"** has become outdated in contemporary limnology and biological oceanography, many current studies of cultural eutrophication are actually still using this approach. One can understand the enthusiasm among civil engineers about

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* Some of these can be modified by man directly or via eutrophication induced changes, e.g. locally increased temperature by heated effluents, reduced depths of euphotic layers due to mineral turbidity or shading by phytoplankton blooms, modified trophic chains etc.

** Plant growth is limited and controlled by a nutrient for which the available concentration is approaching the critical minimum as needed for normal physiological processes and reproduction. In freshwater lakes, the limiting nutrient is usually considered to be phosphorus but rarely so (e.g. for the Adriatic) in studies of marine productivity, in which nitrogen is usually considered as geing the limiting factor.

phosphorus being the cause of eutrophication, for it can be rather easily precipitated from waste waters, but among ecologists such "sancta simplicitas" cannot easily be tolerated. Even general ecology textbooks provide essential instructions on this subject, e.g. in E P Odum's *Fundamentals of Ecology* (1971) we read: "Liebig's law is strictly applicable only under steady-state conditions........Since cultural eutrophication usually produces a highly unsteady state, involving severe oscillations (i.e. heavy blooms of algae followed by die-offs, which in turn trigger another bloom on release of nutrients) then the either/or argument may be highly irrelevant because phosphorus, nitrogen etc. may rapidly replace one another as limiting factors during the course of the transitory oscillations". There are many other arguments which lead us to believe that all forms of phosphorus and nitrogenous nutrients must be considered in order to understand the processes, and on this basis to outline rational criteria and guidelines for practical measures of eutrophication control and prevention. Just to mention a few of the relevant arguments:*

- generally very fast regeneration of nutrients, both from direct excretion and after the microbial and enzymatic decompositions; this is, however, extremely variable due to changing species composition, population sizes, direct and metabolic thermal conditions, sinking depths and rates of geochemical processes etc;
- substantial differences between species of pelagic and benthic algae concerning requirements, uptake rates, storage and preferences for various forms of nutrients;
- variability of physical conditions as related to primary productivity generally, and in particular of these which control temporal and spatial parameters of euphotic zones.

From the above standpoints it is worthwhile to consider the following nutrients:**

Phosphorus

In natural as well as moderately polluted coastal waters phosphorus usually appears in the following forms:

(Compiled from numerous sources, basically from Nalewajko & Lean, 1980)

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* Details see Morris (1980), Lorenzen & Dugdale (1976), Goldman (1976), Stirn (1975 etc).

** Silicates are not considered for they may become limiting only to populations of diatoms and even that quite rarely, after the peak of exceptionally heavy spring blooms.

Form	%
Particulate[1]	28.5 - 98
Colloidal[2]	1.2 - 4
Inorganic phosphate[3]	0.1 - 22
Dissolved organic[4]	0.1 - 6

1. - particles >0.45 μm;
2. - <0.45 μm, analytically reacts along with orthophosphate, chemical form unknown;
3. - includes some polyphosphates, possible detergent-borne, too;
4. - organic compounds of low molecular weights.

Orthophosphate is the form preferred by unicellular algae, but on the basis of results obtained with algal monocultures, the ability to utilize other forms, such as polyphosphates and organic phosphorus, seems to be widespread. Considering the growth of algae this should be taken into account, for sewage and incorporated detergents present a massive source of organic phosphorus compounds and polyphosphates, respectively, while the concentrations of orthophosphate after a substantial dilution of effluents in sea water might not be drastically elevated.

Average natural concentrations of orthophosphate in euphotic layers of productive temperate coastal waters are around 0.3 $\mu mol.dm^{-3}$ $P\text{-}PO_4$*, and significantly lower after periods of phytoplankton blooms. A typical value for open oceans** is 0.1 $\mu mol.dm^{-3}$ in surface layers and 1.5 (Atlantic) to 2.8 (Indian and Pacific) in deep waters. Values for the Mediterranean Sea are extremely low, typically below 0.05 $\mu mol.dm^{-3}$ in the euphotic zone and at best 0.3 in the deepest waters. The following table shows typical phosphate concentrations as found in euphotic layers of areas with distinctly different pelagic productivity of the Adriatic.

TABLE I TYPICAL PHOSPHATE CONCENTRATIONS IN EUPHOTIC LAYERS OF THE ADRIATIC SEA

TYPICAL ADRIATIC AREAS	TYPICAL CONCENTRATIONS $\mu mol.dm^{-3}$ $P\text{-}PO_4$
Stations along Adriatic median transect:	
Extremely oligotrophic southern basin[1]	0.03
Oligotrophic Mid-Adriatic[1]	0.05
Eutrophic North Adriatic[1]	0.12
Highly eutrophic NW Adriatic[2]	0.30

1 - Vučak, Škrivanić & Stirn, 1982;
2 - Marchetti, 1984.

* 1 μmol P = 31 μg

** Much less in tropical areas, much more in upwelling areas.

The above values for eutrophic waters as compared with normal conditions in the Mediterranean are actually very high. A substantial source of this phosphorus, mainly discharged by rivers, is by dissolution from alpine rocks and soils. However, an important fraction is man-made, although the above localities are remote from direct pollution discharges (20-50 km). In coastal waters which are directly polluted by sewage or similar effluents the concentrations of phosphate are as a rule dramatically increased, for example 2.0 $\mu mol.dm^{-3}$ and more. Other forms of phosphorus are also increased, e.g. in the polluted Bay of Koper (N.Adriatic) the particulate form may contribute up to 5.8 $\mu mol.dm^{-3}$ of phosphorus (Faganeli, 1983)

Considering the Mediterranean Sea with its generally oligotrophic waters, the decisive role of phosphorus as the factor limiting pelagic productivity, as suggested by many authors, appears indisputable. The N:P ratio is as a rule significantly higher than the assimilatory optimal N:P = 15:1, usually above 19:1. For moderately eutrophic waters such as the central and eastern parts of the North Adriatic phosphorus limitation was suggested (Revelante & Gilmartin, 1976; Pojed & Kveder, 1977). However, there are indications of bimodal limitations, and also experimental proof* that nitrogen is indeed limiting, at least during the winter (Šalamun & Štirn, 1982). Highly eutrophic waters, regardless of whether they are fertilized by rivers or man-made effluents, are fairly steadily receiving phosphorus supplies** at levels approaching the optimum needed for the growth of mixed phytoplankton populations at a eutrophic level, e.g. 0.3 - 0.5 $\mu mol.dm^{-3}$ $P\text{-}PO_4$. It appears logical that under such conditions nitrogen might be the prevailing limiting factor: although this has never been experimentally proved in the Mediterranean it is widely known for other marine environments (Goldman, 1976).

Nitrogen

In addition to dissolved molecular nitrogen (N_2)***, the sea water contains many dissolved inorganic and organic nitrogen compounts, the total concentration of which is only about 1/10 of that of the dissolved gas.

The principal inorganic forms of nitrogen are listed over, along with typical concentrations found in euphotic layers of temperate shelf areas of the oceans:

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* Algal monocultures bioassay and artificial enrichment experiments.

** Not only orthophosphate but also other forms of phosphorus, which may not be shown in analytical data, contribute to the pool, and its regeneration.

