MAN-MADE EUTROPHICATION IN THE MEDITERRANEAN SEA

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Abstract

The typical features of man-made eutrophication developments in open waters and in coastal zones of the Mediterranean Sea and their successions during the last 25 years are reviewed and illustrated by descriptions of exemplary cases, mainly from the North Adriatic. These developments are explained as gradual phases of the eutrophication processes that appear characteristic for previously oligotrophic ecosystems. Man-made causes of eutrophication processes, mainly as critical nutrient inputs and reduced herbivorous consumption-rates of excessive primary biomass are reviewed, too, and the elements of a rational strategy for the efficient control and prevention of eutrophication are suggested. These activities are proposed as the most critical component of the environmental protection in the Mediterranean region for eutrophication is considered the most harmful consequence of pollution and other adverse man-made impacts.

Résumé

Les phénomènes les plus typiques du développement de l'eutrophisation anthropogène, au large et en zones côtières de la Méditerranée, ainsi que leurs successions depuis les 25 dernières années, sont ici rapportés et illustrés par des descriptions de cas exemplaires, provenant surtout de l'Adriatique du nord. On attribue ce développement aux phases graduelles des processus d'eutrophisation qui paraissent être caractéristiques aux écosystèmes ayant été oligotrophiques auparavant. Les causes des processus d'eutrophisation, surtout celles provenant des décharges des nutrilites et la réduction des taux de la consommation herbivore d'une biomasse primaire excessive, y sont rapportés aussi; une stratégie rationnelle permettant la prévention et un contrôle efficace de l'eutrophisation, y est proposée. Ces démarches sont suggérées en tant que l'action la plus importante de la protection de l'environnement en Méditerranée puisqu'on considère l'eutrophisation comme étant la conséquence la plus nocive de la pollution et des autres impacts négatifs qui sont produits par les activités de l'homme.

Partial outlines of this paper have been presented at the conference: «Environmental and Sanitary Problems of Land and Coastal Waters of the Mediterranean (Napoli, Oct. 1992) whose main aim was to promote communication between scientists, engineers, teachers and politicians as needed for better management of the Mediterranean environment that should become «a major engagement for the New Europe 1993» (cit. the title of the conference's Roundtable). This is one of the reasons for the author to address this paper, not only to professional marine scientists, but also to other concerned people at all levels of society, and particularly to members of engineering and political lobbies and other decision-makers who are, in many respects, responsible for the use and misuse of the Mediterranean marine environment and hence for the pertinent natural heritage, including the invaluable marine resources which represent the basis of the Mediterranean civilization as well as an important share in national economies and the well-being of people around «*mare nostrum*».

With his 30 years of active involvement in marine pollution studies, the author has gathered quite extensive information and experience which leads him to believe that among all forms of pollution (e.g. toxic metals and synthetic organics, radioactivity, oil and pathogenic microbial contamination) it is man-made eutrophication that presents, specifically for Mediterranean coastal waters, by far the most harmful pollution impact.

However, it seems that, apart from a number of politically and/or «commercially» independent marine scientists, not many share the above opinion. Therefore, comparing all efforts, including pollution research and monitoring on national levels and, quite surprisingly, also within the UN-guided regional framework of the Mediterranean Action Plan (MAP), predominant attention has always been paid to all other pollution forms as listed above, leaving but a marginal interest for the problems of eutrophication. Moreover, quite typical in this respect is also the attitude of E.E.C. by its categoric and repeated refusal to co-finance a eutrophication-targeted (applied!) research project as proposed 1989-90 by a number of partners from France, Italy and Greece (Aubert-Stirn, 1989 & 90).

The only significant exception to this is a set of activities which were launched recently for the area of the North Adriatic by concerned governments in response to public (and touristic) pressure that followed impressive summer 1988-89 episodes of «mare sporco», i.e. massive mucous diatom «blooms». However praised these activities should be, for their obvious merits and remarkable outputs of information and data, one feels a certain tendency to relate both, these episodes and eutrophication effects generally as much as possible to unusual natural conditions rather than blaming man-made impacts. Such an approach would be indeed quite normal and understandable as far as governments and/or responsible investors are concerned because they would always try not to pay for whatever could be avoided, like very expensive eutrophication control measures, but more disappointing in this respect is the attitude of some scientists and engineers who, for one or another reason, support governments' hesitations without having reliable scientific evidence. Apart from such intentional or even manipulated neglect, the very reason for a general underestimation of eutrophication-impacts as mentioned above, might be in the author's opinion, rather common difficulties to apprehend the true nature of eutrophication processes. Taking into account the relevant complexity, variability, unpredictable appearances and seemingly beneficial effects, such difficulties are quite understandable and so is the attitude of a number of fisheries biologists (Bombace 1985, 1992) who consider eutrophication as a useful food supplement that may enhance otherwise quite limited fisheries production. Obviously, a rational consideration of eutrophication phenomena, which present not only an extraordinary complex topic of ecosystem studies, but also a contentious subject, requires good background knowledge of aquatic ecology and a clear understanding of specific terminology. Inevitably, this paper, too, contains a burden of terms which readers, except for professional ecologists, may not be familiar with. As mentioned above, the paper is not only addressed to marine scientists and therefore it seems useful to extend the introduction with some essential explanations as follows.

Eutrophication means a process which causes an aquatic environment to become **eutrophic**, i.e. literally «well nourished», or using another ecological term, having a high **trophic** (nourishment) level. Apart from insignificant inputs of organic matter from land (waste waters and detritus), the bulk of primary-available organic food in the marine environment is photosynthesized in the process of **primary productivity**, mainly by unicellular plants (algae) of **phytoplankton**. Unlike terrestrial environ-

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ments, sea water contains almost all inorganic constituents that are required for the normal metabolism, growth and reproduction of plants (CO_2, H_2O, N, S, P, Ca, Mg, K, Na, Cl, B, Si, Fe and trace bioelements) in inexhaustible amounts, except for nitrogen and phosphorus compounds (and Fe and Si in specific circumstances) whose amounts can be steadily or temporarily insufficient to support a considerable marine plants productivity. Consequently, these compounds (ammonia, nitrate and orthophosphate in the first place), called also **limiting nutrients**, present the most decisive factor which regulates the rates of marine plant **productivity**, provided there are no other environmental restraints, such as inadequate **temperature** and poor **light** conditions. However, due to the geographic position and a mild climate, temperature and light levels in the Mediterranean Sea can rarely be as low as to be limiting, except during short winter intervals, and this only in shallow areas of its northern provinces. Thus, there is ample reason to believe that the impact of limiting nutrients is more effective in the Mediterranean Sea, as well as in other **subtropical** and **tropical** marine environments, than in cold and temperate seas; more pertinent details are shown below in the chapter on nutrients. Nevertheless, marine environments with poor supplies of limiting nutrients, as is still the case in the prevailing part of the Mediterranean Sea, can support but a very limited **biomass** of plants and hence a low density of phytoplankton cells in suspension. Consequently, the water masses have as a rule a clear blue colour, extremely high **transparency**, and more importantly, a low primary trophic potential that cannot feed important stocks of **consumers** such as larger invertebrates and fish. In terms of the entire bioproductivity and overall biomass such environments are typically **oligotrophic**, i.e. «poorly nourished», in **contrast with eutrophic conditions**.

The latter are characterized by rich nutrient supplies and correspondingly elevated bioproductivity, mainly at the expense of unicellular algae in phytoplankton whose density is, as a rule, steadily quite high. Consequently, the transparency of sea water is reduced and its colour is normally greenish, or yellowish-green, brown or reddish during the peaks of maximum growth and reproduction. These are known also as «**blooms**», usually of dominating **diatoms** and «**red tides**» which in most cases appear as extremely dense populations of **dinoflagellates**. The overall production of primary biomass in a eutrophic system clearly exceeds the amount of food the **herbivorous** animal component of the system can consume. Thus, a **surplus of dead organic matter** is formed, deposited and/or consumed exclusively by **heterotrophic decomposers**, mainly **bacteria**, causing a corresponding intensity in **oxygen consumption**. In the case of extremely heavy eutrophication, i.e. **hypertrophication**, the surplus amounts exceed the net rate of oxygen supply required to oxidize them which leads in turn to **hypoxic** (O_2\2 $cm^3 \cdot dm^{-3}$) or **anoxic** (zero O_2) conditions, fish-invertebrate **mortalities** and other harmful effects as described in more detail later in this paper. Turning back to oligotrophic conditions, however low the overall biomass of pertinent ecosystem might be, its components are **communities** whose **biodiversity**, i.e. relative number of plant and animal species, is extremely high, approaching the highest known, e.g. for tropical coral reefs. It seems needless to stress that the biodiversity, in other words the biotic richness represent, not only a **natural heritage** *per se*, but also an aesthetic value which, in combination with the azure beauty of oligotrophic waters, provides an invaluable resource, at least for touristic components in national economies of the Mediterranean countries. Moreover, an ecosystem whose biotic components are communities of **high diversity** also has a highly organized and ecologically well **balanced structure**. Thus, the oligotrophic ecosystem functions through complex internal regulations in a state of **homeostasis**. Consequently, such an **ecosystem buffers** the environmental variability and related stress conditions, therefore it is stable and persistent in time and space. When the above facts are considered, it seems unnecessary to stress that the first priority in environmental issues for the Mediterranean Sea should be protection of its oligotrophic conditions. Having recognized new inputs of nutrients as the only factor that can trigger primary transitions from oligotrophic towards eutrophic conditions, a need for significant reductions in nutrient discharges appears as to be indisputable. This of course, is subject to people's (governments) decisions on what kind of marine environment they would like to have in the Mediterranean Sea. In this respect, it is the aim of this paper to provide evidence which supports the efficient and rational control of growing eutrophication in order to protect the best of what the Mediterranean Sea has to offer.

Changing eutrophication concepts and definitions

According to an interesting statement (GESAMP, 1990b), «the term eutrophication is understood in almost as many different ways as the frequency with which is used». Although exaggerated, this statement clearly reflects conceptual and terminological contradictions which can lead *a priori* to erroneous conclusions, and more so by interpreting eutrophication problems in marine environment with concepts and measures as applied for fresh waters. In order to avoid such misunderstandings, this chapter provides some relevant clarifications and definitions as proposed by the author previously (Stirn, 1988).

It seems that Weber (1907) was the first to introduce the term «eutrophic», in relation to nutrient conditions in marshlands soils. Naumann (1927) transferred the term into limnology, and was the first to perceive relationship between nutrients and primary productivity of lakes which led in turn to a classification scheme for lakes, based on the trophic state. At the same time Thienemann (1925) developed a parallel scheme but based on the oxygen content and related distributions of indicator species. Although there was some simplification in these early works, they not only laid the foundation for the current lake classification, but also developed the classic concept of eutrophication. However, this concept refers to the natural aging of lakes in successions of steadily increasing trophic levels due to natural inputs of nutrients. Only recently, i.e. after ≈ 1950, has the concept been extended to include man-made eutrophication (named also cultural or anthropogenic) which was very soon widely recognized as one of the most threatening forms, or rather consequences of pollution in fresh-waters, causing first the known deleterious effects in lakes and affecting now rivers, reservoirs and indirectly ground waters as well. Moreover, for fresh-waters it has also been indisputably recognized that the current state of eutrophication is due, almost entirely, to excessive, man-made nutrient inputs that originate from sewage, biodegradable industrial effluents, runoff from fertilized land and a polluted atmosphere. In response to the formidable extent of eutrophication and facing a number of consequent practical problems, e.g. in supplies of drinking water, fisheries and fish farming, tourism, etc., important progress was achieved in all relevant fields of fresh-water science, engineering and management. Moreover, having adequate scientific information, including quite reliable predictive models (OECD, 1982), technological experience, and dealing with relatively small, semi-closed ecosystems, the control of fresh-water eutrophication became technically quite feasible and efficient as proven by an increasing number of successfully solved case-problems.

Eutrophic provinces of the Ocean and their purely natural sources of nutrient supplies, mainly through discharging rivers and wind-driven upward circulation of nutrient-rich deep waters (upwelling), have been known and described quite long ago (Harvey, 1928); probably Gilson (1937) was the first to use the term eutrophic in this context. As to man-made eutrophication, similar processes as developed in fresh waters were for some time thought to be unlikely in the marine environment which, being larger and more dynamic, would have the capacity to absorb nutrient inputs. For example, in the Mediterranean region, the early warnings (Stirn, 1966) about potential eutrophication impacts were not seriously considered, either by scientists or governmental authorities, and completely ignored.

Nevertheless, the expansion of man-made eutrophication has become quite obvious during the last decade, thus there is now less need to convince people about relevant problems; these were recently recognized also at international levels as shown in the following statements from the GESAMP (1990a) publication The State of Marine Environment, cit.:

§ 263 - Globally, present inputs of nutrients from rivers due to man's activities are at least as great as those from natural processes. The inputs in different localities vary widely, depending on a range of factors including population density, land use, effluent treatment, estuarine topography, dispersal rates and natural marine sources of the nutrients. In some enclosed waters and coastal seas these inputs have led to clearly detectable and sustained increases in nutrient concentration in the water. The areas thus affected are numerous and geographically widespread but all have the common feature of limited water exchange with the open sea.

