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EFFECTS OF POLLUTANTS ON MARINE ORGANISMS; IMPROVING METHODOLOGY OF EVALUATION—A REVIEW OF THE LITERATURE

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With the passage of new legislation for better control of pollution and improved water quality, the demands for information from water pollution research are increasing overwhelmingly. However, research results now being sought cannot be supplied by traditional water pollution study techniques. It is no longer sufficient to indicate whether a given species of fish will die in waters receiving a given volume of a known type of pollutant. It is no longer sufficient to state merely that dilution will be adequate to maintain dissolved oxygen levels at five mg/l or better. Now, the total aquatic environment must be looked at to determine whether immediate harmful effects will accrue to any or all the aquatic organisms from a certain waste disposal. Also, cumulative effects that eventually might endanger the populations must be studied.

To learn about the nature of these short-term and long-term effects, an integrated approach involving many disciplines must be taken. These facts cannot be learned instantaneously; and time is an important consideration. The effects of the seasons with changing temperatures, precipitation, runoff, and winds must be examined.

This presentation is in the form of

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a literature review with reference, when possible, to studies made at Nanaimo, B. C., which have been devoted largely to the marine environment.

It should be pointed out that most of the biological information documented on pollutional effects has been derived from research on fresh water. Some of the review here is projected into marine environments from strictly freshwater studies. Attention should be directed to a number of reviews of literature on marine pollution (1) (2).

This paper will be subdivided into two basic parts: (a) an exposition of the problems, and (b) a review of some of the advances made in recent years in techniques to solve these problems.

The Problems

Modification of the Marine Environment

Water:—The effect of a pollutant on the water in a given area is dependent on the quantity and physical and chemical characteristics of the pollutant and on the volume, properties, and behavior of the water. A large volume of pollutant entering into a coastal body of water which is very sluggish in movement and has little tidal and wind mixing may cause gross pollution in the water. However, a small quantity of a relatively innocuous pollutant discharged into a coastal channel, which is tide swept and mixed by winds, may be relatively unnoticeable. It is necessary, therefore, to

have a good supply of information on the characteristics of the marine environment to which it is proposed to dispose of a given type of waste. Such information relates to those processes in the sea which determine the rate at which an effluent would be diluted and dispersed. The complexity of these processes becomes apparent when the interaction of tides and winds in mixing and transport of the water is examined.

Reliable data should be available also on the chemical and physical characteristics of the wastes which it is proposed to discharge. The effect of the environment on the pollutant, in the way it partitions, degrades, or re-concentrates must be determined. This often involves painstaking laboratory experiments and field studies.

In general, the waters can be polluted and flushed rapidly following a given period of input of pollutant. Harmful effects of an acute nature can be revealed quickly in coastal waters when highly toxic substances are released. If exchange is relatively fast, the harmful substances also can be diluted and dispersed rapidly.

Bottom:—The bottom of polluted environments is modified much more slowly than the water above it. The bottom sediments acquire pollutional modifications of a long-term nature. By the same token, the modified bottom cannot be restored rapidly to its original condition, short of being dredged by man-made machinery or through some catastrophic disturbances. The bottom materials represent a cumulative effect of pollution that may cause gradual deterioration over a period of many years. A long series of bottom sampling, coring, and sediment trapping is required to understand the changes that occur in the bottom materials.

The Individual Organism

Studies on the individual organism may be carried out *in situ* or in the

laboratory. However, in the field the animal must be maintained in a live box or in some other suitable enclosure where it can be observed under as nearly natural conditions as possible.

Acute Effects:—The highly toxic effects of a pollutant are manifested rather quickly in death or in very obvious distress. In past studies, mortality was the criterion that toxic conditions existed. Standard procedures of bioassay (3) gave a rapid method of evaluation of toxicity of industrial wastes to fish, based on mortality for a given period of exposure. Seldom were autopsies performed to determine the cause of the death.

Sub-Lethal Effects:—The trend in recent years in biological pollution studies has been toward the sub-lethal effects of pollutants, rather than examining only the lethal conditions.