*** In coastal waters which are depleted of nitrate and ammonium. and where the substratum allows populations of blue green algae to settle. these algae can convert substantial amounts of molecular nitrogen by biological fixation to compounds which, after regeneration. can be assimilated by other algae and seagrasses (Morris, 1980)

TABLE II PRINCIPAL FORMS OF INORGANIC NITROGEN IN EUPHOTIC LAYERS OF COASTAL WATERS

Compound	Typical concentration in $\mu mol.dm^{-3}$*
Nitrate $N-NO_3$	2 - 5
Nitrite $N-NO_2$ **	Trace - 0.5
Ammonium $N-N_4$ ***	1 - 3

* μmol N = 14 μg N.
** Often, nitrite maxima are found near the base of the euphotic zone where it is released by phytoplankton assimilating nitrate at a low light regime (Wada-Hattori, 1971).
*** i.e. the sum of ammonia and ammonium ions, the relative proportions depending upon pH.

In tropical surface layers the concentrations are much lower, except in upwelling areas, however in deep oceanic waters the concentrations are high, mainly due to nitrates (20 - 40 $\mu mol.dm^{-3}$).

In the Mediterranean Sea inorganic nitrogen is generally fairly depleted, although not to the same extent as are phosphates. The typical range of concentrations is shown in the table below using data from the Adriatic Sea.

TABLE III TYPICAL INORGANIC NITROGEN CONCENTRATIONS IN EUPHOTIC LAYERS OF THE ADRIATIC SEA

TYPICAL ADRIATIC AREAS	Concentrations $\mu mol.dm^{-3}$ $N-NO_3$	$N-NH_4$
Oligotrophic southern basin[1]	1.0	0.5
Oligotrophic Mid-Adriatic[1]	0.5	0.5
Eutrophic North Adriatic[1]	1.5	1.0
Highly eutrophic NW Adriatic[2]	4.0	2.0

1 = Data from Vučak-Škrivanić-Štirn (1982)
2 = Data from Franco (1983)

In oligotrophic areas, both nitrates and ammonium originate from marine regeneration and from the atmosphere; in eutrophic areas a substantial part of nitrates is river-borne, from natural sources, while the ammonium comes mainly from man-made sources. In coastal waters which are directly polluted by sewage or significantly mixed with discharging rivers the concentrations are generally much higher, above 35 $\mu mol.dm^{-3}$ $N-NO_3$ and 20 $\mu mol.dm^{-3}$ $N-NH_4$.

Dissolved organic compounds of nitrogen are also quite important, with the combined total concentrations in oceanic upper layers at similar levels to the inorganic forms. In shelf waters the level is usually higher, and in eutrophic and/or organically-polluted waters, organic compounds may contribute the highest fraction of the total dissolved nitrogen.
Particulate organic nitrogen, although often at similar or higher than the dissolved forms, cannot be considered within the pool because of the slow rate of decomposition.

Faganeli (1983) reports for the eutrophied Bay of Koper (North Adriatic) the following relative composition of the pool of total dissolved nitrogen (April 1977):

TABLE IV RELATIVE COMPOSITION OF THE POOL OF TOTAL DISSOLVED NITROGEN IN NORTH ADRIATIC

Nitrogen Form	%
Particulate	11.3
Dissolved:	
- Organic	68.6
- Inorganic	20.1

The major part of the total dissolved organic nitrogen (DON) is constituted by a great variety of compounds, many still unidentified, yet from the standpoint of algal nutrition it is worthwhile to mention only the following two which usually contribute about 10 - 30% of DON:

- Urea is the most common product of animal excretion and of bacterial decomposition of purines and pyrimidines, therefore its concentration in organically polluted environments can be quite high, e.g. 5.0 $\mu mol.dm^{-3}$ N. Generally in coastal waters 0.1 - 1.0 μmol and in open oceans < 0.1 μmol occur.

- Amino acids found in the sea originate from decomposition and as the direct input of extrametabolites, produced by microorganisms and lower invertebrates. Although about 2/3 of total dissolved amino acids may be in combined form as peptides etc., it is the free component which is of most immediate use to microorganisms, including some phytoplanktonic algae. The usual oceanic concentrations of free amino acids are below 0.1 $\mu mol.dm^{-3}$, 0.1 - 0.5 in coastal waters, with > 1.0 in eutrophic areas. In organically polluted coastal waters the levels are usually significantly elevated, since the typical concentration of sewage amino acids may be as high as 300 $\mu mol.dm^{-3}$ (Faganeli, 1983).

In principle ammonium is the preferred form of nitrogen for algae, followed by nitrate and nitrite after the ammonium concentration is reduced (<.5 $\mu mol.dm^{-3}$). However, there is a large body of literature providing experimental evidence on partial or sole utilization of the above organic compounds as the source of nitrogen for algal growth (Morris, 1980), particularly when the concentrations of inorganic forms are approaching depletion*, e.g. in "post bloom" conditions. Considering cultural eutrophication this obviously is quite relevant, although very little is known about it.

2. Biomicroelements

There are a number of microelements, such as iron, manganese, copper, zinc, cobalt, molybdenium and boron, which are essential to the growth of

* Moreover, McCarthy et al. (1977) proved for a eutrophic ecosystem that nitrate may be utilized only when the concentration of ammonium plus urea is insufficient to saturate the phytoplankton uptake systems.

marine algae since they occur in their enzyme systems etc. It is unlikely that phytoplankton growth is ever limited by the total concentration of any of these trace elements (except in mass-monocultures of algae), but less rarely, an essential element may be present in a form in which it is not assimilable by the organisms. This is particularly important for iron which has a very low ionic concentration, although algae are able to make use of some particulate and colloidal forms, provided there is a chelating mechanism active in the surrounding sea water*. There seems to be a variety of natural chelating substances in oceanic and open coastal waters, although their chemical identity is still quite obscure (Barber, 1973). The "classic" ligands of humic-complex compounds (Gelbstoff) have an autochthonous marine origin, and similar material also reaches the coastal waters from rivers, estuarine-lagoon marshes, digested sewage and other biodegradable organic effluents. Phytoplankton growth, even in highly eutrophic conditions in coastal waters or during a moderate bloom of diatoms, does not appear to be significantly limited by a reduced availability of trace elements, namely Fe and Mn. However, there is some evidence that these metals trigger or limit the development of the true (i.e. dinoflagellate) "red tides", as a complementary factor to the required high levels of the N/P nutrient pool (Takahashi & Fukazawa, 1982). A parallel function of chelating substances relating to "red tide" development is the detoxication of free copper ions, which would otherwise be present in sufficiently high concentrations in estuarine and polluted coastal water to inhibit the growth of dinoflagellates (Anderson & Morel, 1978).

3. Organic Stimulants of Algal Growth

It has been known for many decades that even when algal cultures are supplied with nutrients and biomicroelements, growth will often not take place unless trace amounts of specific organic compounds are present; similar observations have been made for phytoplankton in natural conditions.

Most extensively investigated in this respect are the vitamins: thiamine (B_1), cobalamine (B_{12}) and biotin. The first relevant reviews (Lewin, 1961; Provasoli, 1963) concluded that practically all marine flagellate algae require exogenous supplies of one or more vitamins for efficient growth. Some diatoms, among them species responsible for heavy diatom "blooms", show similar requirements e.g. *Skeletonema costatum* for B_{12}. The growth of some marine/brackish flagellates (*Ochromonas, Monochrysis, Eutreptia*) is so specifically limited by vitamin supplies that their monocultures are used for bioassay determination of vitamin concentrations in sea water. Although these vitamins are produced by microorganisms, and through autolysis and decomposition occur in normal marine environments, the major input seems to be from estuaries, marshes and land-based sources, in particular from sewage.

