Economic Valuation of Aquatic Ecosystems

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CHAPTER 1: INTRODUCTION AND OVERVIEW

In this chapter we indicate the ways in which aquatic ecosystems are valuable to mankind, and make a first pass at suggesting how these values might be assessed. Our object is to give an adequate appreciation of the many and varied kinds of goods and services provided by aquatic ecosystems, while at the same time beginning the process of organizing the discussion of methods of measurement of the worth of these benefits. The chapter concludes with a detailed outline of the plan of the rest of the study.

A. Goods and Services Provided by Aquatic Ecosystems

The steps involved in determining the economic value of ecological goods and services are to identify what benefits ecosystems provide for mankind, to characterize these benefits in ecological terms, and then to assess their economic value. Even the first step should not be thought of as completed for any actual ecosystem. Indeed, it is virtually certain that as our understanding of ecosystems progresses in the future, we will discover the existence of presently unrecognized goods and services provided by healthy ecosystems. The characterization of goods and services by ecologists must include not only a description of the nature of the good or service, such as how many trout for sports fishing a particular stream maintains, but also how the continuing provision of that benefit is linked to the future state of health of the ecosystem. Generally the ability of ecologists to characterize the magnitude of the benefit under ambient circumstances far exceeds their ability to assess how continuing provision is linked to environmental quality. Finally, valuation must take into account not only the effect of a change in environmental quality on the ability of an ecosystem to provide the benefit under discussion, but also its effect on the overall health of the ecosystem, which in turn may influence the future ability of the system to provide benefits not presently identified. This 'insurance" factor is most difficult of all to include in the benefit-cost calculus because it requires having to guess the value and the ecological interconnectedness of benefits that we have not even identified as of yet.

In order to guide our thinking about methods of measuring benefits we have chosen to categorize the goods and services provided by aquatic ecosystems as being those for which the environment Is an input, that is, the ecosystem provides a factor or means in the production of a good or service to be consumed, and those for which the environment itself is a final good. This distinction is,in a sense, artificial, since many goods and services provided by aquatic ecosystems fall in both categories. It will, however, be useful because, as explained in section B below and further in chapter 7, it corresponds in some ways to a distinction between approaches to economic valuation.

Goods and Services for which Aquatic Ecosystems Provide Inputs to the Production Process

The most obvious set of goods for which aquatic ecosystem provide basic inputs are 'fisheries" products. These products, as indicated in Table 1, include harvested fish, shellfish, and crustaceans; aquatic plants such as kelp, which is used in the manufacture of chemicals and food products; and, to a small extent, aquatic mammals, now used mostly for garments. The rivers and reservoirs that allow hydroelectric production and its control contain aquatic ecosystems. Some types of damage to these ecosystems, e.g. siltation of reservoirs caused by soil erosion and runoff, can affect the output of the hydroelectric system. Rivers, lakes, bays, and estuaries are

TABLE 1: GOODS AND SERVICES PROVIDED BY AQUATIC ECOSYSTEMS

Goods and Services for which the Environment Provides Inputs

Fisheries Products: Fish, Shellfish, Crustacea, Kelp, Aquatic Mammals

Hydroelectric Power

Transportation

Treatment of Human Wastes

Treatment of Industrial Wastes

Water Purification

Drinking Water Storage

Information Produced via Scientific Research

Goods and Services for which the Ecosystem Is a Final Good

Recreational Use of Aquatic Areas (Public Access and Commercial)

- Direct Use of Water: Boating, Rafting, Sailing, Canoeing, Scuba-diving, Swimming, Wading
- Recreational Use of Aquatic Organisms: Fishing, Waterfowl Hunting, Collection of Shellfish and Crustacea
- Waterfront Recreational Activities: Strolling, Hiking, Sunbathing, Team Sports (e.g. Volleyball), Off-Road Vehicle Use, Horseback Riding, Nature Study (e.g. Birdwatching)

Amenities

- Scenic Values
- Modulation of Local Climates by Large Bodies of Water
- Status and Enjoyment of Owning or Having Access to Aquatic Areas
- Informal Education of Children
- Psychological Benefit of Availability of Pristine Areas

Future Goods and Services

- Preservation of Genetic Information: Protection of endangered Species, Preservation of Gene Pool
- Preservation of Wild Areas for Use by Future Generations and for Future High-Value Development

also used as transportation arteries, and thus provide an input to the process of moving people and goods from place to place.