§270 - It is now possible to recognize the sequence of changes that characterizes progressive stages of eutrophication in the sea. An idealized progression of phenomena is (a) enhanced primary production, (b) changes in plant species composition, (c) dense blooms, often toxic, (d) anoxic conditions, (e) adverse effects on fish and invertebrates, (f) impact on amenity, (g) changes in structure of benthic communities. Not all these features are observed in every case and the full sequence is not always obvious. Indeed, changes in the structure of benthic communities are often the earliest signs of eutrophication, probably because the benthos integrates the exposure over time. The effects of concern to man are reduced fisheries yields or gross fish kills, and amenity deterioration with attendant economic losses. More directly, health risks result from exposure to flagellate neurotoxin passed through shellfish. Recognizing this sequence may make remedial action possible at a sufficiently early stage to avoid serious consequences.

The above, very appropriate statements are surely of an extraordinary importance for global views on eutrophication problems and so is, the whole document. Unfortunately, the document failed to provide adequate information about relevant problems in the Mediterranean Sea for it shows the case of the North Adriatic as the only problem and even this one by a rather, «soft» interpretation, cit.: «The northern Adriatic also shows signs of eutrophication». However, in the same paragraph we read: «... anoxic conditions, sometimes resulting in mass mortalities of fish and benthic invertebrates in shallow waters». Obviously, this statement alone confirms that there are not just «signs» but heavy eutrophication, in fact temporarily occurring stage of hypertrophication. Nevertheless, from the standpoint of aforementioned requirements for efficient eutrophication control, this document does not provide much help. On the contrary, it might be used as an indirect support of technocratic tendencies to disregard the impact of eutrophication, including relevant statements within studies, reports etc, the techno-bureaucracy is producing and/or using in order to justify for its own, usually misleading interpretations.

As a rule, such interpretations are based upon the concept and criteria for fresh-water eutrophication which, if applied non-critically for marine environments, may lead to erroneous or even absurd conclusions. An example of such an absurd conclusion is shown most typically in an interdisciplinary evaluation of organic pollution impact in the Gulf of Trieste (North Adriatic), published by Olivotti, Faganeli and Malej (1986). The authors determined the state of eutrophication by comparing the averages of some routine measurements (chlorophyll biomass, transparency and nutrients) with corresponding criteria as proposed by OECD for fresh-water lakes (OECD, 1982) and concluded that the Gulf of Trieste, cit.: «is not affected by eutrophication, rather the major part of eastern waters appear to be essentially oligotrophic». As will be shown later in this paper, it is precisely the above environment which is heavily eutrophied and represents, apart from western coastal waters of the North Adriatic and a few coastal lagoons, the only area within the Mediterranean region where hypertrophication-induced oxygen depletions and concomitant mass-mortalities have become regular, though fortunately still short-lived phenomena during the last decade.

Another exemplary feature of the above publication is the affiliation of suggested conclusions to the following OECD definition as quoted therein: «Eutrophication is an undesirable degradation of the environment resulting in a deterioration 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». It seems needless to stress that by to this definition the Gulf of Trieste appears indeed to be non-affected by eutrophication. Moreover, according to this definition, one would hardly find any eutrophication problems in the Mediterranean Sea as a whole but only in a few coastal lagoons. This and other discrepancies as shown by the above example as well as in many more similar confrontations between purely ecological and exceedingly pragmatical approaches clearly suggest the need for some more adequate principal statements and definitions to be formulated on the basis of pertinent ecological facts, and by recognizing that the phenomenon of eutrophication is typically relative for it varies according to time, space, inputs and given environmental conditions, as most illustratively expressed by Ott (1989), cit.: «Eutrophication in an oligotrophic sea such as the Mediterranean may occur at absolute nutrient levels that would leave North Sea communities starving».

In this context, and knowing that the only generality in ecology is that there are no generalities (Poole, 1974), the author proposes the following statements and definitions (partly from Stirn, 1988) as applicable in the case of specific conditions in the Mediterranean Sea, and perhaps in similarly oligotrophic environments elsewhere in subtropical and tropical seas:

Eutrophication is defined as a substantial and persisting increase of trophic levels in an ecosystem whose productivity was prior a given impact as a rule significantly lower. The stage of eutrophication at which the rate of new organic matter production exceeds the oxygen supply required to oxidize it (which causes hypoxic-anoxic conditions and concomitant mortalities) is identified as **hypertrophication** (modified from Mee, 1987).

French speaking authors tend to use the term dystrophic to describe hypertrophication (Aubert, 1988, etc.). This term, too, is «borrowed» from limnology where it characterizes an entirely different situation, i.e. low trophic level in bog lakes which are loaded with humic acids, thus this term should not be used in marine ecology. Similarly inappropriate is the usage of the term mesotrophic (quite common in Italy) for this stage cannot be assessed adequately in marine conditions.

Natural and man-made eutrophication

Although there is in principle no substantial difference between these two processes as far as the production, storage and decomposition of primary and microheterotrophic organic matter are concerned, ultimate effects upon overall structure and metabolism of ecosystems are significantly different:

Natural eutrophication, which is based on natural nutrient sources (upwelling, coastal mixing, fresh water and atmospheric inputs) supports high trophic levels in ecosystems whose structure, communities and food-webs have been adapted to high levels through ecological evolution (which was going on for, at least >10,000 years). Thus, in such «organized» ecosystems a high proportion of primary organic matter is consumed and cycled by herbivorous and carnivorous animals. Exceptionally, in environments with weak circulation of water masses, e.g. Black Sea, Baltic and upwelling areas of the Indian Ocean, natural eutrophication, actually hypertrophication, results in surplus organic matter which is partly buried in sediments but mainly consumed via microbial decomposition, followed by desoxygenations and mortalities. However, this, too makes a part of long-term adapted ecosystems which still remain relatively stable, supporting, i.a. some among the richest fisheries of the World Ocean. As mentioned

previously, some people think that man-made eutrophication, too, may enhance fisheries production, yet for most known cases the evidence shows just the opposite.
Man-made eutrophication is of course a very recent phenomenon which is showing, apart from obscure initial effects of deforestation and gradual development of intensive agriculture during last two centuries, significant effects in marine environments only as late as after the fifties of this century. It seems quite obvious that, by having a gradual increase of nutrient inputs effective only for a few decades, the time scale is much too small to allow such complex and stabilized ecosystem adaptations as required for an ecological equilibrium to be maintained in an entirely different, highly productive ecosystem. Consequently, the ecosystems which are affected by man-made eutrophication are characterized by typical stress-environments, Margalef's (1978) «immature» communities, chaotic dynamics and unpredictable variability. Taking into account these characteristics, and the most common occurrence of man-made eutrophication which is in coastal zones, i.e. in target areas of human interests, its effects become usually harmful, not only for the environment, but also for the exploitable biologic resources and most of beneficial uses of sea. In this respect and by a generalized consideration, it should be stressed that the heaviest and as a rule most harmful eutrophication effects occur in coastal environments which are recipients of **cumulative, natural and man-made loads in discharging rivers.**
Pollution as defined by GESAMP and endorsed also by the Mediterranean Action Plan
means. cit: «Introduction by man, directly or indirectly, of substances or energy into the marine environment resulting in such deleterious effects as 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».
Considering this definition on the one hand and ecological cause-effect principles on the other, man-made eutrophication is not a form of pollution, it is the consequence of any pollution or other human activities that discharge nutrients and other substances which enhance primary productivity or substances which have harmful effects on herbivorous consumers of primary organic matter. As suggested above, the most harmful forms of pollution and other man-made impacts in the Mediterranean region seem to be those which induce eutrophication processes and related problems.

Assessment of eutrophication

According to the above definition of eutrophication and recognizing its ecological principles, the only direct and fully reliable parameters are combined measures of primary productivity, such as plant biomass, population density and functional productivity, provided these are measured in long-term series and adequate frequencies, and evaluated in relative terms, i.e. as compared with comparable non-eutrophied conditions. Standard data on dissolved inorganic nutrients cannot be used as a reliable measure of the state of eutrophication for a number of reasons as explained later in this paper, unless nutrient data include in-biomass and dissolved organic forms. Similarly, standard dissolved oxygen measurements, unless continuously recorded *in situ* as a long-term monitoring, cannot be considered a reliable indication, either of eutrophic or hypertrophic conditions, even less for the latter. The reason for that is an extraordinary variability of oxygen concentrations which can oscillate, within a given water column and at any fraction of time, in the range from anoxic-hypoxic to supersaturated levels ($\approx 0-8\ cm^3 \cdot dm^{-3}$).
An optimal methodological approach in the assessment and monitoring of eutrophication would include, in addition to the above methods, complete ecosystem and communities studies as described in specific FAO/UNEP manuals (Stirn, 1981; Gray, McIntyre & Stirn, 1992).
However, eutrophication studies which are expected to advise engineering and management on eutrophication control measures and their practical implementation require additional ecophysiological and advanced bioassay research in experimental facilities as proposed by Aubert and Stirn (1988-89).

The ecological process and the causes of man-made eutrophication

The essential features of the process of eutrophication have already been explained in the introduction to this paper. However, in real ecosystems the process is very complex and variable as illustrated by a simplified schematic presentation in **Fig. 1** which compiles the most common features as observed in the known cases of man-made eutrophication within the Mediterranean region; as justified below and in order to avoid an excessive sophistication in this presentation, the compartments of eutrophication-bound natural factors have been omitted. Moreover, it is beyond the scope of this paper to discuss the complexity of both, the process and ecological factors involved, (reviewed by Stirn, 1974, 1987 & 1988 and UNESCO/UNEP 1988), except for a few components which ought to be considered in order to justify and support the request for efficient eutrophication control in the Mediterranean region, which is, as mentioned previously, the «leitmotif» of this paper. However, these process-components will be shown in more detail in the next chapter, along with descriptions of exemplary eutrophication-cases.
When considering the causes of man-made eutrophication one should discuss first the most powerful ecological mechanisms which dominate the control of any form of aquatic bioproductivity, i.e. natural factors such as: light, thermic and osmotic (salinity) conditions, CO_2 - O_2 fluxes, autochtonous (sea-born) nutrient pools and their recycling, flushing and sediment-deposition rates, structure and efficiency of trophic chains etc. which are all also subject to meso-scale and long-term fluctuations of likely global dimensions. However, apart from man-made global modifications of CO_2 - fluxes, climate, and spectral composition of incident solar radiation, that apparently affect eutrophication, too, as shown later in this paper, there is almost nothing man can ever change significantly in this respect. Therefore and since there is ample relevant information available in oceanographic literature (for basic reviews e.g. Parsons & Takahashi, 1975; Harris, 1986, etc.) as far as natural factors are concerned, the emphasis is given here to factors which, altered by human activities, trigger and maintain man-made eutrophication, and which man can, at least partially control by technical interventions, i.e. nutrients on one hand and the fate of produced biomass on the other.

Nutrients - The main cause of eutrophication

However crucially important are the effects of the the aforementioned, mainly natural factors for the development of eutrophication processes, it is always the quantity of available nitrogen and phosphorus nutrients which determines the ultimately produced biomass of plant populations, regardless of which taxonomic group they belong to, except for diatoms and flagellates, if growing in high-density or «blooming» populations, which can be limited by the lack of silicon and/or bio-assimilable iron. These specific aspects as well as the effects of other nutrients *in sensu latu* and biostimulative organic compounds will be briefly discussed at the end of this chapter, however, the emphasis is given to aspects of nitrogen and phosphorus nutrients.
Such a priority is justified, partly for the above reasons, and in the first place, by considering the reduction of nitrogen and phosphorus discharges into the Mediterranean Sea to be far the most important, and technically feasible measure for the control of man-made eutrophication. Since this subject, as related to the conditions in the Mediterranean region, has been adequately reviewed in a number of documents (Stirn, 1988; UNEP/MAP 1978; UNESCO/UNEP 1988 and partly GESAMP, 1990), the information below presents but a summarized, though updated version from Stirn (1988); therefore, and for the sake of a shorter text, the extensive burden of references as given in the original paper has been omitted.