* For this reason, since Føyn (1912), it has been the practice to add natural (soil extracts of humic substances) or synthetic chelators (EDTA) to algal monoculture growth media, in order to make trace elements assimilable and also to compensate their toxicity for algae if their initial concentration is too high.

Sewage, as well as similar biodegradable waste materials, presents a source of a great variety of organic compounds, of which some appear to have a stimulatory effect on the growth of algae. Generally, the suspected stimulants show biological activities which are similar to those of phytohormones, e.g. auxins (Štirn, 1975), but their chemical identity remains unknown; it was proved, however, that these are substances of a relatively low molecular weight, i.e. < 30,000 (McDonald & Clesceri, 1974).

Biostimulants probably do not significantly influence the overall primary productivity in normal marine environments, yet they and the contrasting bioinhibitors may critically control the species composition and the temporal successions of phytoplankton, and in particular the space-time patterns of "blooms". There is experimental evidence that biostimulants control the growth of high-density populations just of those species which are responsible for the most massive and long-lasting blooms in heavily polluted coastal environments (e.g. Long Island, Lake of Tunis etc), such as *Nannochloris*, *Stichococcus*, *Eutrepia* and "naked" dinoflagellate species (Ryther, 1954; Provasoli, 1963, Štirn, 1975 etc).

4. Sources of Eutrophying Substances

In addition to autochthonous marine pools and processes* for the replenishment of algal growth-supporting materials, there are the following allochthonous sources of major importance:

1. *Atmosphere*

Considering the cycling of phosphorus, the atmosphere plays a minor, though not a negligible role, contributing to the oceans roughly 1-2% of the total input, i.e. about 5 $mg.yr^{-1}.m^{-2}$ of sea surface, and significantly more in coastal areas close to large industrial agglomerations (SCOPE, 1976). The atmospheric input of nitrogen compounds that ultimately enter the nutrient pool (N_2 gas excluded): NO_2, N_2O, NH_3, and ionic NH_4 and NO_3 in rain, is much higher, 8-18% of the total input. The amounts of nitrogen oxides are significantly higher in areas of heavy atmospheric pollution (urbanized-industrial areas), as are the levels of ammonia, evaporating also from highly fertilized agricultural land (Robinson & Robbins, 1970). Typical concentrations of nutrient-forms of phosphorus and nitrogen in rain waters are 0.08 and 0.7 $mg.dm^{-3}$, respectively.

2. *Rivers and Runoff*

Although there are almost no rivers that can be considered as "unpolluted" entering Mediterranean coastal waters, it is appropriate to mention their typical natural background concentrations of nutrients:** 0.01 - 0.05 $mg.dm^{-3}$ P-PO_4 and 0.1 - 0.6 $mg.dm^{-3}$ N (mainly

* Instant excretion, extrametabolites, autolysis and decomposition; decomposition and mineralization in aphotic layers and in sediments; nitrogen fixation; abrasion and dissolution of sea shores; submarine volcanism; physical transport processes. Note: the above regeneration processes can be significantly more productive in eutrophied systems!

** This refers to the upper flows of alpine rivers; concentrations in karstic rivers might be even lower.

nitrate). Taking for the example the Adriatic Sea with river-borne inputs estimated at 79,000 $t.yr^{-1}$ of phosphorus and 250,000 $t.yr^{-1}$ of nitrogen (UNEP, 1978), the natural input of phosphorus would represent less than 8% and that of nitrogen up to 30%.

Since in the majority of cases the lower reaches of rivers collect practically all the runoff from intensively fertilized agricultural land, drainage and domestic effluents from urban agglomerations, and a great variety of industrial effluents, the levels of nutrients in rivers are of course drastically increased, generally doubled. Therefore, according to UNEP (1978)*, the relative contribution of river inputs of total loads of phosphorus and nitrogen discharged into the Mediterranean Sea appears to be 41 - 93% for P and 38 - 91% for N. From general experience and from the above reference it can be stated that up to 30% of river-nutrients might be derived from sewage and industrial effluents, the rest being from natural background and runoff, mainly from fertilized agricultural land.

3. *Sewage*

This abundant effluent is no longer composed just of human excreta, for it is invariably mixed with other diverse waste materials, particularly detergents which cause a significance increase in levels of phosphorus. For example, Sawyer (1973) reports a 200% increase of phosphorus concentrations in typical sewage that has occurred during the post-war period; inorganic P in 1945 was about 3, and in 1970 about 8 mg/l. Since the level of nitrogen remained about the same, the N/P ratio changed from the previous ratio of 9:1 to the recent one of 4:1. Typical nutrient compositions for differently treated sewage effluents are shown in the following table (compiled from EPA, 1974; Griffith 1973; NAS, 1969).

TABLE V TYPICAL CONCENTRATIONS OF NUTRIENTS IN DIFFERENTLY TREATED SEWAGE EFFLUENTS

Type of Effluent	Nutrient Concentration $mg.dm^{-3}$ of N, P			
	N_{tot}	NH_4	$NO_2 + NO_3$	P_{tot}
Raw Sewage	45	25	7	9
Primary Treatment	31	15	7	6
Secondary Treatment	25	2	13	6
Oxidation Ponds	11	7	1	6
PO_4-Precipitation	23	2	13	2

On the basis of UNEP (1978) estimates for the Mediterranean, the "point" sewage discharges into the coastal waters in northern areas

* In this authors opinion, however, the river input is overestimated, in particular for arid areas of the Mediterranean.

(dense population and urbanization, important rivers) contribute only about 5% of total phosphorus/nitrogen loads, while in arid and less developed areas this is about 12% of phosphorus and 25% of nitrogen. From the above and other available information it is impossible to get a reliable estimate of the relative sewage contribution to the nutrient loads carried by rivers, hence it is also difficult to estimate what is the proportion of sewage in total nutrient discharges into coastal waters. By comparison with relevant estimates elsewhere in Europe one could suggest that in northern areas of the Mediterranean, sewage may contribute something like 30% of phosphorus and 20% of nitrogen to exogenous nutrient sources, and substantially more in southern areas.

4. *Industrial Effluents*

Some inorganic and most organic industrial effluents can contribute considerable amount of nutrients*. However. considering the Mediterranean, the majority of these loads are again carried by the rivers, therefore the "point" sources along the coastal zones usually contribute less than 5% of total N/P loads.

5. *Sources of Organic Algal Growth-Promoting Substances*

As mentioned previously these substances are produced mainly in aquatic environments with intensive bacterial activities, in particular on abundant or dead organic matter, i.e. in biological treatment plants, swamps, marshes, lagoons and estuaries. Outlets from such systems are usual locations of discharge of these substances into coastal waters, the most important being deltas and estuaries of rivers.