An extremely important and often overlooked set of processes in which aquatic ecosystems play roles are human and industrial waste-treatment and water purification. When human wastes are discharged into bodies of water, biological and physical processes combine to break down organic matter and release nutrients in the wastes, and to kill pathogenic organisms. In a similar manner many industrial wastes are broken down when disposed of in aquatic environments. Coupled with these waste-treatment functions, wastewaters disposed of in lakes, rivers, marshes, and other aquatic areas are purified and recycled either by evaporation and subsequent precipitation or by percolation through benthic (bottom) sediments and soil to groundwater aquifers. Wastewater added to a lake might undergo biological treatment by aerobic (oxygen-using) bacteria associated with oxygen-producing algae growing at the water's surface, chemical treatment by entrapment of metals and other substances in the anaerobic (oxygen-free) bottom waters and sediments, and physical treatment by filtering through sediments and soils before it reaches a subterranean aquifer that supplies fresh water to consumers. Properly functioning aquatic ecosystems in reservoirs also provide appropriate conditions for the storage of drinking water. Clean and/or potable water is an essential input to the production of a vast number of products and services.

Aquatic environments also provide opportunities for scientific research and development. In this case knowledge is the product for which the environment is an input. This knowledge may take the form of information about the improved cultivation of a valuable organism, for example, or data that enables prediction of the behavior of other aquatic ecosystems, and how the goods and services that they provide will vary under changing conditions. The study of one small lake, for example, might provide information valuable in protecting a number of lakes in an area from acid rain or some other pollutant stress.

Uses of Aquatic Ecosystems in which the Environment is the "Final Good"

Perhaps the most obvious set of goods and services in which aquatic ecosystems are in a sense final goods are the recreational uses of watery areas. These recreational goods, as listed in Table 1, include direct uses of water, the recreational pursuit and harvest of aquatic organisms, and waterfront recreational activities. Examples of activites involving the direct use of water are boating, rafting, sailing, canoeing, scuba-diving, swimming, and wading. Fishing, hunting of waterfowl, and collection of shellfish and crustacea are examples of the recreational use of aquatic organisms. Waterfront recreational activities include strolling, hiking, sunbathing, sports such as volleyball? the use of off-road vehicles, horseback riding, and nature study (e.g. birdwatching). Many of the recreational goods mentioned above are available in both public areas and through commercial interests such as tourist hotels and lodges close to the water, tour boats, and fishing and other guide services. Virtually all of these goods and services depend on good water quality for their value.

A much more amorphous class of benefits provided by aquatic ecosystems can be loosely described as 'amenities". These include the pure scenic value of a waterfront area or lake, the modulation of local climates by large bodies of water, and the status and enjoyment provided by owning or having access to areas near the water. While the practical nature of these amenities is clear to everyone, there is a 'spiritual" side to the scenic value of aquatic ecosystems that may represent the dominant benefit that these ecosystems provide. In the informal education of many children, nature plays an extremely important role. From the autobiographies of numerous writers, artists, scientists, and others we read often of how early exposure of pristine wildlands shaped these Peoples' minds beneficially. Such writings reveal the awareness of ecosystem benefits by those that are most able to express these experiences vividly, but these same benefits accrue, of course, to a far wider spectrum of people who are not necessarily as conscious of, or articulate about, their existence.

Beyond the formative years of childhood, amenity values continue to enrich peoples' lives, but in ways that can be disticlty different from the ways in which children benefit. In particular, a greater awareness of the amenities occurs as we mature and the experience of nature becomes less formative than it is restorative. The person in an office in downtown San Francisco, for example, may take comfort in the fact that pristine areas are available for him or her to enjoy. This thought, that escape from the "rat race" is possible, may make it easier to live and work happily in a city. If such a person were asked what this amenity was worth, he or she might quote some figure, but it is possible, since the scenic area has always been available, that the individual would undervalue this amenity relative to what would be considered his or her "share" of the value of the scenic area to society as a whole.

