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ECOLOGICAL EFFECTS OF MARINE POLLUTION

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Abstract

The living resources of the sea provide a substantial part of the world population with an essential source of animal protein, and the marine environment is a valuable resource for recreational facilities. In some of our estuaries, these resources are endangered at present by marine pollution, which has already limited our harvest of sea food in polluted estuaries. The remaining areas of the sea suitable for marine life must be protected from additional pollution if we are to maintain and increase our harvest of protein from the sea and to retain the amenities of the marine waters for recreational purposes. Critical marine pollutants are identified, and various methods of assessing the impact of these pollutants on marine life are discussed. Although additional research is needed before we can make absolute recommendations for acceptable levels of pollutants in the marine environment, it is also emphasized that we already know enough to recommend limits which appear, on the basis of present available knowledge, to provide assurance of minimal risk of damage to the marine environment. Some examples of these acceptable limiting concentrations are presented.

Introduction

The marine environment is subjected to many conflicting demands and uses, some of which are not compatible with others. Historically, the estuaries and harbors were selected for early settlement because of the ease of marine transportation of goods and materials. Even today, our densest centers of population are located either on the sea or in locations where ready access to the sea is available. Today, more than 50% of the population of the United States live in countries bordering the seacoast or the Great Lakes, and the concentration of population in these areas will probably increase in the future. Similar concentrations of coastal populations are found throughout the world. Concomitant with the growth of these coastal populations and for similar reasons, has been the concentration of industries along our seacoast. Thus, the marine environment has been subjected for generations to intensive population pressures and the demands of our ever-increasing technology.

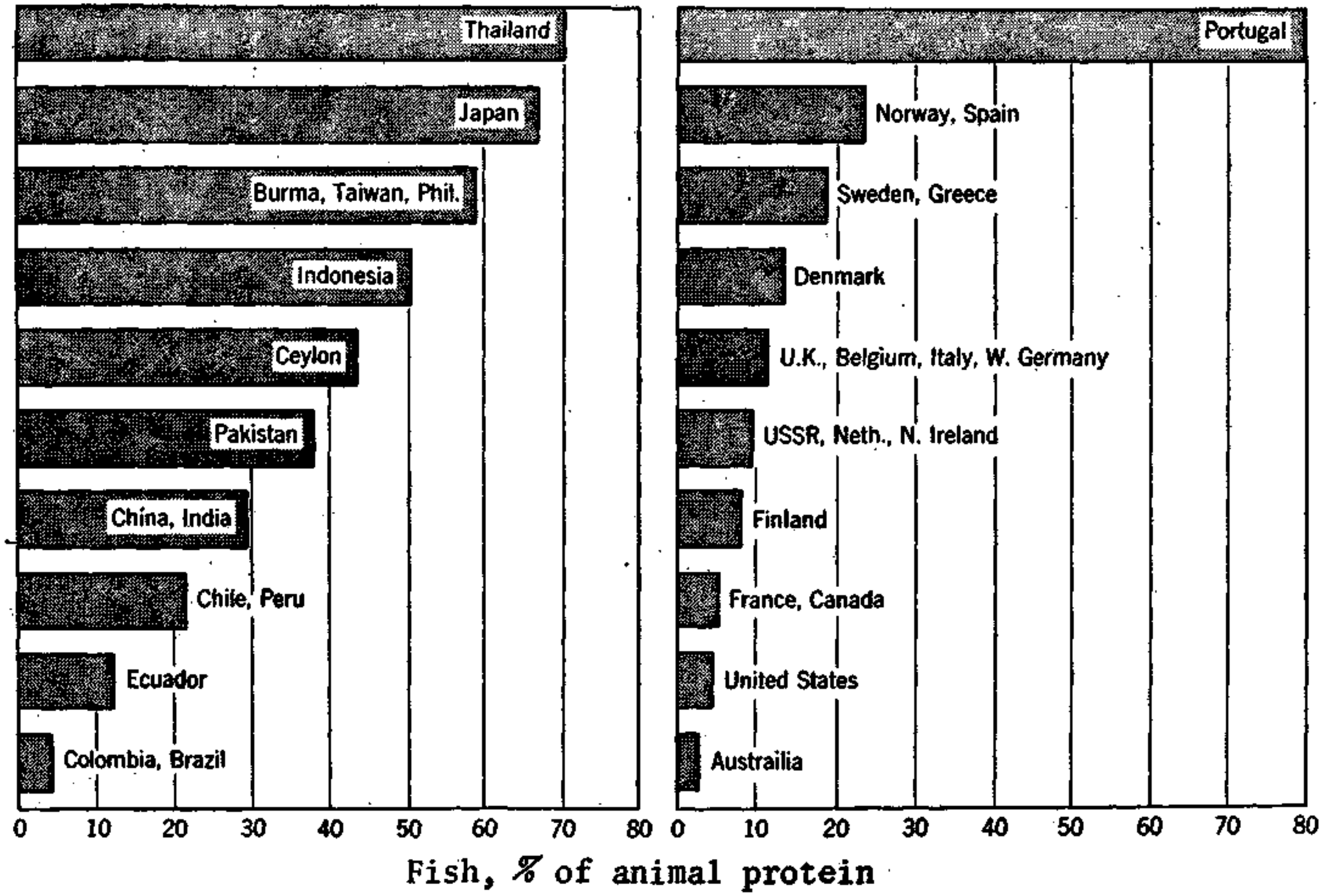

Fig. 1. The value of fish in the nutrition of people in various nations of the world. (After Borgstrom, 1961; Ketchum, 1967)

These combined pressures have led to activities which have greatly modified the marine environment in many places, although some parts of our seashore are still relatively unaffected by man's activities. Harbor development has required extensive dredging and the construction of breakwaters and other structures to protect the shipping. The demand for coastal land and docking space has led to the filling of large areas of salt marsh and wetlands. The waste products of dense populations and of industries have been discharged into these waters with little understanding or appreciation of the possible effects. All of these activities have had impacts on the environment and have produced stresses on the marine ecosystem. So long as the receiving capacity of the body of water is not exceeded, the ecosystem is able to recover from these additional stresses without permanent damage. Today, however, in the most densely populated parts of this country and the entire world, the stresses resulting from man's activity have increased to the point where the marine ecosystem is not able to absorb them without damage, and we now realize that man's mode of action must be drastically changed if we are to retain a marine ecosystem of value to man.