Phosphorus

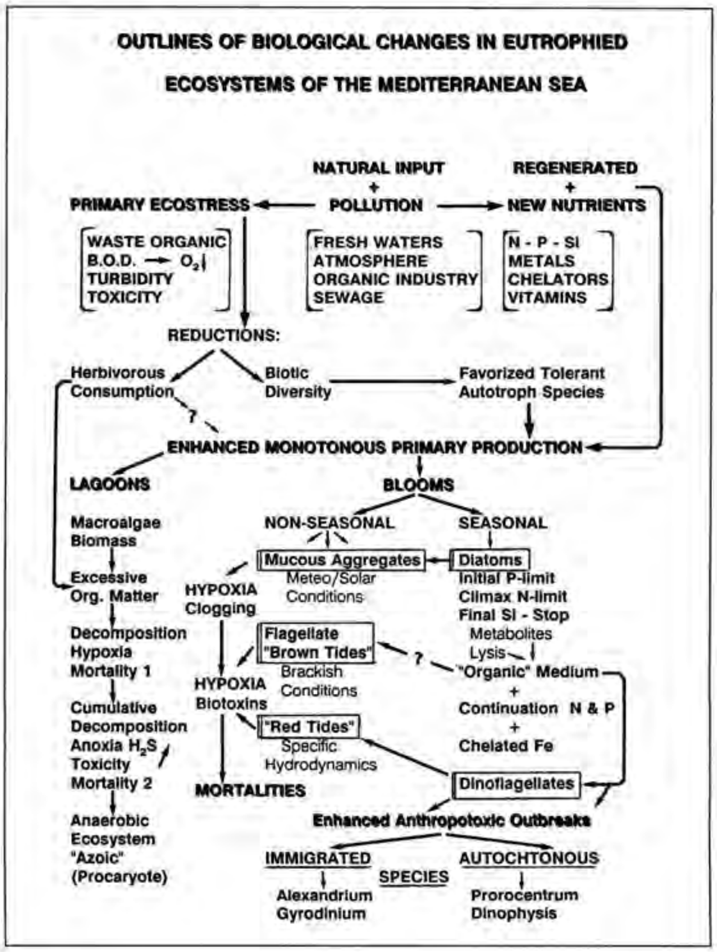
In natural and moderately polluted coastal waters phosphorus usually appears in various chemical forms, however, the orthophosphate is preferred by unicellular algae, but the ability to utilize other forms, such as polyphosphates and organic phosphorus, seems to be widespread. Considering the growth of algae in eutrophic conditions 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 $0.3\mu M \cdot dm^{-3}$ P-PO_4, and significantly lower after periods of phytoplankton blooms. A typical value for open ocean is 0.1 $\mu M \cdot dm^{-3}$ 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 $0.05\mu M \cdot dm^{-3}$ in the euphotic zone and at best 0.3 in the deepest waters.
The most adequate example to show the relationship between typical orthophosphate concentrations (in $\mu M \cdot dm^{-3}$ P-PO^4, $1\mu M$ P = 31 μg of P) in surface waters and riverine and pollution-born enrichments is provided by the case of the Adriatic Sea as follows:

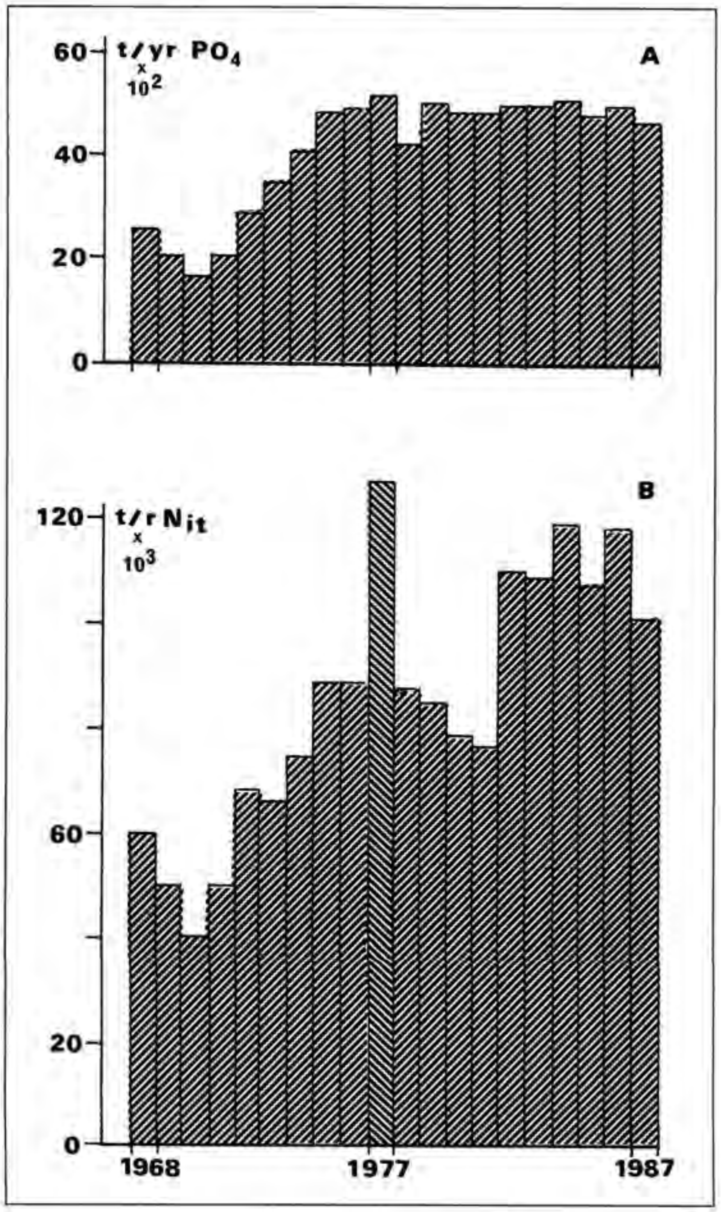
- Extremely oligotrophic southern basin : 0.03
- Oligotrophic Mid-Adriatic : 0.05
- Eutrophic North Adriatic : 0.12
- Highly eutrophic NW Adriatic : 0.30

In coastal waters which are directly polluted by sewage, similar effluents or within the plumes of polluted rivers the concentrations of phosphate are as a rule dramatically higher, e.g. $2.0\mu M$ and more.
Nevertheless, highly eutrophic waters, regardless of whether they are fertilized by rivers or man-made effluents are rather steadily receiving phosphorus supplies at levels approaching the optimum needed for the growth of mixed phytoplankton populations at an eutrophic level, e.g. 0.3 – 0.5 $\mu M \cdot dm^{-3}$ P-PO_4 and often well above the saturation levels the highest plant biomass can ever assimilate under natural conditions.
In addition, other forms which may not be shown in analytical data also contribute to the phosphorus-pool and regeneration fluxes that continuously deliver bioassimilable phosphorus forms. However, the major and ever available source of phosphorus regeneration is intercellular within the plant biomass in which the process of so-called luxury uptake accumulates actually more

***Figure 1** - A generalized succession of trophic and structural ecosystem modifications at typical stages of eutrophication processes as observed in the Mediterranean Sea.*

***Figure 2** - Gradual increase in loads of major nutrients discharged into the North Adriatic by the river Po: (a) as orthophosphate (in 100 tons per year) and (b) as total inorganic nitrogen (in 1000 tons per year); based on data of Marchetti, 1992.*





phosphorus than needed for normal physiological functions. These sources, «hidden» for standard chemical analyses, explain why it is possible for a eutrophic environment to support a high plant production despite its extremely low concentrations of dissolved inorganic phosphates as quite frequently observed in practice as well as considered in the sense of evidence for a phosphorus-limited primary production. At least as far as heavily eutrophied environments are concerned, it appears perfectly logical that under the conditions as shown above, it is not phosphorus but nitrogen which might be the limiting factor; actually this has never been proved correctly for the Mediterranean conditions, though largely recognized for similar marine environments elsewhere (Goldman, 1976).

Nitrogen

Out of the total nitrogen dissolved in sea water, ≈90% goes at the expense of nitrogen gas (N_2) while the rest is composed of numerous dissolved organic compounds (DON) and a few inorganic salts (DIN), mainly in ionic states as shown below, along with concentrations typical for the surface in shelf water of the temperate parts of oceans:

— nitrate ($N\text{-}NO_3$):	2	–	5
— nitrite ($N\text{-}NO_2$):	Trace	–	<1
— ammonia ($N\text{-}NH_4$):	1	–	3

In tropical surface layers the concentrations are as a rule much lower, except in upwelling areas. However, in deep oceanic waters the concentrations are quite high, mainly as nitrates, in the range $20-50 \mu M \cdot dm^{-3}$.
In the Mediterranean Sea, inorganic nitrogen is generally very depleted, although proportionally not to the same extent as are phosphates. The typical range of concentrations (in $\mu M \cdot dm^3$; $1 \mu M$ of N = $14 \mu g$ of N) in surface layers of open waters is shown below using the example of the Adriatic Sea:

Area	$N\text{-}NO_3$	$N\text{-}NH_4$
Oligotrophic southern basin:	1.0	0.5
Oligotrophic Mid-Adriatic:	0.5	0.5
Eutrophic North Adriatic:	1.5	1.0
Highly eutrophic NW Adriatic:	4.0	2.0

In oligotrophic areas both nitrates and ammonia originate from marine regeneration and from the atmosphere; in eutrophic areas a substantial part of nitrates is river-borne, from natural sources and fertilized agricultural land, while the ammonia comes mainly from man-made sources. In coastal waters which are directly polluted by sewage or significantly mixed with discharging polluted rivers, the concentrations are generally much higher, above 35 $\mu M \cdot dm^{-3}$ $N\text{-}NO_3$ and 20 $\mu M \cdot dm^{-3}$ $N\text{-}NH_4$.
In principle, ammonia is the preferred form of nitrogen for algae, followed by nitrate and nitrite after the ammonia concentration is reduced to $<0.5 \mu M \cdot dm^{-3}$. In addition, algae can use a number of organic compounds, e.g. urea and amino acids, as the sole or partial source of nitrogen. With regard to man-made eutrophication this obviously is quite relevant, although very little is known about it.

Silicon

In addition to nitrogen and phosphorus, the available silicon is also an equally determinative, yet specific nutrient required but for the growth of diatoms in silicoflagellates whose skeletons are made of pure silica. Since the former represent generally as well as in the Mediterranean Sea a dominating component of inshore phytoplanktonic communities which normally occur in at least two picks of maximum reproduction (spring and autumn blooms), both in eutrophic and clearly oligotrophic, even offshore waters, adequate supplies of silicon are obviously of great importance for primary productivity as a whole.
It seems that in prevailing conditions silicon is rarely a limiting nutrient, except temporarily after the terminal stages of heavy diatom «blooms» (as typical for eutrophic conditions), in which silicates may be depleted down to as low concentrations ($Si < 1 \mu M \cdot dm^{-3}$) as known to be absolutely limiting considerable diatom growth and reproduction.
As is widely known, diatom «blooms» are normally followed by successions of predominantly dinoflagellate communities which temporarily overrun silicon-limited diatoms component. According to numerous authors (Menzel, 1963; Parsons & Takahashi, 1975, etc.), it is just silicon-limitation that regulates the above successions. Provided the other environmental conditions (as shown below and in the **Fig. 1**) are favorable for the growth of dinoflagellates or other flagellate populations during the periods of such succession stages, these may culminate in flagellate «blooms» (Officer & Ryther, 1980) or «red tides» in the case of predominantly dinoflagellate components. Recognizing a worldwide expansion of «red tide» occurrences in polluted coastal waters and man-made changes of the Si:N:P ratio (whose normal values for natural conditions in coastal waters would be 16:15:1) by decreasing relative values of silicon against increasing levels of nitrogen and phosphorus, one can agree with the hypothesis that man-made relative silicon limitation may be a significant factor in «red-tide» developments (Smayda, 1990). However, assuming this factor to be really effective, this presents an additional justification for the reduction of nitrogen and phosphorus as the prime measures in eutrophication control for one would not think as to increase the silicon levels.

Biomicroelements and chelating substances

As mentioned above in introduction, there is a number of microelements (Fe, Mn, Cu, Zn, Co, Mo and Se) which are essential to the growth of plants 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 an essential element may be present in a form in which it is not assimilable. This is particularly important for iron which has a very low ionic concentration in sea water. Most algae, however, are able to make use of some particulate and colloidal forms, provided there is a chelating mechanism available. There seems to be a variety of natural chelating substances in oceanic and open coastal waters, although their chemical identity is still quite obscure. The «classic» ligands of humic-complex compounds (Gelbstoff) have an autochtonous 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 moderate «blooms» of diatoms, does not appear to be significantly limited by a reduced availability of trace elements. However, there is evidence that iron does indeed trigger or limit the development of «red tides», as a complementary factor to the others as discussed above and shown in the **Fig. 1**.

Bioactive organic compounds

It has been known for decades that, apart from nutrients *in sensu stricto* and microelements, a number of organic compounds, vitamins and phytohormon - like substances in the first place, may significantly enhance the growth and reproduction of algal populations, particularly at high-density or «blooming» levels. In this respect the most relevant example is a widely recognized fact that the population growth of the great majority of flagellate species, including «red tide» dinoflagellates require vitamin B_{12} which they cannot synthesize, hence this should be positively considered one of the decisive factors in «red tide» outbreaks. As a microbial product, B_{12} is much more abundant in organically polluted and/or river-enriched coastal waters than elsewhere in marine environments which suggests another aspect in explaining the heavy and frequent occurrences of flagellate «blooms» precisely in enriched coastal waters.
Furthermore, there is quite a lot of experimental evidence that some specific organic compounds can biochemically regulate both population dynamics and species compositions in phytoplankton communities. Since, apart from some antibiotic algal extrametabolites, the chemical identity of effective substances is not known as yet, these compounds were quite appropriately classified by Aubert et al. (1981) as a group of telemediators. Although their nature and effects still seem to be rather obscure, and therefore quite disputed, there is ample reason to believe that their regulatory effects in ecosystems might be more

significant than one would expect on the base of presently inadequate scientific knowledge.