A final class of goods and services provided by aquatic ecosystems can be loosely described as future goods and services, and the preservation thereof. This includes the preservation of diverse genetic information, the preservation of ecosystems for future generations of humans to enjoy, and the preservation of aquatic areas for future development. The protection of endangered species--for their future commercial use, aesthetic value, use as objects for scientific **study,** and existence value--is one example in which the Preservation of genetic information can provide future goods and services for society. In preserving a diversity of plants and animals we are also preserving a library of genes that, with man's growing ability to manipulate **genomes,** may someday become tools useful in producing valuable drugs or chemicals. The preservation of **scenic** and wild areas for future generations to use--our National Parks are examples--provides future goods and services in the form of both recreational opportunities and aesthetic values, as described above. The knowledge that scenic areas will be available to their descendants in the future may also provide the benefit of peace of mind to a person living today. Finally, preservation of some aquatic areas may allow them to be developed for high-value uses in the future. Mining in a scenic lake area rich in some ore, for example, might have tobe done today in such a way that the scenic **value** of the place is lost indefinitely--through poisoning of the aquatic ecosystem by acids leached from mine tailings, soil erosion from road construction, or physical rearrangement of the area--but it might be possible to mine the same region at some future time, using an as-yet undeveloped technology, in such a way that the aesthetic value of the area remains intact. In the latter case the area continues to provide recreational and aesthetic goods and services in addition to the valuable ore. As described in chapter 5 the presence of future-worth considerations can greatly influence regulatory choices regarding the control of pollution of aquatic ecosystems.

B. Economic Valuation

As the discussion in the first part of this chapter has suggested, the goods and services that can be provided by aquatic ecosystems are many and varied. Yet for the purpose of characterizing evaluation, we must try to collect them into a manageable number of categories, corresponding to methods of evaluation. This we attempt in the table, Table 2, below, with the hope that no major items, at least, are lost in the process. Types of goods and services are classified into those involving the aquatic ecosystem, the environment, as input, and those involving it as a final good (or service). By environment as input, we mean that it enters into a kind of mixed biological-economic production function, along with conventional Inputs such as labor and capital, to yield some desired final good--as the table suggests, a supply of fresh water for drinking, perhaps, or a shellfish harvest. The consumer of the water, or the shellfish, is assumed to care only about the good he consumes, and not the Input mix used to produce it. By contrast, when the environment is valued as a final good, it enters directly into the consumer's utility function. Thus improved water quality can yield benefits both as an input to some production process, and directly to on-site recreationists, nearby property owners, and so on.

A couple of more exotic, or less tangible, goods are also indicated in the table. One is the conservation of genetic information. This can be considered as affecting future commercial harvesting, for example of a plant or animal species for some yet-to-be-discovered medicinal property. The other intangible good is the existence of an unspoiled environment, unrelated to any use or consumption of its resources now or in the future. Some people derive satisfaction simply from the knowledge of existence, and this has been termed 'existence value" in the literature of environmental economics.

Now, why is it sensible to classify the goods and services provided by aquatic ecosystems in this fashion? Consider the first column in the table, headed 'method of evaluation." It is our view that a particular method can

TABLE 2:

METHODS OF VALUATION FOR GOODS AND SERVICES

PROVIDED BY AQUATIC ECOSYSTEMS

Method of Valuation	Type of Benefit
	Environment as Input
Shifting Supply, Given Demand	Water Supply and Quality
	Commercial Harvesting (includes genetic conservation for future harvest)
	Environment as Final Good
Travel Cost	Recreation
Comparative Property Values	Amenities
Contingent Valuation	Existence Value

be identified as best suited to each of the categories. Thus, if the environment is viewed as an input to a production process, such as the commercial harvesting of shellfish, an improvement in quality due to reduced pollution loadings can be expected to lead to a shift (down and to the right, on a conventional diagram) in the cost or supply of shellfish. Given an independent estimate of the demand for the particular shellfish product, the shift in supply generates an increase in combined consumer and producer surplus, the area bounded by the demand and supply curves. Of course, establishing the nature of the connection between reduced pollution and the supply shift is a difficult empirical problem. In section Aof chapter 7 below we consider the problem in some detail, and illustrate our method of solution with some computations based on estimates of relevant demand and supply parameters in the literature. The use of a change in combiend surplus to capture the welfare effect of reduced pollution is justified in chapter 6, a theoretical discussion of the economic concept of benefit.