Some of the newer techniques in studying sub-lethal effects are described by Warner *et al.* (4). In the long run, these effects may be as important in modifying a population of fish as outright mortality. For example, the sub-lethal effects of low concentrations of pulpmill wastes on some of the salmon stocks in the Fraser River system often are discussed. The salmon which migrate through the Fraser River system up to the Stuart Lakes area have to cover a distance of 600 miles (960 km) or more, overcoming many obstacles enroute. The vital question might be asked, "What effect does the low concentration of pulpmill effluent, which exists in the river system at the present time, have on the stocks of salmon going up to the Stuart Lakes area?" It is known that during certain critical years the salmon do not get to the headwaters of the Fraser River system because of slides, low-water conditions, and possibly high temperatures. How many more fish may die unspawned during some years because of the pulpmill effluent?

Clinical examinations of distressed fish and of fish killed by lethal con-

centrations of pollutants now are being carried out in many laboratories. There is a dire need for this type of information if the "how" and "why" of mortality occurring to a given stock of fish under a given set of circumstances is to be understood. Medical techniques are finding great application in this aspect of pollution biology.

Communities

It is, perhaps, as important to examine the aquatic communities in the marine environment as it is to examine individuals comprising those communities. The communities may become modified in composition or in size; they may shift their position; or they may disappear entirely. It is the community of organisms that reflects the integrated effect of pollution over a protracted period of time.

The changes in numbers and predominance of species in a given population of organisms are related to the fact that as the conditions become less tolerable for many species, the more resistant ones survive and gradually take over. First applied by Dr. Ruth Patrick in her studies of diatom populations, the concept of diversity of species has been used widely by consultants and control agencies in assessing pollutional effects (5). The concept now is accepted widely as a tool in pollution studies.

Most of the research on aquatic communities to date has been done on the benthos. A study of the sedentary populations comprising the benthos has advantages over investigation of planktonic populations. Beak *et al.* (6) showed how pollutional effects could be monitored in the benthos through the use of bivariate control charts. For such applications, more information is needed on all marine communities. Studies of these communities can be enhanced by the availability of computer techniques.

The Marine Ecosystem

There is a need for more information on the relationship of the marine environment to the aquatic populations. This can be gained only through a multi-disciplinary approach, using all the latest techniques, with a great deal of team work. Changes in the biological balance brought about by the introduction of pollutants can be represented by changes in the energy balance of the system. Such studies have been carried out by a number of investigators in the inshore waters of the Gulf States where pollutants have modified considerably the estuarine environment (7) (8).

The ecosystem approach leads to a large mass of data, which can be processed only through a set of complex equations being solved by computers. While this approach may seem too fundamental for pollution studies, a need exists for such information gathering and processing so that valid predictions can be made on changes that will occur with a given input of pollutant. The state of knowledge on ecosystems to a decade ago has been reviewed by a number of contributors (9) (10) (11) (12) (13) to the Symposium on Perspectives in Marine Biology held at the Scripps Institution of Oceanography in 1956 (14). A more recent review has been published (15) (16) (17).

New Approaches in Observations

Environmental Studies

The importance of environmental aspects of polluted areas has been documented in a number of studies (18), symposia (19), seminars (20), and conferences (21) (22) (23). For many years, rather primitive techniques have been used for sampling both the water and the bottom in both the freshwater and marine environments. The water sampling bottle and the bottom grab are only too familiar to everyone who has worked

in limnology or oceanography. For preliminary, crude descriptions of the environment these techniques were adequate. However, for the more precise type of information taken continuously in space and time, sophistication in equipment has been necessary. Oceanographers have benefited greatly from advances in space technology. Various types of sensing devices and telemetering instruments, now offered on the market, might not have been available otherwise.

Continuous Observations:—It has been found necessary to procure continuous data on various parameters to examine fully the effects of pollution. Changes occur diurnally, under tidal influence, and from day-to-day with changing winds, temperatures, and insolation. There now are available sensors for measuring a host of different parameters, and techniques for determining continuously certain chemical constituents. Sensors have been developed for measuring continuously salinity, temperature, dissolved oxygen, pH, alkalinity, turbidity, color, and chlorophyll. Continuous-flow systems now are being manufactured for the determination of nutrients (silicates, nitrates, nitrites, and phosphates), phenols, spent sulfite liquor, and any other constituents which lend themselves to a colorimetric determination. Data coming from such continuous analysis can be in the form of a digital output or in analog (chart) form. Digital data can be telemetered directly into a computer and processed for a computed output of information. It is understood that a monitoring system adapted in this way in the Duwamish River, near Seattle, has been operating for some years (24).