Detergents

As is widely known, the «classic» detergents contain considerable amounts of tripolyphosphates which contribute to nutrient pools and hence increase aquatic eutrophication, yet probably much more in really phosphorus-limited fresh waters than in the sea. Therefore the producers of modern «environment-friendly» detergents have replaced phosphates with a variety of synthetic organicals whose effects possibly increase the nitrogen pool instead of phosphorus. Considering eutrophication problems in marine environment with the assumption that nitrogen be recognized as the major limiting nutrient, this replacement obviously appears useless, if not quite harmful. Experimental evidence (Aubert & Stirn, 1989-90) shows quite clearly that all types of phosphate-free detergents such as these currently used in France (which were extensively tested by a number of bioassay methods) have induced far more adverse effects, as far as potential eutrophication is concerned , than the «classic» ones, mainly because the replacement substances enhance the bioassimilation of combined forms of both nutrients and microlements. Moreover, the toxicity of tested «environment-friendly» detergents was as a rule significantly higher and the biodegradability was lower. Consequently, the populations of delicate species were depressed in favour of tolerant species, known as dominants in eutrophic conditions. Although the above information is far from being comprehensive , it indicates an urgent need for in-depth reconsideration of the «detergent issue» before the New Europe (EEC) sets relevant criteria whose ultimate impacts in marine environments may not reduce the eutrophication at all, but introduce other harmful effects in ecosystem equilibria.

Sources of nutrients

In natural marine environments normally a half of all available nutrients is regenerated and originates from autochtonous, sea-born sources, as mentioned above. The rest of the «new nutrients» are provided from allochthonous sources, i.e. the atmosphere, rivers and any other fresh-water inputs as shown below.

Atmosphere

As regards 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 $mg \cdot yr^{-1} \cdot m^{-2}$ of sea surface, and significantly more in coastal areas close to large industrial agglomerations (SCOPE, 1976). The atmospheric input of nitrogen compounds which 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. 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 and heavily from animal farms. Typical concentrations of nutrient-forms of phosphorus and nitrogen in rain waters are 0.08 and 0.7 $mg \cdot dm^{-3}$, respectively.

Rivers and runoff

Although there are almost no rivers enter-

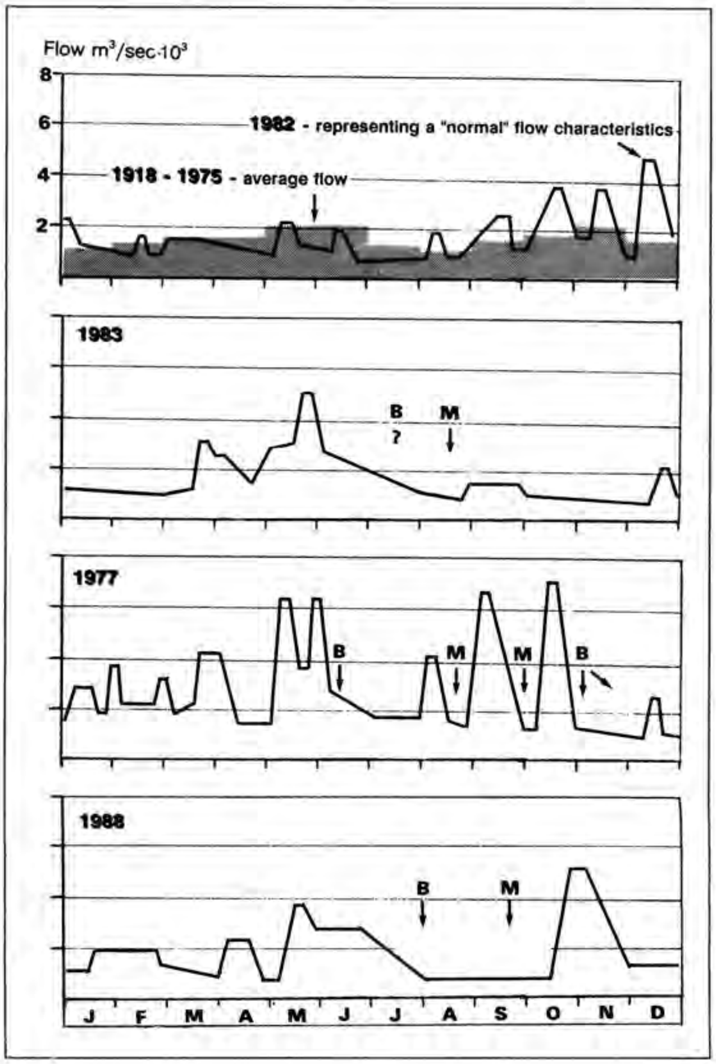
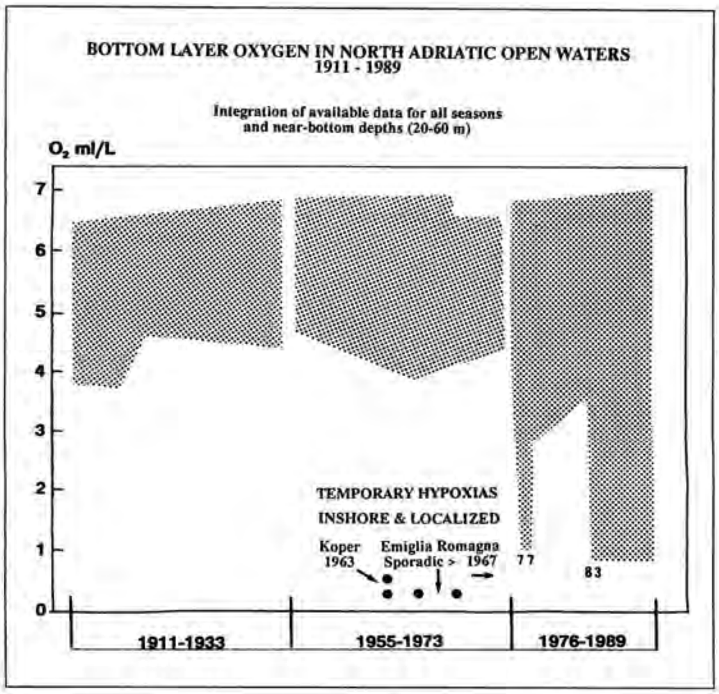


Figure 3 - Exemplary coincidences of the river Po flow-maxima prior non-seasonal and/or unusually heavy blooms (B) and concomitant hypoxia-induced mortalities of demersal fish and benthic invertebrates (M) in the North Adriatic Sea.

Figure 4 - Compilation of dissolved oxygen data as measured in the North Adriatic near-bottom layers during the period 1911-1989, showing recent trends in development of hypoxic conditions; updated from Stirn et al., 1984.



ing Mediterranean coastal waters that can be considered «unpolluted», it is appropriate to mention their typical natural background concentrations of nutrients: 0.01 – 0.05 $mg \cdot dm^{-3}$ P-PO_4 and 0.1 – 0.6 $mg \cdot dm^{-3}$ N (mainly nitrate). Taking as an example the Adriatic Sea with river-borne inputs estimated at 79,000 $t \cdot yr^{-1}$ of phosphorus and 250,000 $t \cdot yr^{-1}$ 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 during the last three decades.

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 still cause a considerable increase in levels of phosphorus. On the basis of UNEP (1978) estimates for the Mediterranean region, the «point» sewage discharges into the coastal waters in northern areas (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 and hence it is also difficult to estimate the proportion of sewage in total nutrient discharges into coastal waters. In 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.

Industrial effluents

Some inorganic and most industrial effluents can contribute a considerable amount of nutrients. As far as the Mediterranean is concerned, 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. Obviously, the increase of man-made nutrient inputs into allochthonous sources results in both increased levels of «new nutrients» and a change in the relative importance of sea-born versus external nutrient sources. Almost all man-made eutrophication processes are induced by nutrient supplies that originate from multiple sources, except in very localized cases (lagoons, semi-enclosed bays) with enrichments from point sources. Multiple causes are most typical in some northern Mediterranean subregions whose coastal zones and adjacent hinterland have a high density of human settlements, industrial plants, animal farms and heavy traffic, both in coastal zones and the catchment areas of discharging rivers on one hand, and intensive agriculture on the other; consequently, the combined loads of man-made nutrients from point sources, diffused runoff, rivers and atmosphere become the major source of nutrients in the receiving coastal waters. Using the case of the North Adriatic as an example, according to Chiaudani et al. (1983) the natural nutrient contributions became almost negligible in comparison with man-made sources as shown, e.g. for the origin of phosphorus loading to the NW Adriatic (in metric tons/year):

Sewage	7,199
Croplands	5,745
Industry	1,589
Detergents	8,688
Animal Farms	4,623
Natural	601

Evidently, natural sources of phosphorus contribute but ~2% of total loads; the share of natural nitrogen-nutrients is most likely much more important, but unfortunately no reliable relevant data seem to be available. On the other hand, the levels of man-made nitrogen loads seem to be steadily increasing, both, in atmosphere and rivers, while the increase in phosphorus loads appears significantly slower during the last decade as shown, e.g. in **Fig. 2**.

Limiting nutrients

About 150 years ago Liebig (1840) introduced «the law of the minimum» which states that plant growth is controlled and limited by a nutrient for which the available concentration is approaching the critical minimum as needed for normal physiological processes and reproduction. Following this concept, phosphorus has been widely recognized as the limiting nutrient of the primary productivity in fresh-water lakes and the critical factor of related eutrophication problems (Vollenweider, 1968; OECD, 1982). Although the above principle seems to be adequately supported by an extensive scientific evidence as far as freshwater lakes are concerned, even in contemporary limmology the rigid application of Liebig's law has become rather outdated. In this regard, it seems quite appropriate to quote a relevant warning from the «classic» ecological textbook by Odum (1971): «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».

The reason for the above discussion, which seemingly has not much to do with the subject of marine eutrophication, is a remarkable tendency among some scientists, engineering lobbies and decision-makers in the Mediterranean region to consider phosphorus as the critical factor in marine eutrophication just as rigidly as in the above, now rather historic approaches. One can understand the enthusiasm of civil engineers for the consequent needs to remove phosphorus as a causative factor of eutrophication for it can be rather easily precipitated from waste water, whereas the pertinent attitude among scientists appears more disturbing. Therefore it seems worthwhile to discuss some aspects of this problem.

Unlike most marine environments whose primary productivity is limited by nitrogen (Carpenter and Capone, 1983), and silicon and iron in specific circumstances, the prevailing part of the Mediterranean ecosystem really appears phosphorus-limited although this has never been proved by reliable experimental evidence. It should be stressed, however, that this might be true only as far as oligotrophic, mainly offshore Mediterranean waters are concerned where the concentrations of bioavailable phosphorus are extremely low, often beyond analytical detection limits. Normally, nitrogen becomes depleted too, yet rarely as extremely as phosphorus because of relatively better conditions for replenishment from modest but steady or at least frequent inputs such as heterotrophic excretion, cyanobacterial nitrogen fixation, rain and the absorption of atmospheric ammonia. Thus, the limiting factor is indeed phosphorus, however, the entire nutrient pool is extraordinarily poor and as a whole supports but a minimum of primary productivity. The causes of extremely low nutrient levels in the Mediterranean Sea are multiple: a weak exchange of water masses with the Atlantic and the Black Sea, a narrow continental shelf, great mean depth and the lack of strong vertical circulations and extraordinarily poor nutrient reserves in deep waters which limit an efficient replenishment of nutrients in euphotic layers.

Apart from the Atlantic influx, the major nutrient supplies originate from rivers and more recently from pollution. Therefore the areas of enhanced productivity are located exclusively within the reach of these two sources. There the phosphorus-nitrogen proportion must be entirely different because the source of nutrients, i.e. sewage and other biodegradable organic effluents, discharged directly or through minor rivers, provide bioavailable nitrogen and phosphorus as a rule in proportions like 5:1.

An exception to this are the enrichment effects of large rivers whose nutrient loads show usually N:P ratio like 20:1, hence there is a nominal surplus of nitrogen. In spite of this, phosphorus still cannot become limiting in those coastal waters which contain significant components of river waters, e.g. at levels of >5% reduced salinity, (for having) bioavailable phosphorus concentrations as high as required for euthropic rates of primary productivity, i.e. >0.3 μM $P\text{-}PO_4$. However, further out in open waters where the river component becomes highly diluted, the above initial N:P ratio may indeed induce phosphorus limitation as, for instance, in open waters of the Northern and Mid-Adriatic Sea as reported by Pojed and Kveder (1977), Revelante and Gilmartin (1976) etc.

Apart from that, the initial man-made enrichments of coastal waters are characterized by both. An absolute and relative abundance of phosphorus. Since marine plants, unicellular algae in particular, normally assimilate 10-20 times more nitrogen than phosphorus, the above sources obviously provide (at the initial stage, i.e. before being dispersed and transformed in receiving coastal waters) a large surplus of phosphorus versus nitrogen which alone can be considered a potentially limiting factor. Despite phosphorus transformations and its gradual biological inactivation while being combined with sediments, etc., it appears most unlikely that phosphorus could ever become limiting in marine environments whose eutrophic conditions result from man-made nutrient enrichments (Goldman, 1976). And yet, there is a number of papers, the most recent ones by Vollenweider et al. (1992) and Mingazzini et al. (1992) in which the authors suggest phosphorus limitation even for heavily eutrophied and/or hypertrophic inshore environments such as the western area of the North Adriatic where neither phosphorus nor nitrogen ever present a true limiting factor because their concentrations are more than sufficient for eutrophic rates of primary productivity. The reasons for such misleading conclusions are of a methodological nature, i.e. simplified applications of Redfield ratio (e.g. by excluding intracellular nutrient pools) which is for such cases of N and P nonlimited environments irrelevant anyway, and inadequate experimental procedures of applied bioassay tests.