An aquatic ecosystem can also, as we have noted, be viewed as an input to the generation of fresh water supplies in a region. Reducing pollution loadings in the system similarly results in a downward shift in the cost or supply of providing fresh water. We shall have more to say about this contribution also in chapter 7.

Turning to the environment as final good, the first item in our table is recreation. There is a large literature on methods of valuing outdoor recreation resources, discussed in some detail in section B of chapter 7. Here we just note that the preferred method, rooted in economic theory and validated in many empirical applications, is the travel cost method. The name is derived from the use of travel cost (from the point of visitor origin to the recreation destination) as the measure of price in an analysis of the demand for recreation at the site in question. Thus our focus has shifted from supply to demand. There is however an interesting parallel to the analysis of the environment as input. Suppose an improvement in water quality makes available a site that can be assumed to perfectly substitute for another (in the provision of recreation). Then recreation at the first or unimproved site is in effect available at lower cost, to those who live nearer the newly available site. Of course, this analytical device requires the assumption that the newly available site provide the same recreation services as the other, so that consumers are indifferent as to which is chosen as 'input."

Reducing pollution in an aquatic ecosystem can also lead to enhanced amenities. Clean water makes nearby residential Property more desirable. An extensive literature has explored the relationship between changes in environmental amenities and property values--the extent to which it exists, the circumstances under which it can be estimated, its magnitude in particular cases, and so on. This literature is reviewed in section B of chapter 7.

We come, finally, to existence value. This differs in an important way from all of the other goods, or benefits, discussed thus far in that it is not associated with use of the resources of an ecosystem. In fact it is often classified, along with option value, as an "intrinsic", or non-use benefit of preserving or improving an ecosystem. We shall have more to say about option value very shortly. With respect to existence value, there is a double problem for measurement. First, one cannot measure units of consumption (to which a value might then be imputed). To some extent this is true also for amenities--as in the case of an improved view. But the value of the view may be captured by a change in property value, since the view is associated with a piece of property, and property is valued in market transactions.

The second difficulty in measuring existence value is that it is a pure public good, and one whose consumption is not associated with consumption of some private good such as residential property. About the only approach that can be employed here--and has been, in a small number of empirical studies--is so-called contingent valuation. This is simply asking individuals what they would be willing to pay for the continued existence of an area or species. The literature has also addressed the difficulties with this approach--the hypothetical nature of the question, its unfamiliarity to respondents, their propensity for strategic behavior, and so on. We provide a review with special reference to the application to aquatic ecosystems in section C of chapter 7.

We mentioned option value as the other commonly identified non-use environmental benefit. Yet it appears nowhere in our table. The reason is that, in our judgment, it is not a separate benefit, corresponding to a separate good or service provided by an aquatic ecosystem. It is instead an adjustment, or "correction factor," to an estimate of any of the other kinds of benefits listed in the table, to take account of uncertainty about their future values. This is a complex issue, however, that has generated considerable confusion and controversy in the literature. Chapter 5 defines option value and some of its properties in an analysis of the valuation of pollution control in a dynamic, uncertain setting. Further discussion, focusing on different concepts of option value, is provided in chapter 6.

c. Plan of the study

In the next chapter we discuss a kind of 'quick and dirty" alternate approach to valuation, the construction of a suite of indicator variables (SIV) that might be used to characterize the response of an aquatic ecosystem to reduced pollution or other disruption. This chapter includes a review of what might be termed ecological scoring methods, such as the HEP and HES systems. It also introduces concepts which will be useful later on.

Chapter 3 is about one of these: the dynamics of ecosystem recovery. A model is developed that generates the often-observed and potentially important hysteresis phenomenon, in which a recovering ecosystem does not retrace the path of its decline. The point of the model is to enable prediction of the recovery behavior of ecosystem populations in which we are primarily interested, higher trophic levels such as fish, from that of the much more readily observed lower trophic levels such as phytoplankton. Chapter 4 is an analysis of error propagation in measuring recovery. That is, suppose we are uncertain about the *degree* of phytoplankton recovery. How does this translate into uncertainty about recovery of the fish population?