The necessity of maintaining the marine ecosystem in a desirable condition is emphasized by two facts: 1) the animal protein derived from marine products is of great importance in maintaining adequate nutrition for many of the densely populated, developing countries of the world and, 2) the increasing demands for adequate recreational opportunities in aquatic environments supports one of the fastest growing industries in the United States' economy and that of other developed nations. Water of high quality is essential both for recreation and for the survival of the majority of the marine organisms of economic importance.

The annual world harvest of sea food is now nearly 60 million metric tons, (FAO, 1968) and this supplies more than half of the animal protein for about half of the population of the world. The importance of sea food in the nutrition of inhabitants of various nations is illustrated in Figure 1. (Borgstrom, 1961; Ketchum, 1967). Schaefer and Alverson (1968) estimated that the rate of harvest could increase four fold as a result of more effective utilization of all of the fish caught and the discovery of new fish stocks not now being exploited. Ryther (1969) is less optimistic and states that the harvest might double, but that further increases, except by intensive aquaculture, are unlikely. Neither of these estimates takes account of potential damage to the fisheries by increasing pollution impacts, though the deleterious effects of pollution are already obvious in most of the world estuaries.

The value of the marine environment for recreation is also high. It has been estimated by Winslow and Bigler (1969) that, in the United States alone, about 112 million people spent about $ 14 billion dollars seeking recreation in the coastal zone. Using the multiplier suggested by Goldberg (1972, p. 271) the world value for recreation may be about triple this amount. Clearly, maintaining the quality of marine waters is economically essential, both as a source for food and for recreation.

To give perspective to the problems of global marine pollution, a conceptual framework for water quality evaluation is presented in Figure 2. The imports to the marine ecosystem and the exports from it are important to an understanding of the entire problem (Goldberg, 1972). A toxic chemical which is produced in large amounts, reaches the sea and persists for long periods of time in the marine environment, will have a vastly different impact than a chemical of equivalent toxicity which is produced in relatively small amounts and/or decays rapidly in the marine system. For the former type of pollutant, a screening mechanism should be available which could confine it to the source and not permit it to reach the environment, after which man loses most or all of his ability to control the impact of the pollutant.

Examples of the persistent pollutants which have been known to reach the sea in substantial amounts are the toxic elements, mercury, nickel, zinc, lead, manganese, copper, chromium, selenium, silver, arsenic and cadmium. These elements are listed in the approximate order of their deleterious effects as a function of their toxicity and the rate of mobilization by man and by natural weathering as shown in Table 1. Data from Bertine and Goldberg (1971) on the rates of mobilization by combustion of fossil fuels and by the present-day

TABLE 1. *Toxic elements of critical importance in marine pollution based on potential supply and toxicity*

Element	Rate of Mobilization (10^9g/yr)* A (man) Fossil Fuels	B (natural) River Flow	C Total	Toxicity† D mg/l	Relative Critical Index (10^{12} liters/yr.) A/D	C/D
Mercury	1.6	2.5	4.1	10^{-4}	16,000	41,000
Nickel	3.7	160.0	164.0	2×10^{-3}	1,350	82,000
Zinc	7.0	720.0	727.0	2×10^{-2}	350	36,350
Lead	3.6	110.0	113.6	1×10^{-2}	360	11,360
Manganese	7.0	250.0	257.0	2×10^{-2}	350	12,850
Copper	2.1	250.0	252.1	1×10^{-2}	210	25,210
Chromium	1.5	200.0	201.5	1×10^{-2}	150	20,150
Selenium	0.45	7.2	7.7	5×10^{-3}	90	1,540
Silver	0.07	11.0	11.1	1×10^{-3}	70	11,100
Arsenic	0.7	72.0	72.7	1×10^{-2}	70	7,270
Cadmium	0.002	0.5	0.5	2×10^{-4}	10	2,510

* After Bertine and Goldberg (1971)

† Water Quality Criteria: Concentration considered to pose minimal risk of deleterious effect except for mercury which is the concentration found in sea water and has already produced deleterious effects. After Waldichuk (1972), NAS (in press).