Factors Reducing Herbivorous Consumption of Algae

Considering "hyperproduction"** and "excessive biomass"** of algae as a focal problem of cultural eutrophication, this is basically caused by substantially increased inputs of eutrophying substances as described above. However, an "excessive biomass" may originate also in a less enriched system with moderate primary productivity, yet with significantly reduced rates of herbivorous nutrition, i.e. due to reduced populations of herbivorous zooplankton (copepods, cladocerans etc.) and benthic filter-feeders (mainly pelecypods, ascidians, serpulids and sponges). There are, in principle, the following man-made impacts that may lead to significant reductions in populations of secondary producers:

- Acute and/or sublethal toxicity of coastal waters as introduced by industrial or large domestic effluents which contain active levels of toxic metals, detergents, phenols, ammonia, H_2S etc.
- "Mechanical" destruction of respiratory-filtering organs of filter-feeders by steadily elevated contents of dispersed mineral particles, or by temporary but massive siltings due to dredgings, coastal engineering works etc.
- Destruction of inshore or bottom hard substrata for sedentary filter-feeders by works as above or due to oil-spills and chronic shore-based oil pollution.

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* For specific data see UNEP/WHO 1982

** This terminology has a relative meaning, i.e. in comparison to the typically oligotrophic ecosystem of the Mediterranean.

ECOLOGICAL PROCESSES OF CULTURAL EUTROPHICATION* AND ITS TYPICAL APPEARANCES IN THE MEDITERRANEAN

It is not the purpose of this paper to consider the rather complex and variable ecosystem - modifications which are induced by eutrophication; there is also much pertinent information available in other papers prepared for this workshop**. Moreover, this subject is less useful from the standpoint of prevention and control of eutrophication, for after the eutrophication-triggering factors having been introduced into the ecosystem, there are few practical improvements which can be made. However, in order to provide a framework for consideration, the enclosed schematic presentation of processes is useful, although it is an inevitable simplication of the complex dynamic structure, of which some elements merely have a hypothetical value. The following account of the most typical ecological systems among the cases of cultural eutrophication reported from the Mediterranean region, shows the comparability between theoretical concepts and actual phenomena. It seems appropriate to distinguish for the Mediterranean region the following types or categories of eutrophication or rather the eutrophication - induced ecosystem modifications:

1. Moderate Inshore Eutrophication

   This is the most common form which can be currently seen almost everywhere along the Mediterranean shores, adjacent to urban agglomeration and tourist resorts, in moderately polluted lagoons, ports and marinas etc. It occupies only the very inshore waters which are enriched by chronic, but modest sewage discharges. Locally, the trophic level is elevated overall; in the pelagic zone this is difficult to distinguish from natural fluctuations, but at the shore the modifications are quite evident, particularly within communities on hard substrata: dominating nitrophilic vegetation (*Ulva, Enteromorpha, Dictyopteris etc*), dense assemblages of tolerant species of filter-feeders (*Mytilus, Crassostrea,* serpulids, etc).

2. Heavily Eutrophied Local Systems

   There are an increasing number of lagoons, semi-enclosed bays and larger port areas where the permanent inputs of enrichment pollutants are at levels which can induce full eutrophication development, similar to the one shown in the enclosed scheme (Fig.1). There are many papers and reports describing cases that fit into this category; actually many more cases exist, but there are no relevant reports available.

   Apart from heavily eutrophied port areas***, the most common cases are

* Often the responsible environmental factors are due to a combination of natural circumstances and man-made inputs.

** For basic ecological details see also UNESCO *Reports in Mar.Sc.* No. 29 and UNEP/FAO Manual, No. 8 (*FAO Fish.Techn.Pap.*209).

*** Characteristic for this type is an extreme degradation of benthic communities, near-bottom anoxia and a continuous succession of heavy blooms, usually euglenids, chloromonads and dinoflagellates.

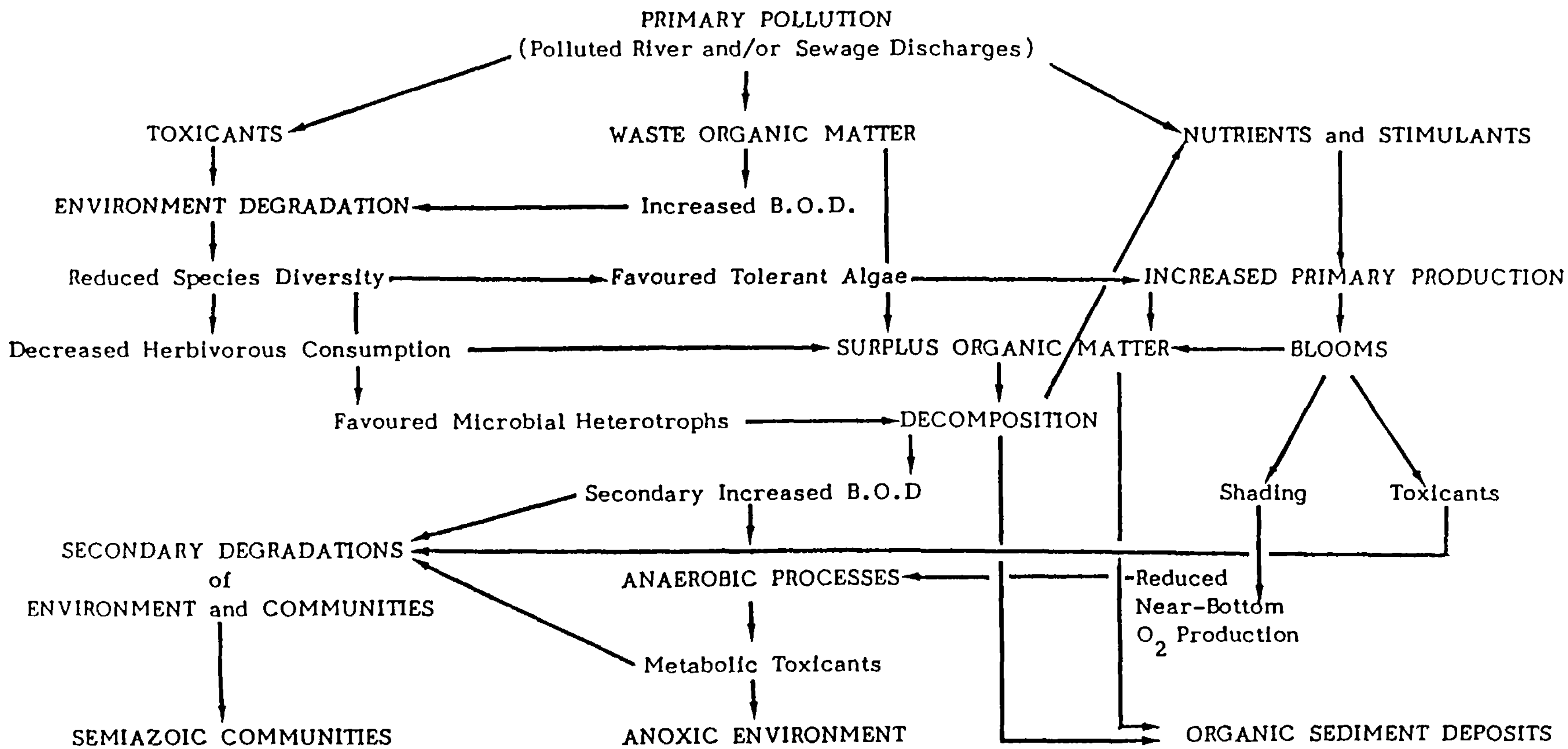

Figure 1 : Schematic Presentation of Eutrophication Processes (Modified from Stirn, 1971).

heavily eutrophied semi-enclosed, shallow bays with a weak circulation in which inner parts are receiving substantial sewage loads (e.g. from settlements with populations of more than 10,000 inhabitants for small and > 100,000 for larger and more open bays) or discharges of polluted rivers or streams. Characteristics of this type of eutrophication are as follows:

- Shore hard-bottom communities are modified as described above but they are less diverse and overgrown by a high biomass of *Ulva, Enteromorpha* etc.