Chapters 2, 3 and 4 are primarily about the behavior of aquatic ecosystems, with no systematic discussion of economic valuation. In chapter 5 we begin this discussion. A model is developed to value the control of pollution, taking account of key features of the ecosystem behavior discussed in the earlier chapters: recovery lags, irreversibilities, and uncertainty. The ❑odel does not address the question of how to estimate the different categories of benefits identified in the preceding section (of the Introduction). This is the task of chapter 7, divided into three parts, also noted in the preceding section: the environment as input (water supply, commercial harvest), the environment as final good (recreation, amenities), and non-use benefits (existence value). The discussion of methods of benefit estimation is preceded, in chapter 6, by a theoretical analysis of the economic concept of benefit. Specifically, we motivate use of combined consumer and producer surplus as the preferred measure of a welfare change following an environmental improvement.

In chapter 8 we consider appropriate directions for further work. Our present intention is to proceed in two areas: (1) comparative analysis of models for policy evaluation? and (2) development of a case study. Both are elaborated in chapter 8.

Chapter 2. A SUITE OF INDICATOR VARIABLES (SIV) INDEX FOR AN AQUATIC ECOSYSTEM

I. The Need for a SIV-Index

Assessment of the damage to ecosystems ideally requires an accurate and precise measurement of the harmful effects. The results of such measurements are needed to establish a numerical relationship between pollution and economic damage to the ecosystem. Although not often used exactly in this way there are several habitat evaluation procedures available to assess the "health or state" of the ecosystem. These measures include several separate procedures (see reviews by U.S. Water Research Council, 1981; Putnam, Hayes, and Bartless, 1983; Canter, 1984) and cover most types of aquatic ecosystem but focus on streams and wetlands rather than large lakes, reservoirs, large rivers, estuaries or the open ocean. None of these indices is ideal but they have served well in some circumstances, especially for evaluation of game habitat used for recreational sport, for example, deer hunting.

Any of these evaluation systems can be used to give a numerical value for the ecosystem over a sustained period of time. The resulting long-term data base is then used to show if a decline or improvement has occurred. When compared with an unaffected or control ecosystem an ecosystem value can be expressed as a percentage of the optimum even if the evaluation procedure does not cover all the period of degradation (or improvement) of the system.

Of considerable practical interest is the need for the maintenance of a complete habitat in the kind of restoration that occurs when sewage or other wastewaters are cleaned UP. For example, a relatively simple single parameter (e.g., the fish of concern) or multiple parameters (e.g., the index proposed in this paper) can be assessed routinely while habitat evaluations are extensive, expensive, and one-time measurements.

11. The Requirements for an ideal index: Selection of variables for use in a SIV index

There are three main requirements:

- Data must be inexpensive to collect.
- Data must already be available for some ecosystems for use in trial projects.
- The connection between the variable and its biological effect must be known from experimental studies.

The purpose of a SIV index is to determine aquatic ecosystem health over time and/or space. The choice of variables can change depending on the ecosystem chosen. For example, dissolved oxygen fluctuations can be deadly in mid-western rivers in summer but the same quantity of waste is unlikely to trouble the temperate open ocean. Since biologically non-functional variables decrease the precision of any index they should only be used where" important.

111. Review and critique of ecological indexes which could be used to estimate ecosystem health.

Critique of existing habitat and other evaluation procedures as applied to aquatic ecosystems

Existing habitat evaluation methods usually focus on

- the physical structure of the ecosystem -- e.g., stream sinuosity, mean depth, percentage of cover, size of the lake
- indigenous, rare, or sensitive species, diverse species composition, and
- maintenance of indigenous (native) sport or game species.

The habitat evaluation procedures are derived from common sense evaluations once made by wildlife managers. The purpose was usually to decide. what mitigation should be given if an area was to be physically destroyed -- as for example if a housing development or a dam were to be built in the area. In many cases mitigation was the creation, donation, or restoration of a piece of land which was of comparable ecological worth to that being destroyed. An example might be the degradation of a stream by treated sewage could be compensated for by the creation of a marshland on the treatment plant property.