In case such conclusions become the subject of only academic disputes, one could consider that by a moderately critical approach. However, taking into account the aforementioned tendencies to focus eutrophication control measures on the reduction of phosphorus inputs, one feel obliged to stress that such conclusions may lead to heavy investment in treatment technologies, economic and «ecologic» costs of «environment-friendly» detergents which may not result in any significant improvements. In this respect an exemplary lesson which one carefully considers, comes again from the North Adriatic. As shown in **Fig. 2a**, the legally introduced limit of detergent-phosphorus content ($<5\%$) significantly reduced further increase of riverine loads from 1975 onward. However, instead of the expected moderations in eutrophication processes, their effects were steadily growing, showing dramatic blooms with consequent hypoxia-induced mortalities (compare this with temporal trends in desoxygenation as shown in **Fig. 4**) first in 1977 and then almost regularly since 1983 which clearly coincides with maximum nitrogen discharges as shown in **Fig. 2b** as well as with the temporal dynamics of river-flows as shown in **Fig. 3**.

Altered food web - A parallel cause of eutrophication

As discussed above, the ultimate result of eutrophication is an extraordinarily high primary biomass whose production is enhanced by enriched nutrient supplies. Given such ecosystem conditions in which the bulk of biomass cannot be readily consumed by herbivorous animals, i.e. at secondary trophic levels of a food-web, (zooplanktonic and benthic suspension feeders and grazers of benthic macroalgae), such biomass becomes «surplus» organic matter. Although a part of «surplus» amounts might be deposited and eventually bioinactivated in bottom sediments or even exported (e.g. accumulations of floating «blooms», macroalgae and seagrasses on shores above high tide level), by far the greatest share is taken up by the heterotrophic microbial loop, decomposed and otherwise transformed. As explained previously, high oxygen consumption as needed for the above processes may result in hypertrophic conditions characterized by hypo-anoxic conditions, mortalities etc.

Whether a eutrophic ecosystem can culminate in hypertrophic conditions or not, depends in the first place on the amounts of available «surplus» organic matter. Since this represents the net result of primary productivity on one hand and herbivorous consumption on the other, the latter, too, should obviously be considered as the parallel causative factor in eutrophication processes, particularly as related to hypertrophic developments.

There are of course numerous ecological situations in which a herbivorous component of a given food-web may consume the available primary biomass at relatively reduced rates. Although very little is known in this regard as far as the Mediterranean ecosystems are concerned, the following two basic aspects can be suggested as related to eutrophication aspects.

By the first aspect it is assumed that neither standing stock nor the community structure of the herbivorous component have been modified and/or ecologically depressed, yet the rate of consumption becomes selectively reduced because certain, possibly predominant species in the primary biomass are simply not edible for the herbivorous species which make up part of a given community. Consequently, the biomass of inedible species becomes «surplus» organic matter. For instance, in eutrophic pelagic environments such a situation may appear quite often because the usual planktonic herbivores avoid feeding on many «blooming» flagellate species as well as the mucous diatom agglomerates. Another example is shown in eutrophic lagoons whose major component of primary biomass is usually produced by the green alga *Ulva rigida*, mainly as massive «surplus», for there are no grazing species that would cause but an insignificant consumption; the relevant consequences for hypertrophic developments will be shown later in the paper.

The second aspect of reduced rates of herbivorous consumption is assumed to be the consequence of impoverished diversity and standing stocks of herbivorous communities as induced, apart from secondary effects of hypertrophication, by primary man-made impacts such as:

— The acute and/or sublethal toxicity of coastal waters as introduced by industrial or large inputs of domestic effluents which contain active levels of toxic metals, detergents, phenols, ammonia, H_2S etc.

— The «mechanical» destruction of respiratory-filtering organs of filter-feeders by steadily elevated contents of dispersed mineral particles, or by temporary but massive silting due to dredgings, coastal engineering works, etc.

— The destruction of inshore or bottom hard substrata for sedentary filter-feeders, removal of sea-grass beds etc., by works as above or due to oil-spills and chronic shore-based oil pollution.

Obviously, the above direct impacts may equally affect both pelagic and benthic communities. However, the effects of hypertrophication-induced hypoxic conditions and anoxia with the concomitant evolvement of highly toxic hydrogen sulphide are certainly much more detrimental in benthic habitats. Firstly, because these processes are usually not only initiated but also most harmful just in near-bottom environments, and secondly because of the incomparably weaker flushing and water exchange conditions in the benthic domain than in upper water masses. Therefore entire benthic communities, except some supertolerant infauna-species, might be killed within a few days of a hypo-anoxic episode (Stachowitch, 1984; Stirn 1968).

Another reason for more emphasis to be given to the consideration of the ecological vulnerability of benthic communities is their relative importance for the maintenance of ecosystem equilibria, particularly in eutrophic conditions. Apart from large eutrophic regions such as the North Adriatic and the Golfe de Lion, the areas which are significantly affected by man-made eutrophication are mainly confined within shallow coastal zones. However negligible benthic communities might be from the standpoint of pelagic-trophic conditions in open sea, their relevant impact within the limited volume of affected inshore waters is indeed of paramount importance because of their positive effects upon the «natural control» of eutrophication, such as:

— the assimilation of excessive nutrients and absorption of dissolved organic compounds,

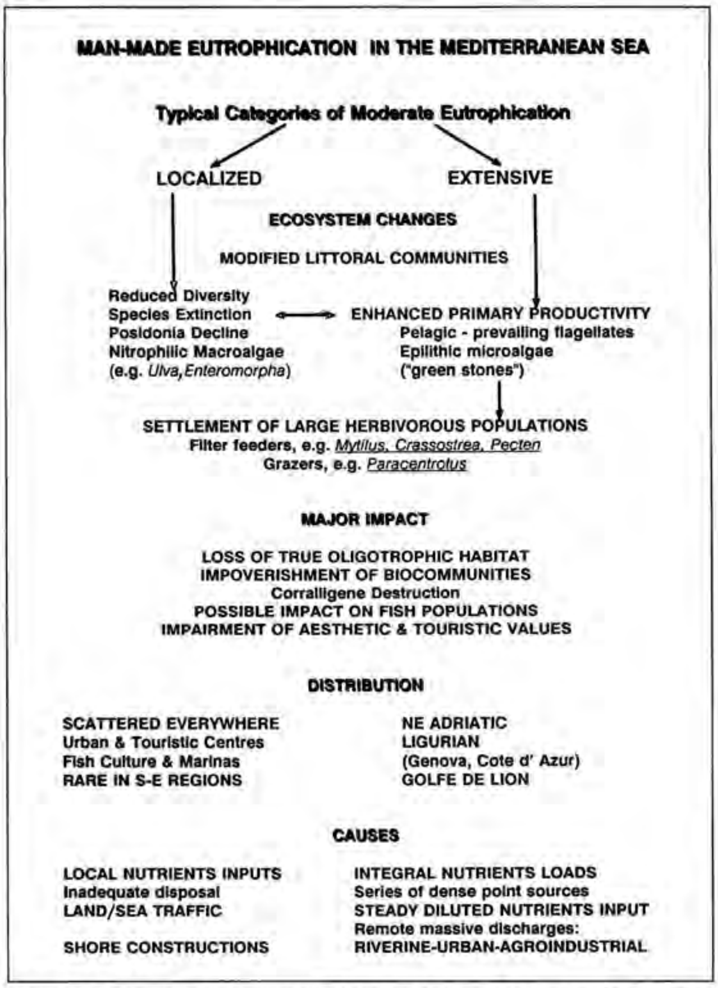


Figure 5 - Schematic presentation of typical features of moderate eutrophication processes as observed in the Mediterranean Sea.

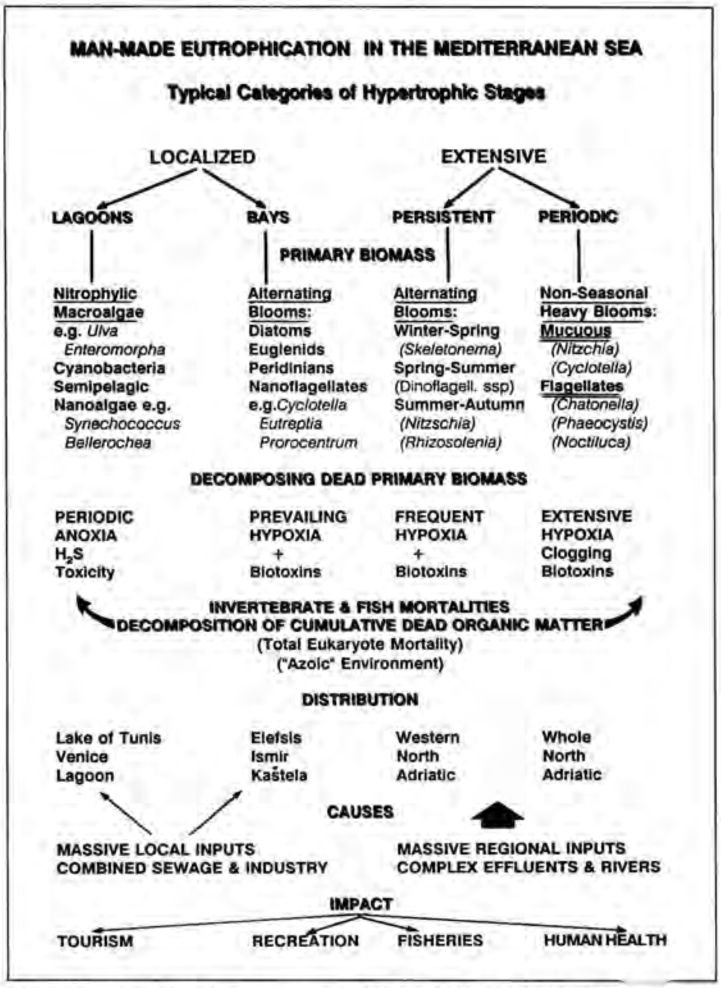


Figure 6 - Schematic presentation of typical features of heavy eutrophication and/or temporary hypertrophic conditions as observed in the Mediterranean Sea.

— the consumption and stabilization of pelagic primary biomass,
— the trapping and stabilization of suspended particulates,
— benthic photosynthetic oxygen production and the consequent reoxygenation of potentially critical water masses.

In this respect it should be stressed that similarly beneficial effects (nutrient assimilation and retention being by far the most important) result also from trophic cycling within fresh-water and brackish communities of wetlands, marshes and estuarine deltas which are the transition zones of nutrient-discharging rivers as well as the recipients of diffused runoff and «point» sources of nutrient-bearing pollutants.

Taking into account all mentioned effects, such ecosystem compartments and communities should be considered, not only from the standpoint of the paramount values of natural heritage and its comprehensive resources as discussed in the introduction, but also as the most efficient systems of eutrophication control - natural «treatment plants» that function more perfectly than any treatment technology contemporary engineering is so far able to offer. Moreover, these natural systems can also control diffuse components of nutrient loads (airborne, runoff from agricultural, urban and land-traffic surfaces) which technology cannot cope with for there is no way to collect them as an obviously required treatment-precondition.

Nevertheless, there is ample reason to propose strict measures as needed to protect any such communities which are still in the state of natural equilibria, and to suggest restoration activities for those which have been structurally degraded by ecologically adverse man-made effects. In this respect, yet considering the eutrophication control measures as needed specifically in heavily affected areas such as the western coastal waters of the North Adriatic, Saronicos Bay etc., it seems justified to suggest a targeted development for the artificial enhancements of herbivorous consumption, i.e. by providing substrata (artificial reefs, suspended mussel cultures etc.) as needed for a gradual increase in standing stocks of sedentary filter-feeders and associated microcosms.

In order to avoid a potentially dangerous misunderstanding, it should be stressed here that all the above statements refer to open systems but certainly not to lagoonary environments which have as a rule an extremely weak exchange of water masses. Nutrient-receiving capacity in the Mediterranean lagoons is at present saturated everywhere, at best only by natural nutrient loads, but unfortunately in too many cases, lagoons are overfertilized and hence highly eutrophic and/or hypertrophic. Moreover, lagoonary ecosystems are extremely vulnerable, particularly their seagrass communities which usually dominate their benthic component. In the case of significantly increased eutrophication, these communities cannot compete with expanding growth of green macroalgae (g. *Ulva, Enteromorpha* and *Cheetomorpha*) which soon results in an irreversible extermination of primordial communities as observed in nature and in an experimentally polluted lagoon (Malej et al, 1978; Stirn,1986) as will be discussed in the next chapter. Nevertheless, the message from these experiments was that, e.g. as little sewage (primary-treated) as is produced by 240 population equivalents, being discharged regularly for less than 1 year, causes a previously perfectly-balanced natural ecosystem to become extremely hypertrophic and temporarily anoxic, just like the Lake of Tunis, an exemplary case in this respect. As regards the management and protection of Mediterranean lagoons, the lesson from the above evidence is that no additional nutrient loads whatsoever should be allowed to enter such environments, unless deliberately sacrificed for intensive aquaculture or oxidation ponds as a part of water water treatment systems. However, for such purposes one would expect to find better solutions, e.g. digging new lagoons. It would not be necessary to say this if there were not so many cases of the use and destruction of lagoons for just such purposes as mentioned above.

Typical features of Mediterranean eutrophication processes

It is beyond the scope of this paper to compile and review all known cases of eutrophication impacts whose number and variability have been also gradually increasing, particularly during the last decade. Therefore this chapter provides only summarized information which has been prepared on the basis of a previous review paper (Stirn, 1988) and updated with additional evidence on some phenomena which have appeared very recently; therefore the relevant references are omitted but for the new information.