- This macroalgal vegetation also invades shallow soft bottomed zones, displacing and eliminating the previous prairies of sea-grasses (*Cymodocea, Zostera, Posidonia*) and also may form surface-floating patches of the above mentioned genera, often combined with floating *Chaetomorpha*.

- The pelagic component is characterized by significantly increased phytoplankton standing crops throughout the year* and by a succession of heavy blooms of diatoms plus a variety of flagellates during cooler seasons and dinoflagellates in summer (Fanuko & Justić, 1986; Štirn, 1971 etc).

- The sediment bottom is enriched by organic matter, it is in a reduced state even at its surface, and the near-bottom water layers temporarily become anoxic. Therefore the structure of macrobenthic communities are considerably modified, most typically by reduced species and trophic diversity versus increased standing crops (Avčin et al., 1973). However, meiofauna, particularly the normally dominating nematodes shows decrease in both the diversity and the abundance/biomass (Vrišer, 1986).

An extreme eutrophication of this type may develop in coastal lagoons, a dramatic example being that of the Lake of Tunis. Comprehensive details are given in the literature (UNESCO, 1984)** and no further comments are needed for the purpose of this paper.

Considering the perplexing subject of nutrient receiving capacities, the case of the Lake of Tunis is of a particular interest, for it is unique in the Mediterranean region in demonstrating clearly the ecological consequences induced by a known amount of eutrophying pollutants (discharge of partly-treated sewage from a city of 300,000 inhabitants into a coastal lagoon of 6,000 ha surface area, resulting in a catastrophic ecosystem destruction).

Similarlarly important results were obtained by research on the experimentally sewage-polluted lagoon in Strunjan in North Adriatic (Štirn, 1986; Fanuko, 1984; Malej et al., 1978). A small partition

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* There are, usually in winter and after heavy blooms, intervals of quite low phytoplankton densities, i.e. seemingly oligotrophic phases, although the supply of nutrients remains at high levels.

** For an ecological explanation of the eutrophication phenomena of the Lake of Tunis see also Štirn (1968) and Crouzet (1972).

($63\ m^2$) of a natural lagoon has been continually polluted for a year by 300 $l.d^{-1}$ of primary-treated sewage (1-2 population equivalents). During the experiment in the "polluted" and a comparable "clean" lagoon partition, extensive environmental monitoring and biological research has been carried out. Results demonstrated that even such modest sewage-enrichment was enough to induce almost* all the phenomena listed above, and within a year the previously well-balanced sea-grass community has been modified into a "micro-version" of a destroyed ecosystem like the one of the Lake of Tunis. Moreover, the original natural community only became restored 4 years after the termination of sewage discharges.

3. Large-Size Eutrophication

For most of the Mediterranean the continental shelf is very narrow, edging deep waters, and hence the dispersion of nutrients is relatively easy; their inputs are generally very modest except in a few northern areas. Therefore widespread offshore eutrophication cannot be expected, even in the future, except for the North Ligurian Sea, Golfe de Lion and the Northern Adriatic, or perhaps the major part of the Adriatic Sea. In the areas mentioned we are already facing significant indications of cultural eutrophication combined with natural, river-borne enrichment.

Although four of the Workshop's papers specifically consider the above cases, it seems worthwhile to give some additional information on the North Adriatic case. There is a widely held opinion that the problems in this area are confined to its western part (coastal waters of the Emilia-Romagna province) where it is expressed as local "red tides" and consequent mortalities of fish and marine invertebrates; however expanding eutrophication appears to affect the entire North Adriatic ecosystem.

Unfortunately the environmental monitoring and ecological research in the area has not been carried on as systematically and continuously as required, and the frequency of observations has been inadequate. It is difficult, therefore, to make an exact evaluation, in spite of clear indications of widespread eutrophication, such as the following examples.

Until about 1960-65 the Eastern waters of the North Adriatic have been so oligotrophic that the nutritional potential has not been sufficient to sustain dense littoral communities of large herbivores such as *Mytilus*, *Crassostrea* etc., and this is still the case elsewhere in the Mediterranean. Now, and for the last 20 years, the mediolittoral and the upper infralittoral along the entire shore of the Istrian Peninsula is densely covered by populations of the above mentioned shellfish, such as one normally seen on shores of the boreal Atlantic and the North Sea. Such a drastic modification would not be possible unless the primary trophic level was substantially elevated. More

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* There was no increase in phytoplankton standing stocks for the limiting nutrients (these were as a rule the nitrogen compounds) were competitively taken by macro-algae.

hypothetical, but also quite probable, are indications that for the same reasons the stocks of small pelagic fish (anchovy and pilchard) are steadily increasing, as are the fisheries catches*.

Since there has been little increase of nutrient-inputs from local sources of the eastern part of the area, it appears quite clear that the bulk of nutrient enrichment orginates from the Po and other Alpine rivers; this has been proved by numerous oceanographic investigations. Unfortunately, this effect is not always as "harmless" or even apparently "useful" as described above, for it may occasionally ** trigger almost catastrophic phenomena everywhere in the North Adriatic (as it does regularly in the Emilia-Romagna coastal waters: "red tides", mass-mortalities etc. Most obvious in this respect are the widespread "extraordinary summer blooms" and their consequences. Some authors (Bombace, 1985; Olivotti et al., 1985) tend to interpret this as a more or less natural phenomenon, based on historical information on blooms recorded even by the end of 19th century. Indeed, blooms have always occurred in the North Adriatic: regularly as the spring phytoplankton maxima, occasionally also during the autumn, and locally in later summer. However, until recently these were moderate blooms of diatoms (10^6 - 4.10^6 cells.dm^{-3}). No anoxia, nor any decrease of the oxygenation has ever been reported in this connection; between 1914 and 1964 no oxygen values measured in the North Adriatic were less than 4 ml.dm^{-3}. The blooms which have occurred during the last decade are really "red tides" of extremely high densities of flagellates (10^7 - 3.10^7 cells. dm^{-3}) appearing during the summer and leading ultimately to anoxic conditions and to mass mortalities. The most extensive bloom until now was that of June 1977. although strangely, very little information was published on it (Degobbis et al., 1979). Due to the extraordinarily high flow of the river Po during the late spring (up to 8,000 m^3.sec^{-1}, Montanari et al, 1984) the entire North Adriatic was over-enriched which resulted in "explosive" growth of the chloroflagellate *Chattonella* sp. at densities about 3.10^7 cells. dm^{-3}. These produced dark brown waters (Secchi 2 m) with intensive red at the very surface due to co-dominant *Noctiluca* at much lower densities of 10^6 cells . dm^{-3} (Štirn J., unpublished data). During the late summer the decomposition of dead algae caused a drastically decreased oxygen saturation in the bottom layers (13 - 45% oxygen saturation over the whole of the bottom of the central North Adriatic, where previously never less than 90% was recorded; Degobbis et al., 1979). Mass mortality of benthic macrofauna in a large area of the central and western part of the North Adriatic, and migration of demersal fish escaping from the affected area laterally and towards shallow waters, was reported by Stefanon & Boldrin (1982). These biological effects indicate that the central-western area was actually anoxic for a period during which, it seems, no oxygen measurements were made. Oxygenation of the North Adriatic was restored back to normal only in December 1977 (Degobbis et al., 1979).