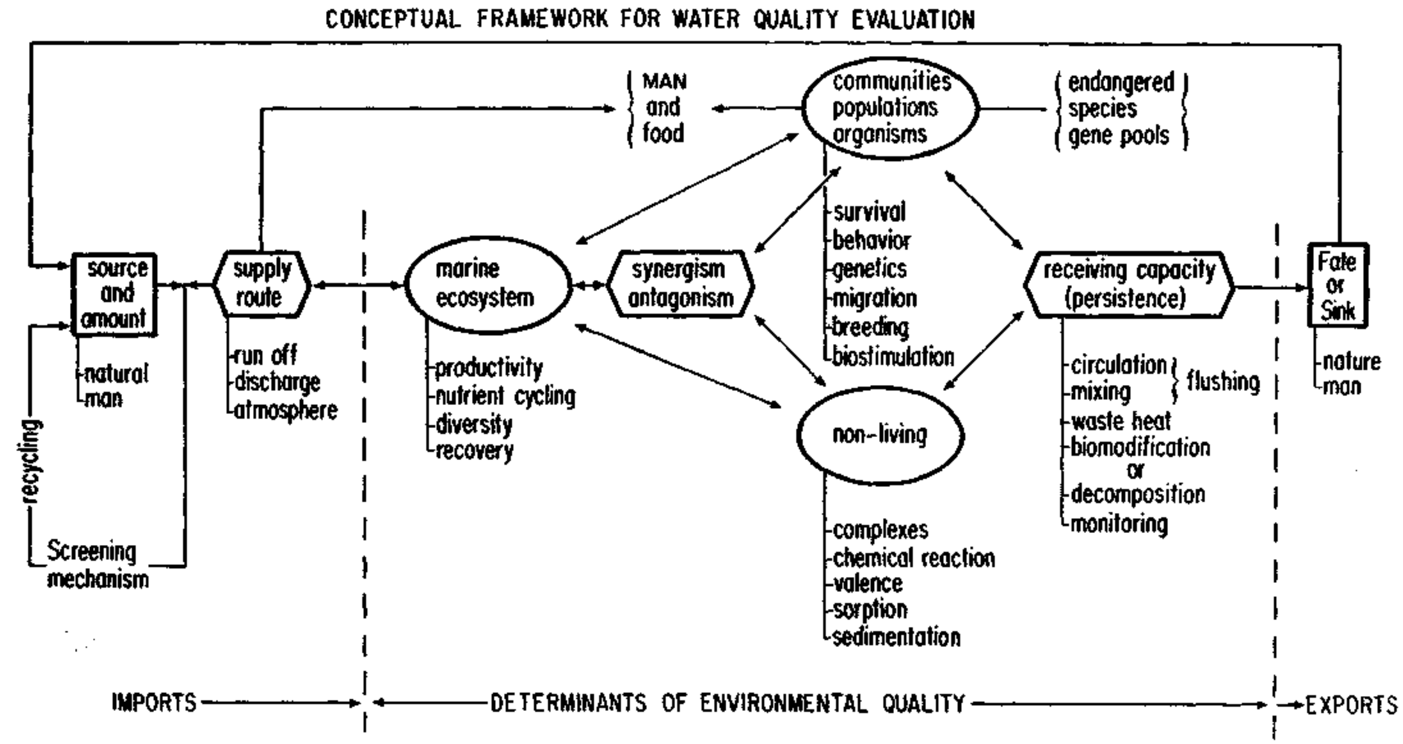

Fig. 2. Conceptual framework for water quality evaluation, showing the various parts of the ecosystem and processes which determine the importance of pollutants in the marine environment.

transport of the element to the sea in river flow are combined with data from Waldichuk (1972, NAS, In Press) on the comparative toxicities. Combined, these data produce an index of how critical the element may be as a marine pollutant. The supply from the combustion of fossil fuels provides a significant part of these materials carried by the atmosphere to the sea. The river transport is based upon analyses of dissolved material in river waters and known rates of flow, and reflects natural weathering, agricultural runoff and pollution sources. There are unquestionably other sources of supply for these elements, but the data used, although uncertain on a global scale, are adequate to rate the relative hazards.

Actually, this index gives the volume of water which would receive an annual increment of the element equal to the concentration shown in Column D (toxicity) at the given rates of mobilization. The unit, 10^{12} liters/yrs., is equal to a cubic kilometer per year. Thousands of cubic kilometers of ocean water are being seriously contaminated by these elements annually. Most of the input is natural geochemical cycling, but for the elements listed, man's contribution is also significant. Since the total water volume of the oceans is about 1.4×10^{21} liters, the time to raise the concentration of the whole ocean to toxic levels could also be calculated giving times, in each case, of many thousands of years. This is really a meaningless computation, however, because the oceans are not uniformly mixed, and the concentration at the locality where the pollutant is introduced will invariably increase more rapidly than the average for the whole ocean.

A wide variety of synthetic organic chemicals are also reaching the environment, particularly the chlorinated hydrocarbons such as DDT and its decomposition products and polychlorinated biphenyls (PCB's). These are not readily biodegradable, and the ocean is the ultimate sink for such compounds. Woodwell *et al.* (1971) have modelled the circulation of DDT in the biosphere and they conclude that the largest reservoir for DDT is in the atmosphere, but also that the amount not decomposed by ultravilot rays in the troposphere will ultimately be added to the surface of the sea. If production of DDT stops in 1974 the model predicts maximum concentrations in the mixed layer of the sea (upper 100 meters) in 1971 after which it would decrease to 10 percent of the maximum by 1993. If production were to increase, however, the concentrations in both the sea and the atmosphere would also increase.

Harvey *et al.* (1972) found substantial concentrations of DDT and its breakdown product, DDE (up to 100 μg/kg wet wt. in a shark) and even higher levels of PCB's (up to 1056 μg/kg wet weight in a dolphin) in a variety of organisms collected from the open sea many miles from land, confirming the probability of atmospheric transport. As expected, these compounds are concentrated in the lipid pool of the organisms with a maximum concentration of 3300 for DDT and DDE and of 21,100 μg/kg lipid for PCB's. None of the concentrations observed by Harvey *et al.* (1972) were as great as those assumed by Woodwell *et al.* (1971) for oceanic fish or plankton to estimate the accumulation in the biota (assuming dry weight to be 25% of wet weight). If further evidence confirms this difference, the residence time in the surface ocean waters might need to be modified in the latters' model.