In spite of the great variability of eutrophication phenomena, most of the cases can be somehow systematized into a few categories of typical features as shown schematically in **Figs. 5** and **6**. If successions of functional steps in the development of eutrophication processes, as theoretically outlined in the **Fig. 1** are compared with features observed in nature, the theory matches quite nicely with actual observations in spite of rather poor relevant knowledge, particularly as far as reliable ecophysiological data are concerned. Nevertheless the bellow «categorization», illustrated by examples of typical features, seems rather justified at least as an orientation.

Moderate inshore eutrophication

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

Heavily eutrophied small-size systems

There is an increasing number of lagoons, semi-enclosed bays and larger port areas where the permanent inputs of enrichment pollutants normally reach levels which can induce full eutrophication development, more or less like the one shown in *Fig. 1*. Apart from heavily eutrophied port areas, the most common cases are heavily eutrophied lagoons and semi-enclosed, shallow bays with a weak circulation whose inner parts are receiving substantial sewage loads (e.g. from settlements with populations above 10.000 inhabitants for small and >100.000 for larger and more open bays) or discharges from polluted rivers or streams. Typical of this eutrophication appearance is as follows:

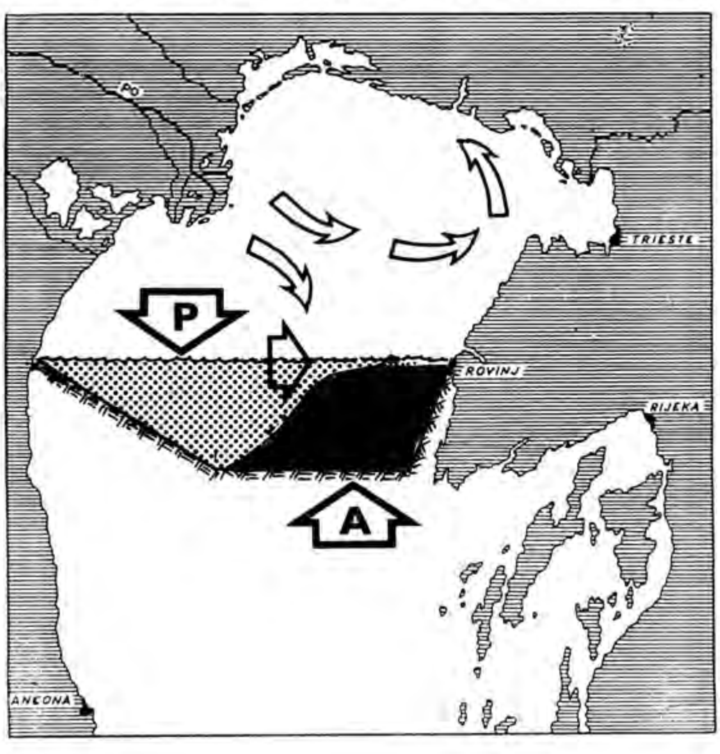
— Shore hard-bottom communities are modified as described above yet they are much more monotonous and overgrown with a very high standing stocks of macroalgae as above.

— The macroalgal vegetation also invades shallow soft bottom communities replacing and exterminating previous prairies of seagrasses (*g. Cymodocea, Zostera, Posidonia*) and may also form surface-floating mats of the above mentioned macroalgae often combined with floating *Chaetomorpha* spp. and filamentous cyanobacteria.

— 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 «chloromonads» and dinoflagellates in summer.

— The sediment bottom is enriched by organic matter, it is in a reduced state even at its very surface, and the near-bottom water layers temporarily become anoxic. Therefore the structures of macrobenthic communities are modified in many ways, most typically by reduced species and trophic diversity versus increased standing crops, however the meiofauna, shows decrease in both the diversity and the abundance.

The case of the Lake of Tunis is a drastic example of such extreme eutrophication as may develop in coastal lagoons. Nutrient in-



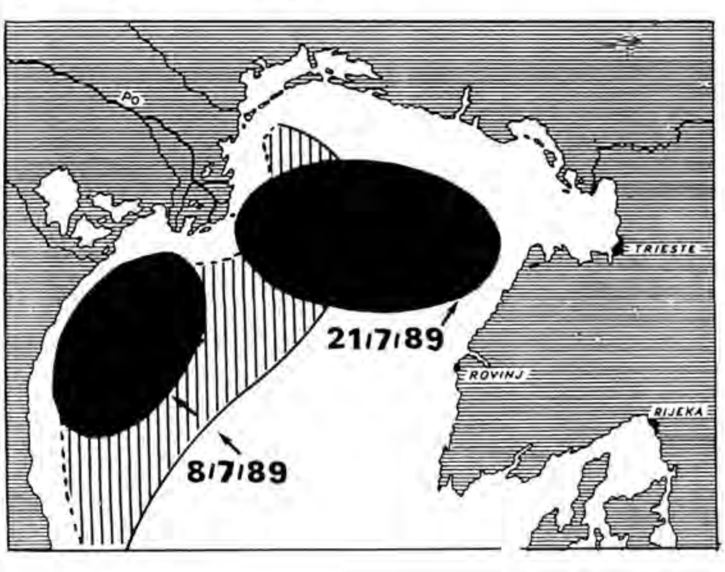


Figure 7 - Generalized distribution and circulation of the major water masses in the Northern Adriatic: (A) - inflowing mid-Adriatic, originally oligotrophic Istrian water and (P) - outflowing and laterally surface-spreading, diluted and eutrophic western waters.

Figure 8 - Exemplary distribution of a heavy «normal bloom» of diatoms, dominated by* Nitzschia *spp. in comparison with the area of origin and successive spreading of the mucous diatom «bloom» dominated by* Cyclotella *spp. during the summer 1989.

puts from partially treated sewage (~ 1 million population equivalents) and their efficient recycling, result in the massive and as a rule quite steady production of pelagic unicellulars (>50 $\mu g \cdot dm^{-3}$ chlorophyll), mainly coccal g. *Nannochloris* (>10^7 cells/$\cdot dm^{-3}$), and green macroalgae, mainly sedentary and floating *Ulva rigida* (0.5-5.0 kg w.w. biomass/$\cdot m^{-2}$). In spite of an intensive herbivorous consumption of primary organic matter, particularly by reef-forming community of the tube-dwelling worm *Merceriella (Ficopomatus) enigmatica*, there is a substantial surplus of dead organic matter formed and microbially decomposed. In consequence, during the summer total anoxia appears, along with the mass-mortality of fish and less-tolerant invertebrates which are also killed by evolved H_2S, ultimately oxidized by «red water» populations of purple sulfur bacteria (g. *Thiocapsa* and Chromatium).
As already mentioned in the previous chapter, in principle almost the same hypertropication-induced modifications and ultimate ecosystem destructions as observed in nature were also shown as the result of intentional sewage discharges (300 l of primary-treated effluent per day) into experimental lagoons (63 m^2 each) performed during 1976-78 in a sacrified portion of the Lagoon of Strunjan (North Adriatic, Slovenija).

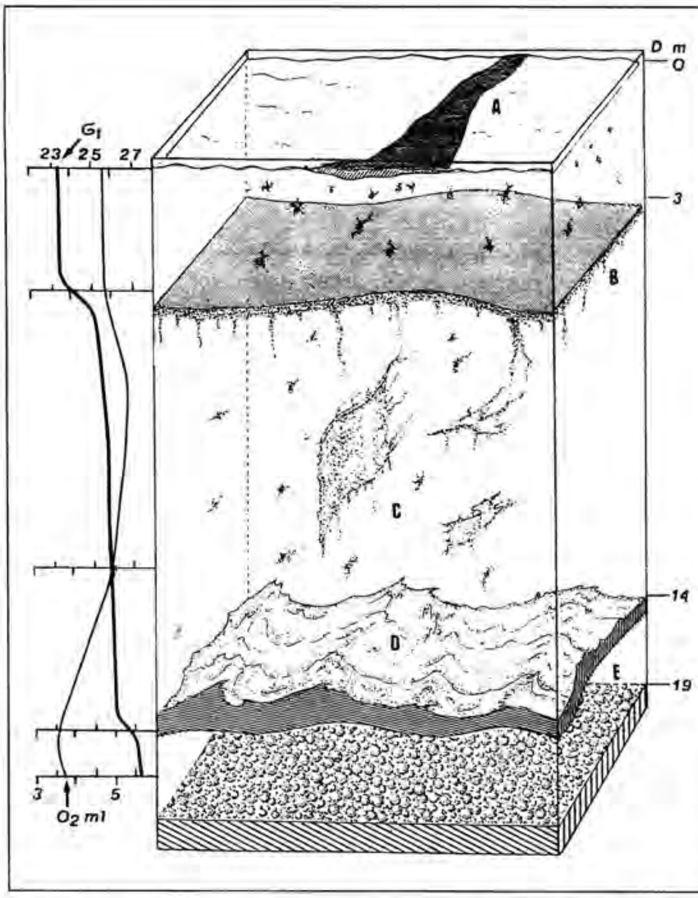


Figure 9 - Mucous diatom «bloom» in the Northern Adriatic, summer 1988: typical distribution of macroaggregates within the water column as related to the density stratification (σt) and showing also the initial near-bottom depletion of dissolved oxygen; symbols: D-depth (m), A-floating surface bands and «carpets», B-upper discontinuity accumulation, C-macroflocs, «clouds» and «curtains» of original diatom-colonies in statu nascendi, D-lower discontinuity accumulation, E-initial bottom deposits (from Stirn, 1989).

Extensive eutrophication of Mediterranean coastal waters

The major part of the Mediterranean continental shelf is very narrow and edging deep waters. Hence the dispersion and the dilution of nutrients within the offshore oligotrophic waters is very efficient, whereas the nutrient inputs are generally quite modest except in northern regions and in a few localized areas, e.g. in the Aegean Sea. Therefore offshore or widespread eutrophication of coastal waters in southern areas is unlikely ever to appear, except in the Golfe de Lion, Alboran, North Liqurian and Adriatic seas where the evidence does indeed show indeed an extensive eutrophication, particularly in the Golfe de Lion and, of course, in the northern and partly middle provinces of the Adriatic. Since the North-Adriatic shows one of the heaviest man-made eutrophication impacts known in the World Ocean on one hand, and the entire spectrum of various eutrophication features on the other, it is used here as an appropriate example which also indicates what kind of impact one can predict for the above mentioned eutrophied areas in ecological response to the galloping urban-industrial developments along the northern shores of the Mediterranean Sea.

Eutrophication features in the North Adriatic Sea

As the recipient of large river-discharges (the average cumulative flow being 1900 $m^3 \cdot sec^{-1}$) the North Adriatic nutrient-enrichments have probably always been much higher than in the middle and southern Adriatic provinces or elsewhere in the Mediterranean Sea. The initial man-made increase of nutrient inputs was probably the consequence of the first significant deforestation in the 16^{th} century (Molin et al., 1992). Thereafter deforestation obviously continued, along with agricultural developments, and more recent (19-20^{th} century) engineering works in river beds and deltas for land reclamation. This all contributed to a gradual increase of nutrient inputs up to the levels recorded during the the first half of this century.
Just a little after that period (1964-66) the author had the privilege to accomplish extensive investigations of oceanographic conditions and pelagic bioproductivity, using as a rule monthly cruises aboard «R.V. Argonavt» which occupied the entire area of the North Adriatic as well as the upper zone of the Mid-Adriatic (Stirn, 1969). It should be understood that the reason for these, now almost «historic» investigations to be mentioned, is not a reflection of the author's personal intentions, but the opportunity to use this «historic» evidence as the baseline in comparisons with recent conditions as discussed below.

Trophic conditions and the state of eutrophication around 1965

The North Adriatic showed as a rule two major water masses (**Figs.** 7 and **8**) which were distinctly different as were the basic ecosystem features in pertinent areas:

Eastern (Istrian) waters

Due to prevailing inflows of typically oligotrophic waters from the Middle Adriatic, pelagic provinces were still oligotrophic for the major part of the year, except during spring and autumn phytoplankton maxima of dominating, yet high-diversity diatom communities which did not reach «blooming» levels (~ 10^6 cells$\cdot dm^{-3}$). The origin of nutrients that supported these maxima was the inflow of river-diluted western water masses, driven by transversal circulations (**Fig.** 7). The summer season was characterized by the lowest phytoplankton standing stocks! No «red tides» have been seen and/or recorded, except sporadically in the harbour of Pula. Throughout the yearly cycle the oxygenation was always at or close to saturation levels; the minimum measured oxygen concentrations in bottom layers were never below 3.5 $cm^{-3} \cdot dm^{-3}$ (compare with **Fig. 4** - no hypoxic conditions till 1977!). However, the hypo-anoxias with concomitant benthic mortalities appeared for the first time in the bays of Muggia and Koper which locally became hypertrophic due to heavy sewage pollution and extensive engineering works (hydraulic dredging).
As regards the coastal zone, this was characterized everywhere along the Istrian shores

by high-diversity seaweed communities (phytal) on rocky bottoms, and the unique coralligen-like communities on detritic sediment bottoms; note: there were no mussels, «imported» oysters (*Crassostrea gigas*) or nitrophilic green algae to be seen at all, except in harbours and a few brackish areas.