With solid-state electronics available nowadays, some of the continuous monitoring systems can be adapted to carry out measurements on battery power remote from standard line power. Various thermographs and tide gauges, of course, have been in

operation for some time with simple hand-winding, clock mechanisms allowing them to run for seven days or more at a time without attention.

Buoy techniques developed in recent years have allowed a great deal of information to be gathered *in situ* on currents and temperatures at stations remote from shore. Some of the available current meters are designed to operate for 30 days at a time and have an output punched on tape or recorded on photographic film. Such equipment was used in studies of Departure Bay and Saanich Inlet during the summer of 1968. The current meter output often is made compatible to various types of computer systems and can be analyzed directly.

It might be of interest to know that one of the operations from the Defence Research Establishment Pacific at Esquimalt, which has carried out acoustical studies in the Arctic over the past few years, has had research instrument packages (RIP) mounted on the bottom at a number of Arctic stations. These instruments were left there for a period of a year, and four out of the five were recovered this past summer. Acoustical release devices were used to bring the submerged buoy to the surface. An automatic dye-emission system was used to identify the location from the air. One system which surfaced under the ice was observable because the bright dye showed through the ice. Acoustic records for a year were obtained. Only 1 of the 5 instrument packages was not recovered, and it is anticipated that this package was "rubbed out" by a large iceberg which was estimated to extend to a depth of something like 1,400 ft (425 m).

Continuous observations are necessary if time-series data are to be studied to understand the dynamic processes which occur in the sea. Unfavorable conditions could occur at times when they normally would not be observed by spot measurements. Mis-

leading information could be gained by single observations at atypical times. A long series of data can be used to obtain a valid statistical mean from which deviations can be measured.

Advances in Oceanographic Survey Instrumentation:—Because of the need for a better understanding of the vertical structure of the water, instruments have been designed to give, precisely, profiles of water characteristics with depth. The old bathythermograph which gives the temperature with depth on a smoked glass slide (latterly on a gold-plated slide) is a familiar device. There has been a device to record temperature and salinity continuously with depth since about 1948 (25). But this was not too satisfactory, partly because of lack of precision and partly because it recorded salinity, temperature, and depth on a multi-channel recorder with considerable effort needed to extract the data. The present system is much more accurate and can be lowered readily on an armored electrical cable to 1,500 m. In competition with this American system, there is a Bathysonde made in West Germany. There have been conflicting reports on the reliability of the latter system, although the Bedford Institute in Dartmouth, Nova Scotia, is using one for their oceanographic studies. While improvements still have to be made in the temperature sensor for the American system, it has yielded much useful data.

Presently, a system is being built by the National Research Council of Canada to carry out observations on the wider range of salinities prevailing in inshore coastal waters. A similar system, built as a prototype, already has been tested in the Bedford Institute and appears to offer much for speed and versatility in coastal oceanography.

To satisfy the needs of the Navy for carrying out temperature surveys

without losing a great deal of slow-down time needed in bathythermograph surveys, an expendable device has been developed. This device is launched at speeds up to 30 knots (55 km/hr) and provides temperature data which appear to be at least as good as given by standard equipment. The cost of these expendable probes is still comparatively high, but the instrument is finding acceptance in many oceanographic institutions. An expendable device also has been developed for launching from helicopters, which may find application in projects requiring rapid temperature surveys.