A variety of synthetic organic chemicals, including other pesticides, detergents and pharmaceuticals are also undoubtedly reaching the marine environment with impacts which are virtually unknown. The detrimental effect of DDT on bird breeding potential is well documented and some experiments have been done on a few forms of marine life, but the information is still inadequate for a complete evaluation of the impact on the marine biota of DDT and even less adequate for the other synthetic organic compounds (SCEP Task Force, 1971; NAS, 1971; NAS, in press).

Petroleum, including crude oil, refined products and petrochemicals are also reaching the sea in large amounts. Numerous studies on the toxicity and effects of oil pollution have been made, but more careful studies of selected fractions of this complex mixture of hydrocarbons are needed and virtually nothing is known about the rate or turnover of this material in the marine environment (Revelle *et al.*, 1971). A number of scientific studies are needed for each of the pollutants listed above in order to evaluate adequately the "determinants of environmental quality" shown in Figure 2.

Biological Effects of Pollution

A marine pollutant may have subtle indirect effects on the ecosystem, which may be the result of a more direct effect on a certain species or group of species essential to the ecosystem (Fig. 2). The indirect effects may not be predictable from studies of individual parts of the ecosystem, and a change in the characteristics of the ecosystem may be an early warning indicator of deleterious effects. Laboratory micro-ecosystems, and experiments in ponds or tanks which include several components of the ecosystem can be useful in extending bioassays to longer time scales. Knowledge of ecosystem processes is necessary as a foundation for ecosystem models, which are valuable in defining critical studies or observations (Odum, 1971).

Ecosystem Analysis

The marine ecosystem includes all of the biological, chemical, geological and physical components of the environment and their highly complex interactions. The impact of water quality on the total ecosystem may be greater than the sum of the impacts on individual parts of the system. For example, eliminating or decreasing the abundance of an organism or life stage which is essential as food for another organism might disturb the entire pattern of energy flow throughout the system. It is essential to understand the interrelationships among organisms and between organisms and their environment in order to evaluate these subtle and secondary effects.

Studies of ecosystems must also include the imports to and exports from it. In the marine environment, imports and exports continually occur from coastal runoff, tidal action, oceanic currents, atmospheric fallout and exchanges with adjacent water bodies and with the benthos or the atmosphere. Each local environment is somewhat different from all others but the species inhabiting any given environment have evolved over long periods of time and each individual species in a community plays its own role. Any additional stress, whether natural or man-made, will tend to eliminate some species, leaving only the more resistant and tolerant forms to survive. Stresses which are transient may permit replenishment of the species by recruitment from adjacent unaffected areas. In such a case the impact may be reversible and the ecosystem can reestablish itself. A change which is chronic and permanent, such as the excessive pollution of some of our harbors, will never permit the recovery of the original ecosystem until the source of unusual stress is removed. Although the effects of water quality on the marine ecosystem are difficult to establish and evaluate, methods are now available which makes the interpretation of ecosystem studies much more meaningful than it was a few years ago.

In order to assess the impact of any new pollutant on a body of water, it is necessary to acquire information on the conditions existing before, during and after the addition. Information on the physical and chemical characteristics of the system, on the distribution and abundance of species, and on the normal variations of these characteristics over at least an annual cycle will be necessary. Evaluations of productivity, nutrient cycling, diversity and recovery potential should be emphasized.

Productivity and energy flow

The productivity of marine ecosystems varies from place to place and from time to time depending upon a variety of environmental factors including the availability of essential plant nutrients, the clarity of the water, and consequently the depth of penetration of sunlight of adequate intensity to permit photosynthesis, the stability of the water column, and the import and export of various materials into the system (Ryther, 1963). Methods for the study of primary production or photosynthesis, particularly of the planktonic populations, depend either upon the use of Carbon 14 and its assimilation by the plant in the production of new organic material (Steeman Nielsen, 1952) or by the evolution of oxygen in the process of photosynthesis (Riley *et al.*, 1949). The radiocarbon technique in polluted estuaries requires certain modifications (see Qasim *et al.*, 1969). Similar methods can be used in evaluating the productivity of the sedentary plant populations in shallow waters. It should be emphasized, however, that a high rate of productivity is not necessarily an indication that the ecosystem is healthy. The statement that Lake Erie is "dead" is biologically absurd since it is the most productive of the Great Lakes. It is not, however, necessarily a healthy ecosystem, since the species produced in Lake Erie today are not the ones most desirable for man's use (Hubschman, 1971; Beeton, 1969).

Nutrient cycling

The marine ecosystem provides a natural mechanism for the recycling of those elements which are essential for photosynthesis and growth of both plants and animals. Unlike energy, which follows a one-way path from its fixation in photosynthesis to its ultimate dissipation as heat regardless of the number of transfers through the foodweb, nutrients are returned to the system as a result of decomposition and can be used over and over again (Ketchum and Corwin, 1965). The productivity of the marine ecosystem is frequently limited by the lack of nutrients which are commonly reduced to very low concentrations in the illuminated part of the water column. Various types of pollution, such as domestic or food processing wastes, enrich the waters with nutrients and when present in excessive amounts can result in the replacement of the normal phytoplankton population with noxious species and change the entire biotic structure of the marine ecosystem in the process known as "cultural eutrophication" (NAS, 1969).

We need to develop more precise methods to evaluate the mechanisms and efficiency of nutrient recycling under a variety of marine conditions. In the shallow, inshore waters and estuaries the exchange of nutrients with the bottom sediments is an important part of this process (Sankaranarayanan and Qasim, 1969), though in the waters with depths greater than 100 or 200 meters, most of the organic material formed in the illuminated surface layers decomposes before reaching the bottom (Menzel and Ryther, 1970; Ketchum and Corwin, 1965).