This ecosystem crisis presents an example from which we can learn a number of lessons which are relevant to the consideration of practical preventive measures and related activities.

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* Corrected for the parallel increase in fishing efforts.

** The frequency of "occasions" is typically increasing.

THE IMPACT OF CULTURAL EUTROPHICATION ON BENEFICIAL USES OF THE MEDITERRANEAN SEA

There is no need to introduce this subject with further basic considerations of harmful effects upon the ecosystem for this has already been done. However, linking the views from a purely ecological standpoint with practical targets of beneficial uses, it is suggested that we should consider any type and rate of cultural eutrophication as being, in principle, harmful to the ecosystem, and hence quite probably also to its beneficial uses. The only exception to the above principle would be a controlled eutrophication, serving aquaculture or a similar enhancement of marine food-production. Technocrats would consider this as a scientific-romantic exaggeration, but there is justification presented in previous sections of this paper and in other papers presented to the Workshop. However, the following example might also help to clarify the statement. Biologically the richest and the most diverse communities along the Mediterranean shores are the infralittoral assemblages of macroalgae (phytal) and circalittoral belt of filter-feeders etc. (coralligen). Considering these communities only from a utilitarian point of view, they present an irreplaceable environment for many fishes and invertebrates of commercial value, hence they are obviously important to fisheries. These communities also form a part of the natural beauty of the Mediterranean (like coral reefs in the tropics) which attracts the tourist, of such significance for the national economies. As mentioned in previous sections, and shown in many scientific reports, these communities can be quickly destroyed by the effects of even modest rates of eutrophication*.

Apart from such subtle effects, there are a number of obvious harmful eutrophication effects which have a clear impact on beneficial uses. Since a number of recent reviews provide relevant details (e.g. UNEP/WHO, 1982; UNEP 1982) the following list seems to be sufficient for the purpose of this paper:

- Reduction of tourist-recreational value of the coastal waters due to inadequate transparency and colour of water, blooms and mucus-modified shore communities etc.

- Loss of fisheries resources**, mainly as:

  - mass-mortalities of demersal fish and invertebrates,
  - reduced or collapsed recruitment of estuarine and lagoon fish,
  - hindrance of aquaculture and/or impairing the quality of its products.

- Health effects: see paper by Aubert (this Workshop).

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* The statement is even more justified for estuaries, lagoons, secondary hard bottom communities, posidonia prairies etc. all of which may be similarly affected.

** There may be some positive effects in increasing natural stock which, however, should be considered with caution.

RECEIVING CAPACITY AND STRATEGY FOR EUTROPHICATION CONTROL

As already stated, it is difficult to propose reliable guidelines for the limiting values of eutrophying substances which could be absorbed by the receiving capacities of the Mediterranean Sea without inducing any significant effects in the ecosystem and/or an impact on beneficial uses. The basic problem is an inadequate knowledge of the quantitative dynamics of eutrophied systems in their entire complexity. This approach has had limited success* even in the case of fresh-water lakes which are much simpler than the simplest and smallest marine systems. For the Mediterranean Sea the relevant tasks seem to be particularly handicapped for two reasons: its ecological heterogeneity, and the traditionally descriptive ecological research, which is deficient in quantified and experimental approaches. Also, there are no long series of adequate environmental/ecological data which should be gathered by continuous observations and appropriate sampling programmes. Some responsibility for the lack of pertinent knowledge can be assigned, ironically, to UNEP-MAP, for until now it never seriously considered supporting research on ecosystems, although this has been repeatedly proposed by ecologists since 1974. If part of the funds spent on trace analyses had been allocated for ecological research, we might now, a decade later, be capable of giving some reliable facts on receiving capacity, not just an estimate which offers, in the author's opinion, only the following preliminary conclusions**.

In the south and east of the Mediterranean Sea*** where the shelf is narrow and human settlements scattered and modestly inhabited, there is in principle no risk of substantial cultural eutrophication, provided that the sewage and similar effluents are adequately disposed of and dispersed in the coastal waters, away from the immediate inshore zone. Disposal of mechanically pretreated effluents via submarine pipelines with diffuser outlets at an appropriate distance from the shore and in a depth which is below the summer thermocline can be proposed as an adequate control measure, and surely the most economic one. It must be stressed that this strategy does not, of course, apply to stagnant marine environments such as estuaries and lagoons, in which the receiving capacity is practically nil as was shown in previous sections of this paper.

Also on the northern side of the Mediterranean there are extensive areas of coastal waters where conditions are similar to those described above, and hence the control strategy should be similar (e.g. South Adriatic, Tyrhenian, partly Ligurian and NW Basin). However, it seems that for these areas the control strategy should be considered cautiously, and

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* Recent applications of ecological modelling, accompanied with extensive monitoring and experimental work produced for some exceptional cases quite reliable parameters of receiving capacity, mainly for fresh-waters and a few estuaries.

** For information on engineering and technical possibilities of the prevention and control of eutrophication see the manual UNEP/WHO (1982) *Waste Discharge into the Marine Environment.*

*** With the exception of the area influenced by the river Nile, and areas close to metropolitan cities.

reliable monitoring must be undertaken. Because of urban, industrial and tourist expansion, the intervals between settlements (and between effluent discharges) are getting smaller and smaller, and there is a possibility that the integrated enrichment loads may induce more than insignificant local eutrophication.

The North Adriatic, and perhaps also the inner Golfe de Lion, are areas where the integral of sewage-agriculture-industry and natural loads carried by rivers and of "point" discharges along the shores evidently surpasses the receiving capacity. Therefore the above strategy with offshore outfalls is obviously not a solution, except for smaller settlements scattered along the shores. In this case it is of crucial importance to reduce the loads of nutrients entering the coastal sea, wherever this is feasible. Unfortunately a substantial portion of the loads cannot be controlled by technical measures and will continue the enrichment of the coastal waters. From the engineering and management standpoints this necessitates advanced treatment of any effluents discharging into rivers and also of those from larger settlements and industries along the shores, as well as significant improvements in use of agriculture fertilizers. It is unnecessary to stress that such an exercise would require very large funds to cover the capital and running costs, and it would be wrong to use them in a misguided way or where they are without significant effect. For example, as was shown in previous sections, it is still quite unclear which are the limiting nutrients; however in treatment technology and in pertinent costs it makes quite a difference whether phosphorus or nitrogen is to be eliminated from the effluents. Therefore the best suggestion one can propose for the time being is to launch an efficient, interdisciplinary and eutrophication-focussed research/monitoring programme, to be executed internationally for those areas of the Mediterranean where the eutrophication threat really exists.

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SPECIAL SESSION

EUTROPHICATION IN THE NORTH ADRIATIC AND COASTAL WATERS

OF THE REGIONE EMILIA ROMAGNA

Chairman : Prof. R.A. Vollenweider.