Synoptic Areal Surveys:—Because of the need for rapid surveys in coastal waters to overcome the short-term effects of tides, runoff, and winds, airborne platforms of various types are finding increasing use in such studies. Fixed-winged aircraft and helicopters already have met with much success; and now hovercraft (air-cushion vehicles) are being considered. Aerial photography has provided a synopticity not available previously with the traditional type of oceanographic survey. Black and white aerial photography has been used for studying the movement of clouds of silty water and of various types of targets to measure currents (26). Studies of aquatic vegetation have been carried out by color aerial photography in California (27) (28) (29). Color has provided a new dimension in aerial photography of coastal waters. The trend toward color has been stimulated by photogrammetric engineers using the technique in terrestrial aerial photography (30) (31). The use of dyes for the study of diffusion in surface waters has found a good deal of application among some of the oceanographic institutions, particularly the U. S. Coast and Geodetic Survey (32) and the Chesapeake Bay Institute of The Johns Hopkins University (33). Use of a special filter with black-and-white photography has provided tremendous

sensitivity for recording patches of rhodamine-B dye (34). Analysis of fluorescent dye concentrations with a fluorometer (35) can be used as a check on data from aerial photography.

Aerial photography in oceanography has found a great impetus from the recent photographic probes of satellites. Aerial photographs from the meteorological satellites, ESSA-1 and ESSA-2, as well as from Nimbus, have been used primarily for mapping cloud cover around the earth. However, it is gradually becoming apparent that this type of aerial mapping also may find application in oceanographic studies. Using infrared and color imagery, it has been found possible to delineate certain biological phenomena and temperature variations in marine waters (36).

Infrared photography was used in wartime for detecting camouflage because it can distinguish living plant life. It now is being used for finding patches of algae growing in the water (29). A study on the latter was reported to this Association at its annual meeting last year (37). It appears to have a great deal more potential than recognized so far in marine pollution studies.

Infrared sensors have been used for measuring surface temperatures at sea and on the Great Lakes. While not too accurate ($\pm 0.5^\circ\text{C}$), these air-borne radiation thermometers have been useful in providing broad pictures of temperature distribution along the coast. Infrared scanning has been used to map the surface temperatures of the waters. When the temperature is related to currents, as in the case of the Gulf Stream, the current patterns are revealed clearly. The infrared scanning techniques are shrouded somewhat in military secrecy, but gradually are becoming available to civilian scientific users.

It has been suggested (38) (39) that the property of strong absorption in the ultraviolet, visible, and infrared

parts of the spectrum by gases and vapors emitted by certain substances can be used for detecting materials on the water surface. Iodine vapor was one which showed a very strong absorption and could be detected by an aerial spectrometer. The possibility was expressed for remote detection of fish-oil films and schools of fish associated with them. It was speculated also (38) that vapors from various polluting substances at the air-sea interface might be detected in this way.

The whole subject of aerial remote sensing barely has been touched. There was a symposium of the American Society of Limnology and Oceanography and the Ecological Society of America in June 1968 to report on some of the latest findings in this exciting field. Although aerial techniques have been primarily profitable for studying the surface waters, it has been suggested that mapping and identification of aquatic vegetation and bottom sediments of shallow waters might be possible (28). Aerial photographic studies of shallow water benthic conditions already have been reported (40).

Bottom Surveys:—Studies of the bottom materials can include the traditional techniques employed in marine geology. There is a need for information on the character of recent sediments as obtained with bottom grabs, dredges, and piston corers. Sample analysis can be tedious and the proper classification of data onerous. As in other compilations of voluminous environmental data, attempts are being made to record the data on cards for rapid computer sorting and analysis (41).

Bottom photography to record the surficial character of the sediments now is standard practice. Underwater closed-circuit television often is used to explore phenomena at great depths. The growth of SCUBA diving as a popular sport has been a stimulus to marine geologists who want to study shallow, marine areas *in situ*. Now

submersibles are coming into their own. During the Arctic expedition, mentioned earlier, the Canadian submersible, PISCES I, was used successfully in geological surveys and for collecting biological specimens which would have been impossible to procure otherwise.

In addition to the above techniques, it is necessary to study the dynamic processes present in the sediments. The changes in bottom characteristics caused by pollutants can be determined by periodic bottom sampling surveys. The sedimentary materials added by pollutants can be monitored with traps set on the bottom to collect sediments during weekly or monthly periods (42) (43). It also is necessary to determine the changes in dissolved oxygen, in the sediments, and in the overlying water caused by decomposition (44). Associated with this, redox determinations should provide a measure of the activity of bacteria.