The efficiency of the nutrient cycling system and the concentrations of nutrients which produce objectionable growths in the water require further and intensive study under a wide variety of marine environmental conditions.

Diversity

A wide variety of indices have been developed to evaluate the diversity of ecosystems (Sanders, 1968, 1969; Slobodkin and Sanders, 1969). These all relate the number of different species with the total abundance of organisms. In general the ecosystems with high diversity are also the most stable, in part because there are large numbers of pathways for the transfer of food and energy from one part of the system to another. Even natural and undisturbed ecosystems have, however, different degrees of diversity depending upon the natural stresses on the system. High diversity is generally associated with minimum stress such as is found in the tropics, where the annual cycle of change is small, or in the deep sea where it is continuously cold and dark. Low diversity is generally found in strongly stressed ecosystems such as the Arctic, where seasonal changes are severe, or in estuaries where the ebb and flow of the tide and fluctuating river flow produce severe stresses on time scales ranging from hourly to seasonally. Consequently, before diversity can be used as an indicator of change, the natural diversity of the environment being studied must be known.

Pollution, or any other man-made modification of the environment, can be considered as an additional stress imposed on the ecosystem and will tend to eliminate some species, leaving only the more resistant and tolerant forms to survive. The diversity will tend to be decreased by this additional stress, even under situations where the total productivity is increased. When the natural diversity of the system is known, the disappearance of sensitive species and the consequent decrease in diversity may be the first indication of impending deterioration of the environment. We need to study the diversity of a wide variety of marine ecosystems and learn to interpret changes in diversity as indicators of overall water quality.

Recovery of ecosystems

Very little is known about the ability of ecosystems to recover if the stresses imposed by man are modified or removed. Some man-made modifications are irreversible. A salt marsh which is filled, paved over and built upon or which is dredged for a navigation channel cannot be expected to return to its original condition. There is clear evidence, however, that the removal of sources of pollution, either by improved treatment processes or by transferring the pollutant to a water mass of greater receiving capacity can permit recovery (Edmondson, 1969 and 1970). This is especially true if the original species can be recruited from nearby unmodified areas. Much remains to be learned about the potential for deliberate restocking of a cleaned-up water body with imported species. For anadromous species, such as salmon which return to their birthplace to spawn, intentional restocking may be the only way to re-establish the population in the ecosystem.

When pollution has continued for many years, the sediments may form a large reservoir and may take years to recover. However, for pollutants which remain in solution, and are not changed by biological, chemical or geological processes, the recovery time will be a function of the flushing time of the system (see Fig. 2). The rates of exchange, which determine the flushing time (Ketchum, 1955), need both fundamental studies to improve our understanding of the mechanisms and application to many local situations which have not yet been investigated.

Effects on Communities, Population and Organisms

Knowledge of and an ability to work with organisms, populations, and communities which make up the living part of the marine ecosystem is fundamental to the understanding of the system and the effects of potential pollutants on the system. The biological effects of pollution may be reflected by acute toxicity to individual organisms or by chronic, sub-lethal effects on the survival of populations through modification of behavior, genetics, migration or breeding potential. Some pollutants may stimulate or accelerate biological processes, for example, fertilizers can increase the rate of photosynthesis and increased temperatures can accelerate the rate of respiration. These effects can modify the functioning of the ecosystem, but cannot be evaluated directly without full evaluation of the impact on the system.

Acute toxicity

The acute toxicity of a pollutant is generally evaluated by means of a bioassay test on a selected organism. These tests determine the concentration of a substance which will kill one half of a population of test organisms within a given period of time, usually 48 or 96 hours. The results are reported as the lethal concentration for 50% of the test organisms (LC50), or median tolerance limit (TLm or TL50). The bioassay may be a static test, in which the organism is exposed to the test solution in a tank, or a flow-through system in which the test solution is continuously renewed. Both may determine sub-lethal effects as well as mortality. Methods for routine bioassays are described in standard methods for the examination of water and waste water (APHA, 1971) and their application is evaluated by Sprague (1971). Clearly, the LC50 is not a "safe" concentration and water quality criteria are set at a fraction (application factors of 0.1, 0.01 or less) of the L C 50.

Because organisms, and life stages of organisms, may vary considerably in their resistance to a given toxic substance the selection of the least tolerant life stage or organism is critical to the sensitivity and validity of the test. Research is needed to develop more effective bioassay methods for potential toxicants. The most sensitive marine organisms should be identified and cultivated on an egg-to-egg basis under laboratory conditions to provide genetic variability information on the test species and to form a basis for intercomparison of experiments and results.

Equipment and methods are needed for the collection, isolation, and production of all life stages of important aquatic organisms so that they may be available at all times in sufficient numbers for bioassay studies. The effects of organic and inorganic pollutants on marine organisms should be investigated with controlled variation of environmental conditions, including salinity, temperature, dissolved oxygen, and pressure.

An advantage of bioassays which duplicate existing conditions of the area being studied is that they measure the effect of the substance including the valence state and natural complexing with materials in sea water, and synergistic or antagonistic effects (cf Fig. 2). Thus, the total effect can be estimated without a clear understanding of all mechanisms involved. This does not, however, obviate the need for such an understanding because only with firm knowledge of the mechanisms involved can transfer of information to other systems and prediction of effects be achieved. Application factors relating acute toxicity data (bioassays) to long-term effects must be developed in order to define more precisely tolerable environmental levels.