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1. Introduction

The chairman introduced the session by giving a brief historical review of developments in eutrophication and its control in the Regione Emilia Romagna. Increasing frequency of algal blooms in the coastal waters to the south of the River Po had become notable especially in the second half of the 1970's. In 1977 the first meeting had been called to try and determine the relative importance of the Rivers Po, Veneto, local rivers or the tourist inputs, and Professor Vollenwider had been asked to co-ordinate the activities and guide the research programmes of about 80 people.

Preliminary studies had demonstrated a strong North to South gradient. and also an inshore-offshore gradient. Vertical relationships had also been examined on the gently sloping seabed. 3 compartments were recognized in the water itself :

Inshore waters
Offshore, upper waters (low salinity)
Offshore, lower waters (tending to anoxia)

and the sediments constitute another important compartment. A comprehensive monitoring programme had been established, in which samples were taken along transects, 0 to 20 km offshore, with more intensive monitoring in the first 3 km; Cesenatico had been selected as a critical site needing even more intensive sampling, even daily at some periods of the summer.

It was soon established that more information was required on the inputs from the land, and efforts were channelled in this direction, with a particularly intensive assessment of the inputs in the basin of the River Savio.

In addition, field studies and laboratory studies had been made, but in spite of all these efforts, the problem has not been completely resolved. Some information is incomplete, e.g. on inputs from the River Po, and little modelling of the system has so far been done.

Annual reports have been produced, and C.N.R. have produced synthesis reports from time to time. From this vast body of work, some of the most significant findings are summarized in the following accounts.

2. **Red Tides in the Northwest Adriatic**, R. Marchetti, G.F. Gaggino and A. Provini. The full text of this paper is given on page 133. It summarizes the trends in algal blooms during the 1970s and 1980s, and lists the various species identified in these studies.

3. **Eutrophication in the Coastal Area of the Regione Emilia Romagna**, E. Todini and A. Bizzari. The full text of this paper is given on page 143. It describes the development of a simple and a more complex ecological model of eutrophication, produced in a month-long workshop in Bologna.

4. **A Simple Model of Eutrophication on the Adriatic Coast - with a Field Experiment to Disprove the Model**, J.P. O'Kane. The full text of this paper is given on page 153.

The approach described in papers 3 and 4 met with cautious approval. Clearly only a simple model could be produced in such a short-term exercise, but the effort had been justified and had prepared the basis for further research. The model had given qualitative agreement with the field data, predicting Dinoflagellate blooms only in the late summer but not in spring. Points of detail which were clarified in discussion were that the one-box model was a dynamic rather than a steady state model, in which self shading was expected to occur, rather than a completely mixed system. The model predicted blooms when the residence time of the water, rather than the phytoplankton in the box, was prolonged. The point was made that the one-box model was assuming water of uniform density, therefore it did not take into account the stability of the water column. This was an aspect which could be taken into account in future developments.

5. **Eutrophication Problem in the Northern Adriatic Sea. Total Phosphorous Dispersion Model and Statistical Distribution of Chlorophyll Data : Methodological Approach**, F. Giovanardi,[1], G. Montanari,[2], and A. Rinaldi,[2],

A tentative classification of trophic levels of the entire coastal area of the Emilia-Romagna region, based on the criteria recommended by O.E.C.D. was reported.

To evaluate and discriminate between Total Phosphorus originating from the Po river-basin and from other secondary coastal river basins, a simple numerical model was developed, based on the salinity changes in the sea-area.

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[2] Assessorato Ambiente, Regione Emilia Romagna, Battello Oceanografico Daphne.

Fundamental inter-relationships were described between total P versus trophic indicators (Chlorophyll and Maximum Chlorophyll values). Log. transformation of data and results of a statistical study on frequency distribution of chlorophyll and Maximum Chlorophyll values were presented; log-normal distribution and Gumbel's distribution for decimal logarithms of the chlorophyll peaks were respectively plotted. The effects of reducing Total Phosphorus loads on the trophic conditions of the sea, in terms of probability, were defined.

In discussion of this paper it was suggested that this statistical model, based on real data, was much more reliable than the time-dependent, deterministic model described in the preceeding papers. There was considerable discussion on the fact that Total P was used, rather than orthophosphate, since only about 25% of Total P was available for algal uptake, and since it was unusual to use Total P in marine studies. However, it was pointed out that it is usual to use Total P in lake systems and was justified in this case, since Total P showed the best correlation with chlorophyll *a* concentrations. Unfortunately, Nitrogen data was only available on filtered samples.

Doubts were expressed about the suitability of applying the O.E.C.D. criteria for lakes to Mediterranean waters; separate criteria need to be defined for coastal waters.

Precipitation of phosphate appeared to occur, with high nutrient concentrations all along the Emilia-Romagna coast, perhaps indicating a similar 'nutrient trap' effect to that which occurs in estuaries. It was explained that precipitation of phosphates, and sedimentation of algal blooms occurred near the mouth of the Po, and that sediment transport could then take place, releasing sediment-bound phosphate, particularly at times of stratification (and anoxia).

From the data presented in the paper, the range of Total P (0.3 - 5 μ moles l^{-1}) indicated an orthophosphate range of 0.1 - 1μ moles l^{-1}, an extremely low concentration of orthophosphate to give rise to such high productivity. The author pointed out that during algal blooms the orthophosphate was virtually 0 $\mu g.l^{-1}$, although the Total P was quite high.

In conclusion, it was agreed that the Emilia-Romagna case study was excellent material to use for data analysis to get a definition of eutrophication.

6. <u>Northern Adriatic and River Po : in-situ investigations, modelling and remote sensing as a contribution to the understanding of transport phenomena</u>, F. Clement,[1], P. Franco,[2], L. Nykjaer,[3], P. Schlittenhardt,[4].

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[2] Istituto Biologia del Mare, CNR, Venice, Italy
[3] Institute of Geophysics, University of Copenhagen, Denmark
[4] Joint Research Centre-Ispra of the European Communities, Ispra (Varese), Italy
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The integration of in-situ investigations, a hydrodynamic mathematical model and remotely sensed data is a promising method for a better understanding of the oceanographic dynamics in the Northern Adriatic Sea.

The main determinant of the oceanographic characteristics of the Northern Adriatic Sea on an annual basis appears to be the variations of the density field. The structure of the density field, its effects on the mixing processes and on the basic dynamics were qualitatively discussed, on the basis of the available knowledge and with reference to experimental results.

A three dimensional non linear passive hydrodynamic model has been developed for the determination of meso scale circulation in the Northern Adriatic Sea. To calibrate and test the model the M_2 tide component has been computed and compared with conventional observed data. A further simulation was performed for a period of approximately one week to show clearly the role of the thermohaline forcing in fostering and sustaining the typical flow pattern in the area.

The utility of remotely sensed data for mesoscale circulation studies was demonstrated by a series of Coastal Zone Color Scanner images (CZCS). The CZCS-Satellite images were corrected for atmospheric effects and were processed to geographically rectified maps of chlorophyll-like pigment concentrations. The atmospheric correction procedure and the pigment algorithm were briefly described.

The results confirm the utility of hydrodynamic modelling and satellite ocean colour observations to extend the knowledge of the oceanographic characteristics of the Northern Adriatic Sea.

In discussion it was clarified that this was a hydrodynamic model rather than a circulation model.