Data Analysis:—The large volume of data that emanates from the use of the new, sophisticated instruments for continuous recording and rapid synoptic surveys demands that a more rapid way of data analysis be made available. Wherever possible, a systems approach is being used. The data are being programmed directly from instrument into the computer to provide the type of output needed. In oceanography, the trend is toward obtaining real-time data. As in meteorology for predicting daily air flows, such data are needed for making rapid, reliable predictions on water movements. This provides information on the presence of fish stocks which may be associated with the water masses.

The availability of much physical and chemical data on the marine environment and computers for analysis allows an analytical study of the given area to be made. This means that a mathematical model can be set up to simulate conditions in nature, and the various terms of the model can be changed according to the needs. Be-

cause of the complexity of the model, it usually is tested on the computer. A number of studies of this type have been carried out on the east coast of the United States (45) (46) (47) (48) (49). For consulting engineers dealing with oxygen balance in some of these heavily-polluted estuaries, it appears that the systems approach with an analytical, mathematical model is the only way to obtain satisfactory solutions.

Biological Studies

The studies of biological effects of marine pollution have to be subdivided into two basic parts: field and laboratory. Field data unsupported by laboratory studies do not provide the full picture of the biological effects. On the other hand, the laboratory worker without support from a field program tends to work somewhat in a vacuum.

Field:—A program of biological studies in the marine environment may be subdivided into a number of projects, including primary productivity, plankton studies (phytoplankton and zooplankton), larval and juvenile fishes, and benthos investigations. A full study to determine the impact of pollution on the environment and on the biota should include an investigation of the food chain in the sea. At the Biological Station in Nainimo, just such an investigation presently is underway in the Strait of Georgia. While it is not directed toward pollution research, the same approach could be used to investigate the effects of pollution on the marine ecology.

By standard chemical techniques (50), the nutrients are studied to determine the seasonal levels at a number of stations in the Strait of Georgia. The nutrients investigated include the silicates, phosphates, nitrites, and nitrates. The only nutrient which appears to limit the growth of phytoplankton at any time of year appears to be nitrate, although other forms of

nitrogen compounds may be made available during periods of low nitrate. The phytoplankton are studied both by sampling for microscopic examination and by analysis of the pigments. This provides a gross overall picture of the phytoplankton standing crop.

In conjunction with grazing of phytoplankton by the zooplankton, a laboratory study is underway on plankton dynamics. Basically, the predator-prey factor has been investigated under different conditions maintained in cultures of phytoplankton and zooplankton. This experiment could be modified by introducing another variable—a pollutant.

The abundance of larval and small fishes has been examined in different areas of the Strait of Georgia in relation to the zooplankton, both from the stomach contents of the fish and from zooplankton sampling. Again, similar field investigations could be extended to include waters affected by different concentrations of pollutants.

One of the features appearing from studies in Nanaimo, B. C., is that a shift in composition of plankton affects the next trophic level. It has been found that the extent of zooplankton grazing depends very highly on the cell size and concentration of the phytoplankton blooms (51). Although the total biomass of organisms present as food for a given species is important, it appears that the size of the particular organisms used as prey may be even more vital. Also, the protein content of the particular organism in the food chain is an important factor in maintaining proper nutrition for animals in the next trophic level. A shift in the composition of organisms caused by adverse conditions may lead to a profusion of "weeds" which are useless as forage organisms. In the experiments conducted at Nanaimo, it has been found that diatoms are preferred to dinoflagellates by certain copepods (*Calanus plumchrus*).

The above studies of the size and cell-number relationships to grazing have been possible only because equipment was available that could count and give the size frequency of the phytoplankton. The counting device used, originally designed for blood-cell counting, can be made adaptable for analyses of phytoplankton and microzooplankton. The Nanaimo research instrumentation shop is working on an instrument that will count and give the sizes of the macro-zooplankton greater than one mm long. An *in situ* plankton counter and sizer has been developed. This device will provide the same type of information on zooplankton in the actual environment that heretofore has been obtained only in the laboratory.