Chronic, sub-lethal effects

Many biological effects of pollution may not show up in the bioassay test for acute toxicity. This would be true if the effect were slow to develop or if the effect were to produce a general debility which might interfere with some of the normal life functions of the organism rather than killing it directly. Long-term exposures to sub-lethal concentrations may be necessary to produce the effect, and evaluation of this type of action is difficult in a laboratory analysis. Long-term exposures to sub-lethal concentrations may produce effects on migration, behaviour, incidence of disease, life cycle, physiological processes, nutrition or food chains, or genetics which are not revealed in tests shorter than complete life cycles or number of generations. Unfortunately, little is known about these chronic, sub-lethal effects. Behavioural scientists should be encouraged to seek methods for evaluating the effect of pollutants on activities of marine organisms and to identify low levels of pollutants which may have undetectable short-term effects. Long-term studies on sensitive life stages of organisms should be undertaken to provide a basis for application factors.

a. *Migrations*

Sub-lethal concentrations may interfere with the normal migration patterns of organisms. The mechanisms used for orientation and navigation by migrating organisms, though extensively studied, are still not well understood (Hasler, 1966; Bardach and Todd, 1970). In some cases chemotaxis plays an important role. Salmon and many other anadromous fishes have been excluded from their home streams by pollution though it is not always known whether the reason is that a chemical cue has been masked or because the general polluted environment is offensive to the fish.

b. *Behaviour*

Much of the day-to-day behaviour of species may also be mediated by means of chemotactic responses (Bardach and Todd, 1970). The finding and capture of food, or the finding of a mate during the breeding season would be included in this category of activity. Again, any pollutant which interfered with the chemoreceptors of the organism would interfere with behavioural patterns which are essential to the survival of the population.

c. *Incidence of disease*

Long-term exposure to sub-lethal concentrations of pollutants may make an organism more susceptible to a disease. It is also possible that some pollutants which are organic in nature may provide an environment suitable for the development of disease-producing bacteria or viruses. In such cases, even though the pollutant is not directly toxic to the adult organism it could still have a profound effect on the population of the species over a longer period of time.

d. *Life cycle*

The larval forms of many species of organisms are much more sensitive to pollution than are the adults which are commonly used in the bioassay. In many aquatic species millions of eggs are produced and fertilized, but only two of the larvae produced need to grow to maturity and breed in order to maintain the standing stock of the species. For these species the pre-adult mortality is enormous even under the best of natural conditions. Because of an additional stress on the developing organisms enough individuals might fail to survive to maintain the population. Interrupting any stage of the life cycle can be as disastrous for the population as would death of the adults because of acute toxicity.

e. *Physiological processes*

Interference with various physiological processes, without necessarily causing death in a bioassay test, may also interfere with the survival of a species. If photosynthesis of the phytoplankton is inhibited, algal growth will be decreased and the population may be grazed to extinction without being directly killed by the toxic. DDT has been shown by Wurster (1968) to depress photosynthesis in planktonic algae, but only at concentrations greater than its solubility in water (about 1 ppb). Menzel. *et al.* (1968) demonstrated that different phytoplankton species showed various responses to DDT, dieldren and endrin ranging from no effect to toxicity at concentrations of 0.1 to 1 ppb.

Respiration might also be adversely affected as could various other enzymatic processes by sub-lethal concentrations of pollutants. The effect of DDT and its decomposition products on the shells of bird eggs is probably the result of interference with enzyme systems. Mercury is a general protoplasmic poison but has its most damaging effect on the nervous system. In humans this is known to be serious; how it affects fish and other aquatic organisms in sub-lethal concentrations is still unknown.

f. *Nutrition and food chains*

Pollutants may interfere with the nutrition of organisms by affecting the ability of an organism to find its prey, by interfering with digestion or assimilation of food, or by contaminating the prey species so that it is not accepted by the predator. On the other hand, if predator species are eliminated by pollution the prey species may have an improved chance of survival. An example of the latter effect was shown for the Kelp resurgence after the oil spill in Tampico Bay, California (North, 1967). The oil killed the sea urchins which used young, newly developing Kelp as food. When the urchins were killed, the Kelp beds developed luxurious growth within a few months.

g. *Genetic effects*

Many pollutants produce genetic effects which can have long-range significance for the survival of species. Radio-active contamination can cause mutations directly by the action of radiation on the genetic material. Also oil and other organic pollutants may include both mutagenic and carcinogenic compounds (Blumer, 1970). From genetic studies in general it is known that a large majority of mutations are detrimental to the survival of the young, and many are lethal. Little is known about the intensity or frequency of genetic or developmental effects of pollutants, except for radioactive materials (Donaldson and Foster, 1957). The doses required for serious damage greatly exceed the radioactivity present as pollution in the marine environment (NAS, 1971).

h. *Food value for human use*

Sub-lethal concentrations of pollutants can so taint sea food that it becomes useless as a source of food. Oil can be ingested by marine organisms, pass through the wall of the gut and accumulate in the lipid pool. Blumer (1969, and 1970) states that oil in the tissues of shellfish has been shown to persist for several months after an oil spill in Wets Falmouth, Mass. The polluted area was closed for shellfishing for a period of 18 months. Sea food may be rendered unfit for human consumption because of the accumulation of pollutants. California mackerel and Coho salmon from Lake Michigan were condemned because they contained more DDT than the permissible amount in human food (5 ppm,. Likewise tunafish and swordfish were removed from the market because the mercury content of the flesh exceeded the allowable concentration (0.5 ppm). There was no evidence that these concentrations had any adverse effect on the fish, but their removal from the market has adversely affected the economics of the fisheries.