The evaluation procedures have a terrestrial bent (e.g., deer, partridge) since lakes and streams cover only a small portion of the landscape. Thus physical features such as trees, browse, overhanging banks (for fish), are important, even dominant in existing habitat evaluations -- and rightly so for terrestrial and some aquatic systems.

However, most lakes, oceans, estuaries, larger streams, and rivers are structured on the basis of thermal stratification, the chemical stratification which follows, and an ever-changing biotic structure. Wetlands are intermediate in this respect depending on the degree of submersion and the life times of the plants which constitute the base of the food chain.

Pollution in aquatic systems alters the biotic structure, sometimes the overall chemical structure, but rarely the thermal or physical structure of aquatic ecosystems. In this it differs from terrestrial habital destruction. The rebuilding of a damaged landscape requires the regrowth of a complex of physical habitats, while the restoration of an aquatic one may in principle require only the cessation of pollution. In both cases it is assumed that the biotic component is readily available to migrate in from adjacent areas.

Most of the indices, especially the habitat evaluation procedure (HEP), the habitat evaluation system (HES), and the ecosystem scoping method (ESM), also incorporate an implicit (HEP, HES) or explicit (ESM) belief that diversity = stability = desirability. That is, the more different types of organisms there are (or the more links there are in the food web) the higher the ecosystem will score. Thus the most valuable ecosystems tend to be the most diverse by this rationale.

The diversity-stability argument has a 20 year history in ecology. One might sum up the conclusion as the relationship between diversity and stability depends on the definition of stability and the time scale of observation. For example, if stability is equated with constancy over time then, when using typical northern temperate human time scales of years the simple non-diverse arctic owl-lemming-grass food chain appears unstable. When viewed over decades the opposite conclusion can be drawn (i.e., a perpetually oscillating population). Other definitions of stability can lead to yet other relationships with diversity which are not discussed here. It is unfortunate that the early discoveries of high diversity in tropical forests and coral reefs were not put in a better perspective for seasonally-controlled temperate-polar systems.

The intent of this paper is to review in brief existing habitat evaluation procedures and attempt to derive a specifically aquatic index which can be used to describe the "health" of the ecosystem. Such an index will be imperfect but is needed if one is to assess change over time, and thus see effects such as hysteresis (e. g., Edmondson and Litt, 1982, also see later in this report), improvement, degradation and ascribe some economic value to the measured changes.

The choice of variables for an aquatic health index can, in theory, be made from any or all trophic levels in the ecosystem. Unfortunately the organisms of most direct economic interest (recreational or sports fish and shellfish) do not seem to be either easy or inexpensive to sample or to use for robust indices. Because of their size, relative rarity and biological complexity fish and shellfish produce variables which vary widely from the mean value. These parameters have a high coefficient of variation and when combined into any index these large errors propagate to the point of rendering the index useless for practical purposes.

An example of this is the "scope for growth" (SFG) index which has been widely proposed for the assessment of the health of fish and shellfish. In a recent (1983-1984) and costly study of the effects of the large sewage effluents of Los Angeles, the California Dept. of Fish and Game (Monterey Office), together with the local discharger and various other regulatory agencies use the SFG method. Analysis of this data shows that changes shown near outfalls using the "scope for growth" (SFG) method are not statistically significant. Both increases and decreases in SFG relative to controls occurred at outfalls but similar changes occurred between replicated samples in the same place. The SFG method has a poor and inexplicably variable precision relative to other methods of growth measurement. SFG can only resolve changes of 282% (average of all Cal-COMP data) while simple measurement of length or weight have uniform precision and can resolve differences of 4% length and 14% weight (Home, 1984).

If we are to detect the biological effects of pollution near outfalls, a more precise measurement of mussel growth must be used to replace scope for growth tests. Such a precise method has been developed for Region #2 (San Francisco Bay Regional Water Quality Control Board) by scientists at the University of California, Berkeley. It is clear that SFG is still very much at the research stage and not a monitoring tool.

Why is the Scope for Growth Test so Imprecise?

The reasons are both physiological and statistical and both are inevitable. The physiological reason is that it is common for organisms moved from field to laboratory to experience long-term stress (see Knight and Foe, report to RWQCB, 1984). This together with individual genetic variation gives a highly variable end result.