Microbiological studies have been carried on concurrently with macrobiological investigations in the Strait of Georgia. Recent work has shown that bacteria contribute substantially to rapid conversion of nutrients from detrital material in the sediments into available form for phytoplankton (43). Also, it has been found that bacteria contribute to the food for young salmon by as much as 10 percent (52). In bacteriological studies associated with the zooplankton work, it has been discovered that a parasitic yeast infects some of the copepods in some near-shore waters, possibly causing a substantial mortality in the copepod populations under certain circumstances (53). There is no doubt that a great deal more will be discovered in these bacteriological studies, thus elucidating certain processes associated with the food chain in the marine environment.

Benthos studies in relation to pollution, except for some research on pulp-mill effluent vs. oysters, have not been carried out at Nanaimo. Studies of the benthos in waters adjacent to Vancouver Island have been conducted by others (54). Classification and archiving of benthos data in a systematic way have been achieved by putting the

benthos information on IBM cards which are later put through a computer for rapid analysis, printout, and/or storage.

It would seem that the study of benthos has the greatest potential for revealing certain cumulative effects of pollution on the marine biota. Bottom animals, because of their sedentary nature, tend to integrate the effects of long-term exposure to adverse conditions. Therefore, it would be anticipated that studies of individual animals and of communities should be quite rewarding. A great deal of research has been done on the bottom organisms off the coast of California in relation to conditions arising from wastewater pollution (55) (56). There is a great need for similar work in association with other investigations on marine pollution, both on our coast and elsewhere.

All the foregoing biological pollution studies should be integrated carefully in an ecosystem investigation. Procedures of experimental design and analysis developed in other studies (57) (58) (59) (60) (61) (62) should be explored. A recent volume (64) examines the problem of resource management from an ecological point of view. Pollutional stress could be included in one of the models which brings into play various environmental parameters.

Laboratory:—Biological studies in the laboratory may be extremely diverse when effects of pollutants are considered. But in general, biological laboratory studies on effects of water pollution may be subdivided into two parts: (a) bioassays for acute toxicity, and (b) investigation of sub-lethal effects. At the Nanaimo station, most of the work on pollution biology has been on the bioassay aspects. Some of this early work has been devoted toward the determination of the 96-hr LD₅₀ of various pollutants tested on young Pacific salmon. However, lately the research has moved toward a multivariate analysis of the effects of pol-

lutants under different conditions of the environment. This has been essentially a factorial design to incorporate tests of pollutants on fish—varying salinity while the temperature and dissolved oxygen are maintained constant, then varying the temperature at constant salinity and dissolved oxygen, and finally varying the dissolved oxygen while maintaining salinity and temperature constant. These studies have been described by Alderdice (58) (59) (60) (61) (62). There is a great output of data from such an approach in experimental design and it is necessary to program the processing into a computer. The experimental design and analysis of data are based on techniques first proposed for industrial experiments (57). The output is one which provides information on response surfaces rather than just on response curves for each pollutant with each species of animal tested.

The sub-lethal effects of pollutants become increasingly more important as one moves into the examination of biological effects of low concentrations of polluting effluents. A number of studies for sub-lethal effects already have been reported for tests on fish (65) (66) (67) (68). Other research has been reported on sub-lethal effects of various life-stages of shellfish (69). It would suffice here to summarize only some of the techniques which have been used and perhaps comment on others that might be adapted for studies of sub-lethal effects. Histo-chemistry is a technique that is common to biological studies where changes in the cell structure of different organs are examined in stained thin sections under the microscope. It seems particularly suited to examining the effects of low concentrations of pollutants on the vital organs of fish. Blood serum electrophoresis provides patterns which appear to be different for different degrees of exposure to pollutants when fish from the same stock are used (65). Hematocrit and other clinical hematological examinations

(72) are being applied increasingly in studies of pollutional effects. The inhibition of enzyme activity, as observed with cholinesterase (73), seems to offer considerable hope for determining the subtle effects of insecticides on organisms. Extensive research and reviews have been conducted on the sub-lethal effects of insecticides (4) (74) (75).