Western waters

The nutrient inputs as shown above as well as strong mixing processes in extensive areas of very shallow waters which are typical for western coastal zones, supported pelagic bioproductivity which was throughout the yearly cycle at eutrophic levels, as it probably always was, well before any man-made impact. Maximum nutrient inputs, which clearly coincided with maximum river discharges, induced during the spring and autumn typically monotonous diatom «blooms» (characteristic dominant species: *Nitchia delicatissima, N. cf. seriata* and *Skeletonema costatum*). These, perfectly seasonal and regular «blooms» (not like summer «mucus» episodes of 1988-89 and ephemeridically also much before), too, were known to fishermen as «mare sporco» which clogged the fishing gear. Although the seasonal diatom «blooms» normally occur as dense suspensions, without any significant agglomerations, they normally contain a massive component of diatom-produced mucus which obviously is not «fishermen-friendly». As regards phytoplankton standing stock minima, there was only a short winter minimum (likely because of limitation by low light and temperature); the summer season was characterized by an early pick of dinoflagellate component (non «red-tides», yet with patches of dense populations of *g. Noctiluca*); followed by a minor summer maximum with dominating diatom species *Rhizosolenia alata*.
Considerably more eutrophied were inshore waters, particularly along the region of Emilia-Romagna which are receiving the maximum loads of nutrients, both from the river Po and numerous local sources. The sporadic occurence of bottom deposits of decaying diatom «blooms» and the first outbreaks of true «red tides» indicated the initial development of temporary hypertrophic conditions. It should be stressed, however, that in spite of quite heavy eutrophication no desoxygenations have been observed as yet, either inshore or in open «western waters».

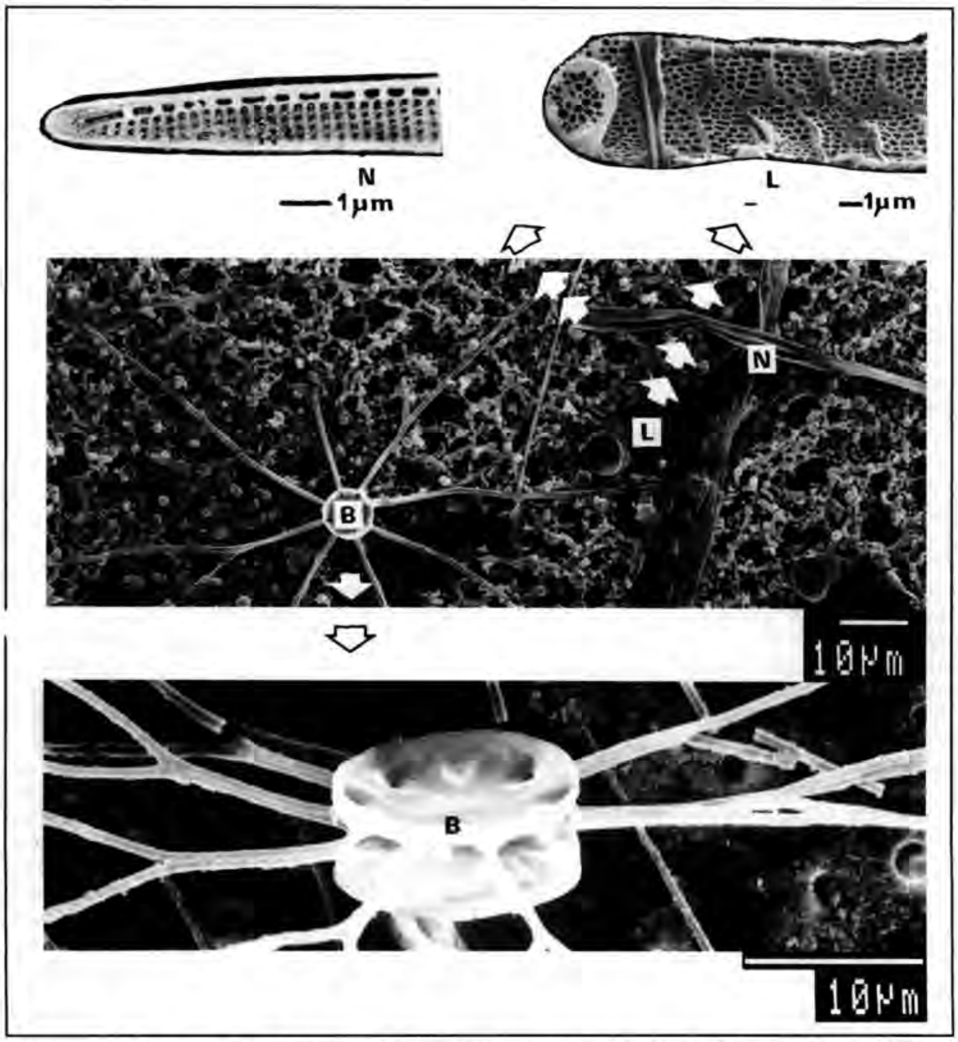


Figure 10 - Microstructure of mucous diatom aggregates from the North Adriatic «bloom» in summer 1988 with dominating g.* Nitzschia (N), Leptocylindrus (L) and Bacteriastrum (B)*; electron-SCAN-microphoto by Drasler, Rode and Stirn.

Eutrophication successions during the last two decades

During the last quarter of this century we have had the privilege (?) to witness the booming development of urban and tourist settlements, industry and maritime constructions in coastal zones as well as in the catchment areas of the rivers discharging into the North Adriatic. Simultaneously agriculture was remarkably intensified, mainly by the massive use of fertilizers and forced irrigation, while animal husbandry has gradually expanded and become a flourishing industry. In addition, synthetic detergents, whose use was gradually increasing, became a considerable component of combined nutrient loads from the above sources. Consequently, nutrient inputs seem to have been increasing dramatically at the expense of all above sources. However, reliable evidence is available only for river-discharges, e.g. for the river Po, as shown in **Fig. 2** (Marchetti, 1992). These data indicate that nutrient loads have increased since 1968 as two-fold orthophosphate, and three-fold total nitrogen concentrations. Although difficult to prove by using available analytical data, it seems quite obvious that the discharges of such loads into the North Adriatic have resulted in corresponding increases in the levels of «new» nutrients and consequently in significantly enhanced eutrophication processes as shown, i.a. in below-presented exemplary features that can be compared with conditions as observed 25 years ago.
Despite some serious methodological problems and the lack of adequate long-series data, the available evidence suggests that these recent additions of new nutrients has resulted in a generally increased productivity, at least within the primary trophic level, all over the North Adriatic as well as in previously oligotrophic open waters of the Middle Adriatic (Pucker-Petkovic et al., 1988). However, this extensive eutrophication would be much less remarkable if it were not for coincidence with other factors (global maxima of temperature and solar activity) which the last decade have been extraordinarily favorable for primary productivity, but less so or even harmful for the functional structures of the ecosytem as a whole. As shown below, the unusual parameters of these extramarine factors induced synergistic conditions for the outbreaks of formidable mucous «blooms» in 1988-89. It seems obvious that eutrophication processes in coastal waters have been equally affected, or as is more likely, quite significantly boosted by these factors; however, these conditions have been specifically relevant only during the last decade, whereas the gradual increase of eutrophication as supported by increasing nutrient

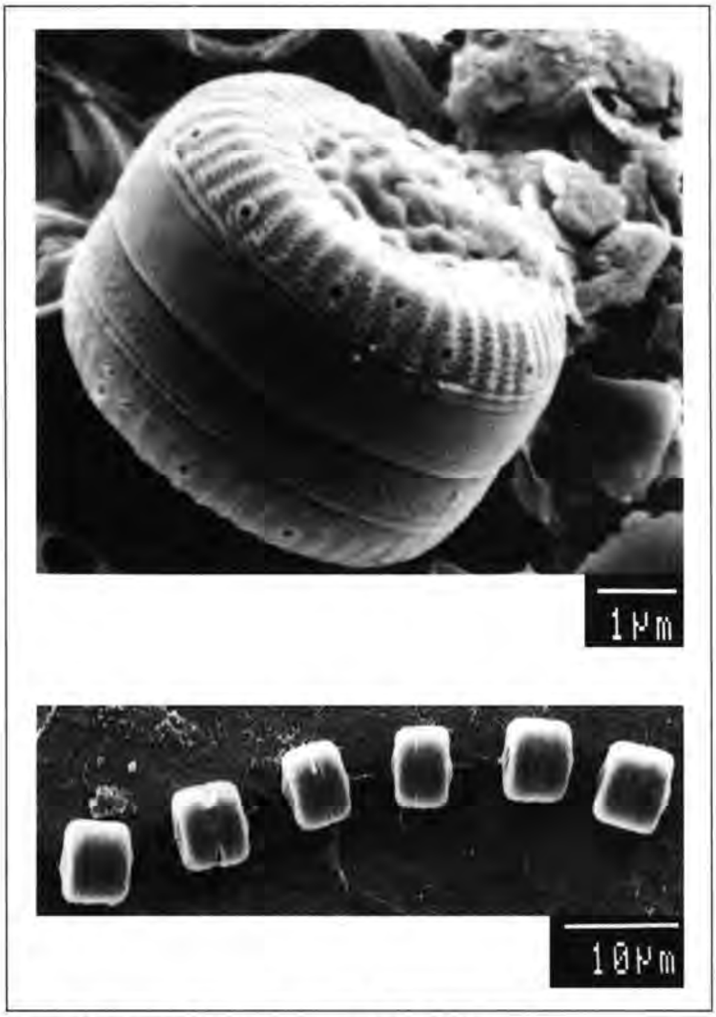


Figure 11 - Mucous diatom «blooms» in the North Adriatic were dominated during the summer of 1989 and 1990 by g.* Cyclotella (C); *electron-SCAN-microphoto by Drasler, Rode and Stirn.

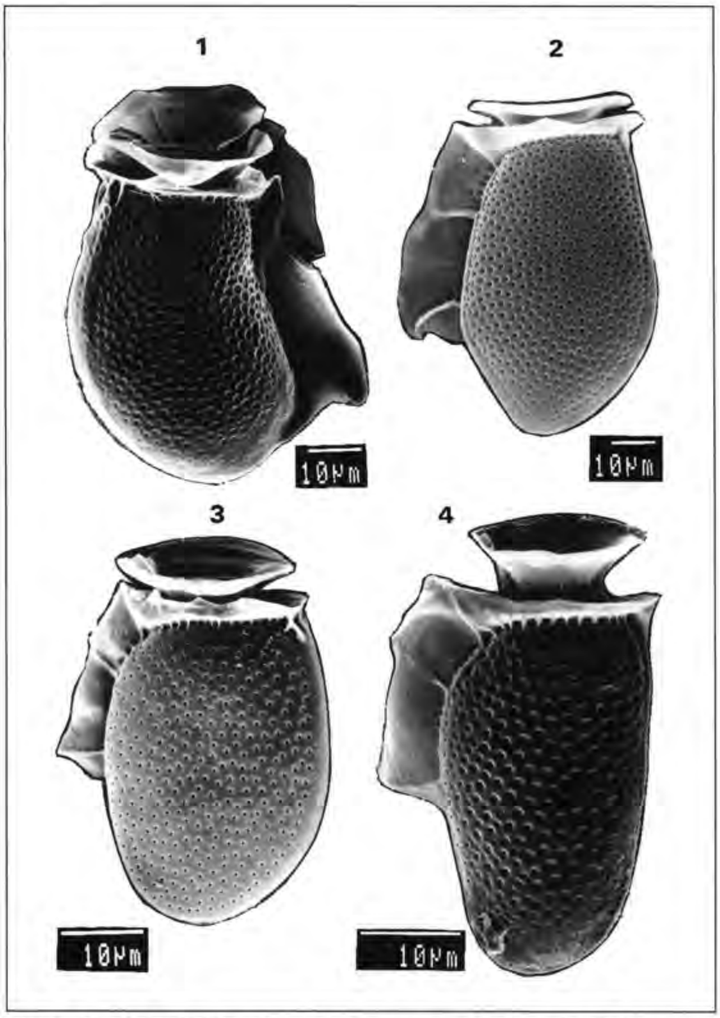


Figure 12 - Potentially anthropotoxic species of g.* Dinophysis *from the eutrophic areas of the Golfe de Lion and the Northern Adriatic Sea (1.* D. fortii, *2.* D. acuta, *3.* D. acuminata, *4.* D. sacculus*); electron-SCAN-microphoto by Drasler, Rode and Stirn.

supplies developed well before and in perfectly normal light and temperature conditions as shown by the following, most characteristic features:

Moderate eutrophication of eastern (Istrian) waters

As the result of a fluctuating but steady increase in phytoplankton standing crops, mainly at the expense of nanoplankton, including small diatom species, phytoplankton densities are now throughout the yearly cycles (except during winter minima) relatively high ($>10^5$ cells·dm^{-3}), hence the sea colour is no longer blue but green-blue, at best, and transparency is significantly lower than was the previous «historic» average (Justic, 1987). Previous seasonal phytoplankton maxima (spring and autumn) became true «blooms», while instead of previous summer minima, there are now regular nanoplankton maxima (Gilmartin and Revelante, 1980) and summer diatom «blooms», dominated by *Rhizosolenia alata* (Fanuko, 1983). The first true «red tide» occured in 1974, since then the frequency of outbreaks has been increasing (Honsell, 1992) and so is the relative abundance of potentially toxic dinoflagellates (*g. Alexandrium* and *Dinophysis*). However, the toxicity of shellfish has not been demonstrated as yet.
As far as the coastal zone and its benthic communities are concerned, there were some dramatic and as it seems, irreversible changes, of which at least the following can be associated with eutrophication effects: previous intertidal seaweed communities have been replaced by dense mussel (*Mytilus galloprovincialis*) populations showing a remarkable ecological response to a eutrophication-induced increase in the amounts of available food from phytoplankton, and at least one, relatively positive eutrophication impact.
Unfortunately, this was quite different and disastrous as far as the soft-bottom benthic communities are concerned. As shown below, the ultimate effects of summer mucous «blooms» which were also widespread also in coastal waters, caused hypo-anoxic conditions and consequent heavy mortalities of benthic invertebrates. These phenomena, which occurred repeatedly in 1983, 1987 and 1990, destroyed benthic communities, including commercially important scallop populations (Stirn, 1988), over vast areas of north-eastern Adriatic benthos in depths of 15-35 m (Zavodnik et al., 1989), most severely in the Gulf of Trieste (Stachowitsch, 1984).