Sub-lethal effects on chemotactic responses, reproductive efficiency, survival, growth, vigor, behaviour, and general activity should be studied. A debilitation index developed from this type of research could provide indications of incipient toxicity. Studies of metabolic rates under multifactorial combinations of various environmental components in the presence of pollutants are needed.

NON-LIVING COMPONENTS OF THE MARINE ECOSYSTEM

The aqueous chemistry, biochemistry, and geochemistry of substances within the marine system control the form of substances available to react with and affect marine organisms. Relatively little is known about the reactions of substances in sea water, the dynamics and equilibria involved or the rates. There is a need to understand the natural chemical system of sea water and the interaction of man introduced substances with the system. Of particular concern are the role of synthetic organics in complexing inorganics, the role of surface films in water-atmosphere exchanges, and the residence times of organic and inorganic constituents.

Because of the presence of a large number of salts in sea water of various concentrations, it can be expected that in some cases there may be an antagonistic effect and, in some cases, synergism with respect to certain inorganic constituents in sea water. This should be carefully studied on species that are extremely sensitive to small changes in pollutant concentrations. The effects of sea water on the synergistic and antagonistic aspects of inorganic chemicals in the marine environment need further study. When heavy metals are present in combination in effluents, synergism or antagonism can be expected. A series of combinations and permutations should be tested under different conditions in both fresh water and sea water to understand more fully the mechanisms involved.

Many inorganic chemicals exhibit different degrees of toxicity when they are present in different valence (oxidation) states. There may be some logical order, according to the periodic classification, for toxicity of inorganic constituents, based on atomic number, molecular weight, number of electrons in the outer orbit, etc. Preliminary examination has already shown some measure of consistency with respect to the periodic classification, in acute bioassays.

Different elements vary widely in toxicity according to their chemical form. For example, the methyl mercury form is highly toxic compared to the ionic mercury form (Ui and Kitamura, 1971). There may be other metallo-organic forms of the elements which are highly toxic also, and which we do not recognize at the present time. Organic complexes such as those formed with NTA Nitrilotriacetate) and EDTA (Ethylene diamine tetraacetic acid) appear to be relatively harmless and tend to detoxify the heavy metals. However, there have been shown to be some side effects at high concentrations of NTA complexes and these should be further investigated. The complexing and dispersion of inorganic constituents by various organic materials in water, both natural and introduced, must be more fully examined.

We require more sensitive methods of chemical analysis for the detection and measurement of both inorganic and organic constituents in water and organisms. This particularly applies to sea water where there is a great deal of interference from the numerous elements and compounds present. Identifying effects of concentrations of substances in aquatic organisms have been hampered by the lack of adequate methods of detection of the particular material in the water or organism. Recognition of the importance of various pollutants in the sea has followed improved methods of analysis. This is particularly true of mercury and DDT. Improved methods of chemical analysis for many organic and inorganic chemicals are needed. Intercalibration or comparison of results obtained by investigators in different laboratories or using different methods is essential.

The Assimilative Capacity of Marine Systems

We need to learn more about the receiving capacity of various marine areas in order to evaluate the amount of waste materials which can be introduced without exceeding the concentration recommended for water quality criteria. The receiving capacity of a system is determined both by the physical processes of circulation and mixing and by the biological and geological processes which modify, decompose or remove the pollutant from the system. Fundamental studies of these processes are needed to develop the methodology which can be applied to a variety of locations. Each location, however, will have some unique characteristics so that local conditions and the processes operating there which determine the fate, concentration and distribution of a pollutant must be studied in order to assure that a proposed rate of disposal will not exceed levels harmful to the ecosystem.

Flushing times

A conservative pollutant is, by definition, one which is not modified by biological, chemical or geological processes. If such a pollutant remains dissolved or suspended in the water column its distribution in the marine system is determined by the same circulation and mixing processes which determine the distribution of salt or river water (Ketchum, 1955). The average retention time or the half life of the material in the system can be used to estimate the average concentration which the pollutant will achieve in the system if it is added continuously at a uniform rate. If the disposal is stopped, the rate of removal from the system can be evaluated if the rates of circulation and mixing are known. The faster the flushing time of a system the greater the receiving capacity of the system will be without exceeding unsatisfactory levels of concentration. Also the recovery from a stress imposed by a pollutant will be more rapid if the circulation and mixing provide a rapid flushing.

Estimates have been made of the rate of flushing of numerous estuaries (see Wyatt and Qasim, 1973 for Cochin Backwater), but additional fundamental studies are needed in order to improve our capability to predict and evaluate the flushing rate of a variety of systems. The methods developed in these fundamental studies can be applied to different systems, but always with the caveat that the model selected must be validated for each system in order to assure that it is applicable.

Waste heat

Disposal of waste heat from power plants requires accurate knowledge of the volume of water available for dilution which is a function of the circulation and mixing of the water column which determine the rate of flushing. It is a special case because the warm water modifies the circulation and mixing. The density of heated water is less than that of the receiving body of water so that it tends to accumulate at the surface. Heat is not a conservative property since it is dissipated to the atmosphere at a rate which depends upon both the gradient of temperature in the water column and the difference between the temperatures of the heated water and the atmosphere. Better methods are needed to predict the fate and extent of warm water plumes as a function of the permissible temperature increase. Information is needed concerning the rate at which the heat is dissipated to the atmosphere under a variety of conditions.