Respirometers are now quite common to measure the metabolic changes which occur in fish with increasing activity. A great deal of work has been done on the respiration of young salmon (76) (77) (78) and of other fish (79) in a closed respirometer where they are subjected to different current speeds. However, measurements have not yet been made on this apparatus to determine changes in metabolism when the fish are exposed to a pollutional load.

The changes in buccal-cavity pressure seem to be a good criterion for adverse effects of pollution on fish. Work along this line has been carried out by the British Columbia Research Council (80) to measure the effects of pulp-mill wastes with different degrees of treatment. The trend is toward closer adherence to medical techniques, particularly clinical toxicology as used in medicine (81). The toxic action of many poisons now is being examined (82) (83) (84) to determine further ways of exploring effects of sub-lethal concentrations on organisms.

Sub-lethal effects also can be manifested at very low pollutant concentrations. For example, it has been found with extremely low concentrations of pulp-mill effluents (about one-thousandth of the lethal concentration) that certain avoidance reactions can be detected in Atlantic salmon (85). The learning ability of Atlantic salmon definitely is affected by concentrations of DDT at levels of 50 ppb (86). It is probable that other behavioral actions—aggressiveness, territorialism, and courting of fish—are affected in

varying degrees by low concentrations of certain types of toxic materials.

Discussion

From the practical point of view, the question might be asked, "What makes a system degrade?" It is known that the cumulative effect of pollutants causes gradual deterioration of the aquatic environment. But how do these factors act? From casual observation, the effects are insidious. One year, fishing in a given body of water may be enjoyed; 10-yr later there are no fish available and the waters have a noxious odor. Where trout or salmon once abounded, only carp or some other types of coarse fish are found. Why has this occurred? And how has the changed environment changed the biota?

To appreciate the effects of pollution in the marine (or any other) environment, the conditions or requirements which allow living organisms to grow, mature, breed, and replenish their stocks must be known. The so-called "weak links" in the life cycle of the involved forms must be understood and appreciated. Knowing what circumstances are favorable then allows a search for departures which may be unfavorable.

The ecological implications of pollutional effect (i.e., the effect on an ecosystem) which may not be apparent from studying selected individuals or selected species must be appreciated. Since very complex interrelationships exist within animal communities, changes which influence limited numbers of the community directly are liable to influence many members (species) indirectly, as the community seeks new balance under the altered set of environmental conditions. Too often the study of an already affected environment and ecosystem is the first acknowledgement of pollutional effect.

Two general approaches to understanding the interrelationships between animals and environments are employed—field studies and laboratory

studies. The former seeks understanding among a host of operating circumstances which are difficult to sort with respect to their significance. The latter provides direct and sensitive information, but its significance in the natural environment may be difficult to evaluate.

In general, pollutional effects are of three types: (a) indiscriminate, direct, and easily observable. The relation between cause and effect is simple and direct (e.g., oil on birds, or high or low temperature, or high DDT content); (b) sub-lethal and discriminate, e.g., a change insufficient to be rapidly debilitating, but one which causes problems in some part of the food chain, kills the younger or less hardy members of a species, or shifts conditions away from those most favorable for balance in the community (or the "best" balance); and (c) those which change the environment almost imperceptibly or those whose effects are discriminate, yet so small that only time trends will establish the fact that a change is occurring or has occurred. The first (a) is usually easy to discover. The second and third, (b) and (c), are difficult and are the subject of both field and laboratory investigational techniques.

Increased insight into subtle and long-term changes in the marine environment (apart from those which are obvious) will await (a) new and improved techniques for determining subtle biochemical and physiological changes in organisms comprising the community, (b) extension of multi-variable quantitative methods of ecological study which will allow examination of large numbers of variables and variates (i.e., temperature, salinity, turbidity, K, P, N, etc., vs. population numbers; numbers of species, biomass, growth rate, etc.), and (c) a sampling program to enable the detection of long-term drifts in physical and chemical attributes of water (including organics and inorganics), and of bottom sediments in coastal waters.

An inter-disciplinary approach must be taken, both in laboratory and field. Collection of field data of a monitoring type seems tedious, but it is needed for examination of long-term effects. Time-series analysis must be carried out to determine the dynamic processes in the system and the deviations from a mean condition. Computer analysis of data must be applied if the large volume of information is to be assimilated properly. Mathematical models, designed to simulate a number of pertinent variables, can elucidate processes.