Hypertrophication in western waters

Since the first catastrophic «red tide» in 1969 which caused, i.a. remarkable fish and invertebrate mortalities (Piccinetti and Manfrin, 1969), the frequency and intensity of alternating heavy diatom «blooms» (autumn-winter seasons with dominant *Skeletonema costatum*) and true «red tides (spring-summer seasons with dominant *g. Gymnodinium, Gonyaulax* and *Prorocentrum*) have been growing steadily and previous heavy eutrophication has been transformed into a «chronic state of hypertrophy», Vollenweider et al., (1992); cit.: «Since 1975 algal blooms along the Emilia-Romagna coast have no longer been occasional and have become important enough to cause serious problems to the environment, tourism and fishery. The first alarming event was recorded on September 7, 1975 causing high mortality of benthic shellfish and vertebrate fishes. Since then, more or less serious algal blooms have occurred year after year in various seasons involving progressively larger and larger areas. .....In addition to frequent fish mortality, change in water colour, alteration of the organoleptic characteristics of the water and emissions of unpleasant smells to the air are now a common disturbance.»

A novelty, recorded first in 1989, is the occurrence of toxic species of *g. Dinophysis* at densities which caused DSP (diarrhoetic shellfish poisoning of humans) toxicity of shellfish (Boni et al., 1992). Disturbing, too, is the apparent occurrence of potentially very toxic dinoflagellate species *Alexandrium tamarense* and *Gymmodinium cf. catenatum* (Honsell et al., 1992).

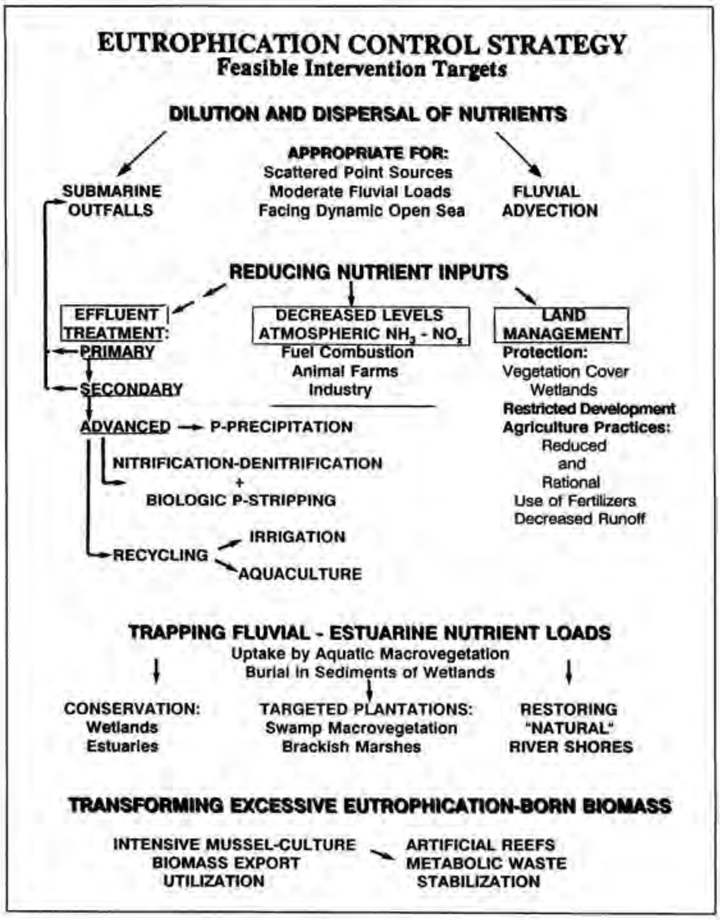
Offshore eutrophication and temporary hypertrophication features

Despite conditions in coastal waters as described above, until very recently North Adriatic open waters were never affected by such levels of eutrophication which could cause a significant depletion of oxygen. As shown in **Fig. 4**, and more precisely demonstrated by Justic et al. (1987), all data as available for the period 1911-1977 show, even for near-bottom layers consistently normal conditions.

However, in 1977 a dramatic change occurred for the first time as the consequence of the most unusual flagellate «bloom» which occupied the entire North Adriatic. This has been largely described as the «red tide» of *g. Noctiluca* which was indeed very abundant in surface patches, feeding on actually «blooming» photosynthetic flagellate *Chatonella cf. marina* at densities up to $3 \cdot 10^7$ cells$\cdot$dm^{-3} (Stirn, 1988) which caused coffee-brown sea colour and transparency as low as 2 m (Secchi reading). As shown in **Fig. 3** this bloom promptly followed the highest ever recorded monthly discharge of the river Po which carried also the highest nitrogen loads (**Fig. 2**). The ultimate effect of the «bloom» was a drastic depletion of oxygen in bottom layers during the summer and autumn all over the North Adriatic (Degobbis et al., 1979); oxygenation was restored, somehow back to normal only by the end of 1977. Consequent mass-mortality of benthic invertebrates in extensive North Adriatic central and western areas as well as escape-migrations of demersal fish and crustaceans (allowing «pesca facile», easy fishing in inshore waters) was reported by Stefanon and Boldrin (1982). In the author's view, the primary mortality was due to the known toxicity as induced by the above flagellate, while the desoxygenation followed the decomposition of both poisoned benthic fauna and deposited organic matter of the «bloom» itself.

The most recent phenomenon whose ultimate effects are about the same as above, are seemingly unusual, mucous «blooms», called also «mare sporco», «marine snow» etc., which incidentally is not the correct terminology. As is largely known, the phenomenon occurred most apparently in summers 1988-89, (in the author's view, also in 1983, 1987 and 1990 in subthermocline layers), as massive mucous aggregates that occupied surface, water column and bottoms of the entire North Adriatic in various forms as reviewed by Stachowitch et al. (1990) and illustrated in **Fig. 9** (Stirn, 1989). The focal area of aggregate formation was in the most enriched western waters as demonstrated, i.a. by satellite records (Zambianchi et al., 1992) and shown in **Fig. 8**, and from where the aggregates were advected and spread over large areas, including scattered localities in the Middle and Southern Adriatic. However, similar patchy aggregates were observed during the same period in some areas of the Adriatic where the above origin appears impossible. This suggests an assumption that aggregates developed autonomously also in other areas, wherever the required initial nutrient levels in combination with calm sea conditions allowed such development, while other factors, assumed by the author (Stirn, 1989) to be of decisive importance (high temperature, intensive solar radiation with correspondingly high UV doses which trigger excessive mucus production as the anti-radiation shield for diatoms) were globally present anyway.

Figure 13 - Outlines of feasible measures and rational strategy for the eutrophication control and prevention.



This also explains also the much disputed puzzle about the fact that similar phenomena, though much more restricted in intensity and spatial extension, were ephemeridically, yet clearly recorded as early as the 18-19th century (reviewed by Umani et al., 1989 and Molin et al., 1992). In this respect it should be stressed that there is a dramatic difference between the historic occurrences of about the same phenomena and recent features. Namely the latter are as a rule causing heavy oxygen depletions and hence drastic ecosystem disequilibria, along with multiple harmful effects, including losses in fisheries resources.

These are affected not only by oxygen depletions and consequent mortalities but also directly by the mucous aggregates which function as the most efficient trapping mechanism for any particles within the water column, including fish eggs as observed by the author. Since, e.g. anchovy is an exclusive summer spawner, it can be assumed that the known collapse of its fisheries in the Adriatic is due to recruitment failures rather than as the result of some obscure natural fluctuations (Bombace, 1992). Although it is beyond the scope of this paper to analyse this phenomenon in any further detail, it seems worthwhile to make a statement about the very origin of these aggregates which still represents a quite disputed subject. Observations of aggregates *in statu nascendi* and experiments with diatom cultures indisputably show that the primary stages of aggregates are patchy, planktonic diatom «blooms» of chain-forming species (*g. Nitzschia, Leptocylindrus, Chaetoceros* and *Bacteriastrum*) with a characteristic and important component of «slimy», very small species of *g. Cyclotella*. Once formed, the aggregates become a substratum for a highly diverse microcosm, including quickly proliferating populations of amoebae which are feeding selectively on diatom protoplasts, leaving behind mucus, empty diatom frustules and the rest of the microcosym, which soon includes important colonies of otherwise benthic diatom species etc. (Stirn, 1992). Moreover, it seems that many authors who have analysed taxonomic compositions of aggregates dealt with variably transformed stages, and have overlooked small but dominant species (e.g. diameter of *Cyclotella* spp. is 4-10 μm) etc. This has caused some exemplary confusions and disputes.

Prevention and control of man-made eutrophication

There is ample evidence, as outlined also in this paper, that the impact of man-made eutrophication cannot be considered only from the purely ecological standpoints of (sometimes romantic) intentions for the conservation of natural heritage, but as one of the serious socio-economic problems concerning beneficial uses of the Mediterranean Sea and its coastal zones which have recently been too often threatened by the adverse or harmful effects of eutrophication, such as:

— degradation of aesthetic and recreational values of oligotrophic waters and its biotic communities which represent an invaluable resource-component of the tourist economy;

— destruction of critical biotic communities in coastal zone and at inshore bottoms which results in reduced natural control of eutrophication on one hand, and indirect losses in fisheries resources on the other for these communities function as most effective self-purification mechanisms and irreplaceable fish-nursery habitats, respectively;

— direct losses in fisheries resources as caused by extermination of species, mortalities and recruitment failures, possibly during embryo-larval and juvenile stages of a given population;

— losses in mariculture by enhanced infections, oxygen depletions, biotoxin-induced mortalities and prohibited marketing of shellfish which have accumulated anthropotoxic dinoflagellate DSP and PSP compounds;

— hindrance of mariculture activities by environmental deteriorations of otherwise adequate habitats of inshore sheltered areas, estuaries and lagoons;

— unpredictable direct losses in the tourist economy because clients avoid and/or abandon areas affected by apparent «blooms»;

— human health-hazard caused by biotoxic sea-food and irritant-allergic effects of sea water and aerosol in areas of heavy flagellate «blooms».

Recognizing these problems, one should fully agree with the Resolution as endorsed by the participants of International Conference «Marine Coastal Eutrophication», Bologna 1990, (Vollenweider et al., 1992) which, i.a. calls for eutrophication control measures as follows, cit.: «Governments are further urged to develop ..... strategic planes to bring the undesirable effects of marine eutrophication under lasting control, and to proceed with the implementation of immediate programs to eliminate all direct and indirect discharges to waterways and marine waters of inadequately treated sewage, combined with programs aimed at reducing the excessive load of eutrophication-causing plant nutrients to the marine environment».

It should be stressed, however, that the above requirements, unless understood in the sense of global principles, refer directly only to those, mainly northern Mediterranean marine environments (as indicated in the previous chapter) whose nutrient-receiving capacities have already been or are likely to be surpassed. Thus an efficient control strategy must include all hydrotechnical and biotechnical measures as presented schematically in **Fig. 13**.

Fortunately, in the south and east of the Mediterranean Sea where the shelf is narrow and human settlements are scattered and modestly inhabited, there is in principle no risk of substantial 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 at a depth which is below the summer thermocline can be proposed as an adequate control measure, and surely the most economic one. Obviously, this does not apply to stagnant marine environments such as estuaries and lagoons, in which the receiving capacity is practically nil as 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, is seems that for these areas the control strategy should be considered cautiously, and 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.

Considering the overfertilized and eutrophic environments again, and the North Adriatic in particular, it appears obvious that the above strategy of dispersal and dilution of nutrient-containing effluents via submarine outfalls cannot provide significant effects (except for smaller settlements if widely scattered), whereas the direct eutrophication-control measures as outlined in **Fig. 13** may result in dramatic improvements, provided the implementation systematically covers the affected areas as a whole with rational engineering solutions based upon reliable scientific evidence which requires considerably more applied research.

The above «relative optimism» refers, of course, to the present levels of urban-industrial activities within coastal zones and corresponding nutrient loads. If, however, the galopping development of these and related activities continues further in the future, the idea of keeping and/or improving marine ecological equilibria may become but an illusion for there will be exponentially growing negative impacts that just cannot be technically controlled. Although beyond the scope of this paper, it should be stressed that the concern of probably by far the greatest importance in this respect, too, is the reasonably restrictive planning of future coastal zone developments. ●

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