An implicit assumption in this method is that SFG represents an obsolute measure of mussel health. For example, it is assumed that "healthy mussels" are always of approximately 40 joules h^{-1}. Values measured on mussels transplanted to other sites are often much lower than this due to transplant effects alone. In addition, spawning stress will reduce growth. These stresses and other uncontrolled variables reduce the utility of SFG as a monitoring tool to almost zero. The statistical reason " for the low precision of scope for growth results from SFG being a value calculated from a series of ratios and assumed values. Errors propagate through such an equation. It is usually better to measure a biologically integrated change directly -- i.e., measure growth directly rather than indirectly.

The problem of high variance is apparently inherent in these higher trophic level indices. Even relatively simple values, such as the percentage survival of animals exposed to an environmental pollutant, can be variable since animals which appear identical in size, condition, and amount of pollutant absorbed may have a very different genetic makeup (Hilvsum, 1983; Home and Roth, in prep.)

There are two ways to overcome this dilemma. First, simpler, more abundant organisms can be used to construct a robust index. Second, functional components of one or more groups of organisms can be used instead of their abundance.

IV. Proposed Suite of Indicator Variables (SIV) index: strengths, weaknesses.

Lacking any absolute ideal indicator(s) for ecosystem health an index is an obvious second choice. This has a history in economics (price index) and in ecology (diversity index, striped bass index). Again in common with economics (consumer price index) but not usual in biology, an index with several components seems desirable. The problem with an index based on any one variable in ecology is two-fold, lack of robustness and risk of being misleading. Over the last century several single indices have been proposed as "master variable". Acidity (pH) has often been proposed (Schindler et al., 1985) but is misleading for acid rain studies and alkalinity has been substituted (Hendriksen, 1979). While alkalinity is an appropriate guide to the susceptibility of a lake to acid oligotrophication (acid-induced impoverishment) it is not a good indicator of the effects of point or non-source wastewater pollution.

What is required is a suite of independent variables which would, if taken together, reliably show the current state of the ecosystem. Only if the majority of variables indicate a change in the same direction will there be good probability that the damage is serious (ecologically important) and persistent. It should be noted that this majority indicator approachimplies that the "cost" of a false warning is greater or equal to the "cost" of a false assumption that all is well. This could be described in terms of the "crying wolf" paradox. It is not usual to consider the damage done by false warnings of severe damage. However, from an ecological viewpoint there is only a certain amount of public concern for ecosystem preservation. Thus false warnings can detract from the effort required to respond to true warnings. An example of this is the hue and cry over DOT and its environmental effects. The cancers and genetic damage now ascribed to PCB are not effects of DOT. Although there are serious effects and a ban on DDT use was appropriate the toxicant PCB was overlooked for many years since its chromatographic signature was confused with DDT. A decade was lost when PCB-filled devices could have been phase out.

The plankton

Large numbers of independent (i.e., physically unconnected) organisms can be sampled with low statistical variance. For example, 'counting 100 single-celled free-floating phytoplankton gives 95% confidence limits of being within +20% 'f the true number (100). It is not always easy to be sure one has overlooked some algae when examining lots of similar-looking cells. If a similar number of cells were counted but were contained in 16 filaments the 95% confidence limit would only be +50% -- a much larger error (Land, Kipling, and Le Cren, 1959, pg. 158). In addition to counting errors if the organisms are also physically well-mixed then genetic variation between individuals is muted. These conditions are best met in the aquatic ecosystem in that group of organisms called the plankton. The word plankton means wanderer and basically refers to those small plants and animals which are more or less at the mercy of water currents. In this paper I will use the term in its widest extent to cover small unattached organisms in ponds, lakes, streams, rivers, estuaries, oceans and coastal fringes including salt marshes. Thus true animal plankton (zoo-plankton), plant plankton, (phyto-plankton) as well as the invertebrate insect drift in rivers and streams is encompassed.

As defined widely plankton includes the young stages of almost all the commercially valuable fish and shellfish and most of the sport fish and shellfish. Those which are not included depend heavily on the plankton for food in the adult stages. For not fully understood evolutionary reasons the majority of large valuable fish and almost all shellfish need a planktonic life-stage and some such as salmon, dungeness crabs, grey mullet or eels swim or crawl thousands of miles to achieve this planktonic goal.