Laboratory analysis must take into consideration all factors when testing a pollutant on a different test animal. The approach used to examine all combinations of environmental factors for determining the response of the animal must be continued. In this way, there will be understanding of the significance of some of the pollutants under different environmental conditions which occur seasonally with different temperatures, runoff, and wind conditions. Suitable field data must be made available for testing the laboratory results. Only then can the laboratory experiments be controlled adequately to provide the information needed in the field.

An ecosystem approach with an intensive examination of all components should be made for a better understanding of the various factors involved. This means often a multi-disciplinary attack on the problem. Quantitative data obtained from various types of observations then can be fitted into a model simulating the conditions and the end effects determined. Only in this way can a valid prediction of the conditions expected with modification of the environment by introduction of pollutants be provided.

It might be appropriate here to insert a quote from Watts (64) on community energetics:

When we examine the details of food cycles, we see that the nonliving and living elements in nature are bound to-

gether in a system through which energy cascades and matter cycles: the ecosystem. Plants use incident solar energy and minerals to manufacture living tissue later eaten by herbivores, which in turn are eaten by carnivores. As the living tissue dies at each stage, it may be broken down into mineral material which then re-enters the cycle. It is important to note that while matter can cycle through the ecosystem repeatedly, energy passes through only once (for a given unit of incoming radiation), and there is wastage at each level of the food pyramid (plants, herbivores, primary, and secondary carnivores). This is why we say that energy cascades, whereas matter cycles through the system.

It generally is conceded that the amount of energy absorbed by a system is modified by pollution, normally being less under polluted conditions than in the original state.

From a more pragmatic point of view, there is a real need to find a better criterion of toxicity than standard bioassay methods. While all the physical and chemical parameters can be monitored and sensed with available equipment, the toxic level of either a given waste or of a waste-receiving stream cannot be detected. It is not likely that a machine can be built to sense toxicity, unless the toxicity can be related to some physical or chemical factors. Perhaps the standard bioassay technique for toxicity will have to be accepted for some time. If this is the case, the technique, should be applied in a more routine fashion for detecting toxic conditions in receiving waters. This might be done by a series of tanks through which the water is channelled. When a given number of fish have died, then some sort of electrical signal should be generated to sound a warning.

Summary

The interrelationships between aquatic communities and the marine environment, between individual communities and between organisms within those communities are extremely complex. To understand these inter-

relationships, teamwork representing many disciplines must be applied. The sophisticated instrumental techniques now available allow examination of the environment continuously and more thoroughly. Aerial techniques for synoptic surveys, as well as continuous recording instruments, are speeding the output of better data than available previously. Advances in computer technology with machine processing allow testing of models simulating changes in the environment.

Biological surveys still are tied largely to traditional sampling techniques—using bottom grabs and dredges of various types, plankton nets, and water sampling bottles of various descriptions. Analysis continues to be slow and tedious, largely being carried out under the microscope by specialists. However, biologists now are taking advantage of computer processing of data for more effective classification, archiving, and retrieval of biological data. New biological data on numbers and sizes of organisms are appearing from the use of counting and sizing devices becoming available on the market. Such information, as well as data collected by instruments, can be processed properly only by a computer.

Laboratory studies of the effects of pollution must swing more and more toward the examination of sub-lethal effects. Methods for detecting responses to deleterious substances in individuals must be improved. Traditional methods of the medical sciences, used in toxicology, hematology, physiological chemistry, epidemiology, pathology, and medical statistics, must be explored and used where applicable.

The output of more reliable data taken concurrently on the various aspects of the marine environment and the biota allows a better approach to be taken for examination of the whole water pollution problem. Such quantitative information, when it becomes available, will allow pollution biologists to provide the engineer and pol-

lution control agencies with the specific details required to make adequate predictions on the effects of a given type and volume of waste on the environment and on the organisms in the given body of water into which it is proposed to discharge such wastes. Pollution biologists must be prepared to diagnose ailing ecosystems. They should be able to recognize incipient ailments of the organisms which arise from pollution.

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