7. <u>Determination of phytoplankton concentration in the Adriatic by satellite (CZCS, TM)</u>, B. Sturm,[1], and S. Tassan,[1].

The paper described the development of a mathematical model to predict the phases in phytoplankton blooms, calibrated by observations on a bloom which had occurred near Ancona in July 1979, for which a series of satallite images of total pigments were available.

The model had incorporated published equations for phytoplankton and zooplankton-carbon and orthophosphate. From the phytoplankton concentration, sunlight and other parameters, the photosynthetic rate was estimated. Comparing the results from the mathematical model to those from the satellite, quite good agreement was achieved, despite the rather low accuracy of the satellite data.

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[1] Joint Research Centre of the European Communities
- ISPRA - Varese, Italy.

In discussion, the value of satellite data was recognized for indicating areas subject to phytoplankton blooms, even before field data had been obtained. It was suggested that the initial conditions selected would adjust the fit between the data and the model, but the author asserted that he had used several starting conditions but still got the same form of curve; the critical point was to weight the parameters to produce a phytoplankton bloom. It was also pointed out that the model did not involve advection but only movement up and down in the box.

8. <u>Circulation of the Emilia-Romagna coastal water and its correlation with eutrophication phenomena</u>, E. Acerboni,[1], and A. Michelato,[1].

The results of a current water survey carried out in the coastal zone of the Emilia-Romagna region from May to October 1979 and from June 1980 to June 1981 were presented and discussed. The goal of the survey was to identify the main features of the coastal circulation and to determine their influence on eutrophication phenomena that, under certain circumstances, take place in this area. Data analysis showed that low frequency currents are the most energetic component of the coastal flow. They are induced by meteorological factors and thermohaline gradients, and generally flow along shore in S to S-E direction even if frequent flow-reversals are observable, mainly during late spring and summer.

Tidal currents are of a mixed type, but with predominance of the semi-diurnal character, and are characterized by ellipses elongated parallel to the coast. However, their contribution to the coastal circulation is not significant (10-15%). Inertial oscillations (period of about 17 hours) are particularly relevant in summer, when the water masses display a marked two-layered structure. They are excited by wind gusts or by the passage of atmospheric fronts. The inertial energy decreases with increasing depth and towards the coast.

Tidal and inertial currents provide an energetic mixing of the coastal waters, but have negative effects on the advective transport. However, water mass turnover is generally assured from October to April, when the intense south-eastward low-frequency current flushes the coastal area, while it decreases during the remaining months, reaching its minimum in late summer. Experimental evidence shows that eutrophication phenomena occur in association with water stagnation in the coastal strip, mainly during the summer season.

It was concluded that the appearance of favourable conditions for eutrophication phenomena is strongly influenced (or controlled) by the behaviour of the low-frequency currents. Further studies are however necessary to understand the mechanisms which produce stagnation of the coastal circulation.

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[1] Osservatorio Geofisico Sperimentale, Trieste, Italy

The discussion on this paper emphasized the tremendous variability of the effect of the River Po, depending on the gyres; satellite data sometimes shows the flow towards the south, but at other times flowing North East to Trieste. It is theoretically possible for the water from the River Po to reach Trieste, albeit in admixture with seawater. At times the water from the Po forms a thin surface layer with water of low salinity spreading over a vast area; when this occurred in 1977 a salinity drop of 27% occurred, giving rise to a disastrous algal bloom, with terrible consequences.

The average low frequency component in this part of the Adriatic was reported to to 20 cm. sec^{-1}.

9. <u>Biostimulation with algal natural populations : field and batch assays</u>, G.F. Gaggino,[1], M. Mingazzini,[1], G. Montanari,[2], A. Rinaldi,[2].

To get a more complete picture of the eutrophication problem in coastal waters of the Emilia Romagna region and to have a scientific basis for plans to ensure recovery, research has been started to investigate the biostimulation processes both in laboratory (batch assays) and field experiments (microcosms) with standardized methods. In both cases, natural populations present in coastal eutrophied water throughout the year were utilized. The aim of the bioassays was to verify the role of different nutritional factors on the development of algal biomass, examining the effects of phosphorus, nitrogen, vitamins and wastes from treatment plants. The results suggest the following indications :

- phosphorus and nitrogen are the main nutrients irrespective of the structure of algal populations;
- a reduction of phosphorus concentration in the medium causes a reduction of growth of both Diatoms and Dinoflagellates, as shown in field and batch tests with sewage from different treatment plants;
- for the Dinflagellates tested, a different behaviour is found with respect to vitamins. For *Prorocentrum micans*, it seems that a vitamin pool produces a stimulation of growth only when nitrogen and phosphorus were present in the bioassay.

One suggestion made in discussion was that the growth rate should be plotted against the standing stock. In fact, this had been done, although not included in the presentation. No changes had been noticed in the species composition of the laboratory experiments, although there had been some changes in the Diatom population in field experiments.

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In most experiments a three day lag appears to occur between phosphate uptake and algal growth. One possible explanation suggested for this was that the majority of the phosphate was adsorbed on the plastic walls, but the authors asserted that this did not occur, since the same effect occurred in glass vessels, and also with Total P. It was also pointed out that the addition of vitamins might also give an increase in nitrogen and phosphorus, but the results presented had been corrected for this. Another recommendation was that in these experiments it was more appropriate to plot the slopes of the growth rates, rather than the final growth level. Some of the enrichment experiments using *Prorocentrum nigrous* were strange in that an unusually long phase of about five days occurred. One explanation of this might be that starved cultures were used in these experiments; another was that, since the water was filtered through 205μ pore diameter membranes, possibly Tintinnids and other grazing zooplankton would have been retained in the water.

10. <u>Considerations on the modelling of trophic processes in coastal marine environments</u>, B. Cescon,[1].

Although almost all mathematical models proposed for simulating trophic behaviour in aquatic systems are based on the assumption that only nutrients, light and temperature are limiting factors of primary productivity, other factors may be involved such as vitamins, trace elements and other unknown factors. The author presented the results of biostimulation tests in Venice lagoon, and in Adriatic seawater mixed with river water or N and P supplements. Further studies on two lagoons in the Oristano gulf of West Sardinia were also reported, with very different nutrient loads. Physical factors such as suspended solids loads and hydraulic residence time of nutrients were also measured there.

The conclusions drawn from all these studies was that phosphorus and nitrogen always behaved as the major factors regulating the trophic processes, and that mathematical models were useful and reliable tools in predicting trophic behaviour, providing that all pertinent parameters and processes were suitably taken into account and formulated. Data collection should be used not merely for descriptive purposes but rather as elements of calibration of mathematical instruments of wind casting and forecasting.

There was discussion on the point that the first model developed was a 2 layered model, although the depth of the system was too shallow to have an aphotic zone. The explanation was that the double layered model referred to inside and outside of the cell. It was established that the model used instantaneous growth rates. The topic of luxury uptake was also discussed; this was not to be confused with loss of phosphate by adsorption. The authors suggested that the effect of additional nutrients depended on the previous history of the cell, i.e. whether the cells were starved or not. The question of how much phosphate could be consumed in luxury uptake was discussed, and it was concluded that this could affect the Redfield Ratios. A question for further debate was : in a situation of nitrogen limitation, if all the nitrogen was used up, would phosphate continue to be taken up by luxury uptake ?

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