Biological, chemical and geological modifications

A non-conservative pollutant is, by definition, one that changes with time by processes which are additional to circulation and dilution. Pollutants may be decomposed biologically or chemically or they may be precipitated or sorbed onto particulate matter and sedimented to the bottom deposits. The half life of non-conservative materials in the environment is the product of these processes and the processes of circulation and mixing. The materials of greatest concern as pollutants in the marine environment are those which are most stable and persistent in the environment, such as the toxic heavy metals which can be removed from the water column only by accumulation in the biota or by sedimentation, and the stable chlorinated hydrocarbons which are only decomposed slowly with the production of by-products which may be as toxic as the original. Petroleum hydrocarbons are intermediate in their persistence in the marine environment but, again, the products of decomposition may be more toxic than the original oil from which they are derived. Organic materials which are similar to those which are naturally found in the sea, such as domestic sewage and food processing wastes, are decomposed more rapidly, with, however, the release of elements essential for plant nutrition and productivity, leading at high concentrations to eutrophication (Qasim and Sankaranarayanan, 1972). We need to know precisely the rates of modification in order to evaluate the long-term impact of various pollutants on the marine ecosystem. Research is needed on the rates of biological degradation and decomposition, on the chemical reactions which various compounds or elements undergo when introduced into sea water and on the rates of sorption and precipitation to the sediments.

Even when materials are incorporated into the sediments they may not be permanently removed from the water column. Decomposition of organic material within the sediments or exchanges between the sediments and the water column. proceed at rates which are virtually unknown. This is exemplified by our lack of information on the ultimate fate of the sewage sludge which has been dumped off New York Harbor for the past 40 years. Until we know the rate at which this is being modified, decomposed or recycled it is impossible to predict whether this is a safe and acceptable procedure or what quantity of such sewage sludge can safely be disposed in this manner.

Various chemicals can be accumulated by organisms to concentrations within their body several orders of magnitude greater than in the surrounding water. For some materials, DDT for example, the concentration may increase at each succeeding step of the food chain. The extent of bio-accumulation for various pollutants and the effects of transfer from organism to organism will determine or modify the magnitude of the biological effect.

Monitoring And Information Exchange

In attempting to evaluate water quality or pollution problems, both scientists and administrators are often faced with a lack of adequate information. It is generally impossible to extrapolate from information on a few local areas to evaluate the total or global impact of a given activity, and frequently the information available on one area is not readily transferable to another one of different characteristics. A monitoring system and a mechanism for the retrieval and dissemination of monitoring data is needed. However, it is abundantly clear that we cannot monitor for all possible pollutants in all possible places so that careful thought has to be given to the design of the system. Any effective monitoring system must satisfy at least the following objectives:

a. To establish present-day baselines
b. To detect and evaluate trends of change
c. To give advance warning of approaching critical conditions
d. To detect accidental critical events
e. To provide an adequate system for data storage retrieval and dissemination

Various international groups such as GESAMP (Joint Group of Experts on the Scientific Aspects of Marine Pollution), GIPME (Global Investigation of Pollution in the Marine Environment) and SCOPE (Scientific Committee on Problems of the Environment) are considering the details of monitoring the global environment for pollution. To insure that such a monitoring system is effective it will be necessary to select the critical materials which should be monitored in the marine environment and the critical locations where the measurements should be made. Research for these purposes should include studies of the necessary frequency, both in space and time, required to give significant information adequate to achieve the objectives listed above for a monitoring system. Standard methods of analysis, or at least intercomparison and intercalibration of the results will also be needed. Chemical, physical, and biological methods of analysis should all be evaluated in this regard. An adequate information storage and retrieval system will be required so that the critical monitoring data are readily available not only to the scientific community but especially to administrators and the elected officials so that appropriate and justifiable decisions can be based upon the best available information.

Discussion And Conclusions

The disposal of wastes to the marine environment has long been an accepted practice but it has been done without understanding or considering the possible consequences. The sea, however, has a finite assimilative capacity for any given type of pollutant. Locally this capacity of the marine system has already been exceeded in many places. For example, Ketchum (1969) estimated that the Hudson River estuary is now receiving 5 to 10 times more domestic pollution than can be absorbed by the ecosystem within a forty-mile length of the estuary. Beyond this distance, dilution reduces the nutrient concentration to acceptable limits. Some pollutants, such as mercury, are naturally present in sea water at concentrations which have already produced deleterious effects. In other cases, particularly the chlorinated hydrocarbons, the material is not naturally produced and organisms capable of metabolizing them rapidly have not evolved, so that these compounds persist for long periods of time in the environment. In cases such as these, further additions as a result of man's activities should be prohibited. The concept of zero discharge rates for pollutants which can be assimilated by the marine ecosystem, however, is not reasonable, but it is essential to know the assimilative capacity and, by further treatment or diversion, maintain the ambient concentrations within acceptable limits for ecosystem maintenance and survival.

Throughout this paper, the need for additional scientific investigations has been repeatedly emphasized. We should recognize, however, that we already know a great deal about the marine ecosystem and that reasonable models already exist and can be applied in many cases to evaluate discharge rates which will maintain acceptable limits of pollutant concentrations. We can evaluate the impact of many pollutants on living marine resources, and can specify the degree of treatment or type of approach necessary to stay within acceptable limits of water quality (FWPCA, 1968; NAS, in press). Generally the technology is available to permit industrial development while maintaining, at the same time, acceptable environmental conditions. It is abundantly clear, however, that we can no longer continue to be indiscriminate in our actions and that drastic changes will have to be made in man's activities in order to maintain the marine environment in a condition of desirable quality for posterity. To achieve this goal will require the best efforts of scientists and engineers of government officials and industrial leaders and of diplomats and international organizations. Marine pollution is no longer a local problem, or one that can be ignored. It is encouraging that the United Nations Conference on the Human Environment in Stockholm in June 1972 recognized the urgency of marine pollution problems, among others, and recommended cooperation among member states and international action to reverse the trend of deterioration of our environment for the benefit of all mankind.

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