The functional components of aquatic ecosystems

The previously mentioned high variance (= high risk of incorrect predictions) was first recognized in the study of stream benthos (e.g., Wurtz, 1960). Here extreme patchiness (large rock adjacent to gravel, sand etc.) could only be overcome by very large numbers of replicate samples. Typically 73 replicate collections in a stream riffle might be needed for 95% confidence in the numbers of invertebrates collected relative to 3-6 replicates which are normally the limit (Needham and Usinger, 1956). This patchiness was later found to be common in most aquatic ecosystems and remains a partially solved problem (Richerson, et al., 1970; Riley, 1976; Sandusky and Home, 1978).

In addition, particularly in streams, wetlands, and estuarine-ocean systems the identification of individual organisms is often impossible. The animals in the above-mentioned ecosystems are numerically dominated by juvenile stage of such groups as clams, oysters, polychaetes, insects, fish and crabs. The taxonomic keys for juveniles in many cases have not yet been written and even when published require expert taxonomists. This problem was again first tackled by stream ecologists who proposed to simplify their ecosystem by using functional group classification instead of taxonomic identification. Thus shredders, scrapers, filterers replaced large crayfish, caddis-flies, and may-flies even though the functional classification cut across traditional taxonomic lines.

In smaller ecosystems such as ponds and small streams it has been possible to measure whole-ecosystems variables such as net photosynthesis or respiration using whole-lake oxygen fluxes, isotope dispersion, or even carbon depletion. The process has provisionally been extended to incorporate large lakes (Tailing, 1976).

Functional components have the advantage of built-in robustness since they incorporate ecosystem homeostasis as explained below (i.e., the intertia and redundancy in ecosystems which tend to reduce overall change). A typical example of this would be the replacement of the attached stream algae Cladophora by the attached stream algae Tabellaria near the inflow of a well-treated but nutrient-rich domestic sewage outflow in the Truckee River, near Lake Tahoe (Home et al., 1978). Insect and presumably fish populations did not respond to this food chain switching presumably because either algae was equally acceptable (or unacceptable) as food.

Combined plankton-functional component index -- the SIV index

For purposes of monitoring the ecosystem effect of pollutants a combination of both the plankton and functonal components will be valuable. Large numbers of individuals (n) can be measured which will reduce type II errors and concomitant failure to detect pollution’s effects until it is too late. A large n will also reduce type I errors and risk of overstating an effect. The use of juvenile stages of commercially and recreationally important fish and shellfish will assist in the economic analysis and will also include “sensitive” species (sensu EPA guidelines on NPDES permits). Both indigenous and rare species can be accommodated in such an index. Finally, the robustness of the index will be ensured by incorporation of ecosystem homeostasis by the use of functional component variables.

The drawbacks to the SIV index in principle are similar to those of any other environmental scoping or health assessment namely:

- Require some measurement or knowledge of the ecosystem.
- Is hard to extrapolate backwards in time to pre- or low-pollution eras.
- May miss important effects if one component of the index was capable of indicating serious harm but the other components lagged behind in their responses.

The proposed SIV index has the advantage for aquatic ecosystem pollution studies that these drawbacks can be minimized particularly in the cost of data -collection since the precision of the index can be very high.

The main purpose of any index is to show changes over time or space. High precision is vital if change is to be detected in time for restorative measures to be put into effect.

The literature shows a number of multi-parameter indices or ranking systems used to measure the "trophic state" of lakes (i.e., their basic fertility of productivity). These include those by Lueschow et al, 1970; Shannon and Brezonik, 1972; McColl, 1972; Michalski and Conroy, 1972; Sheldon, 1972; Uttormark and Wall, 1975; Carlson, 1977; and the EPA's own modified index derived from an extensive study of 757 specially selected lakes (See Hem, Lambou, Williams, and Taylor, 1981). The SIV index does not attempt to improve these models especially those by Carlson 1977 and Hem (EPA) et al., 1981. Our purpose is to extend their use to cover both toxic and biostimulatory effects of point and non-point wastewater discharges as well as extend coverage beyond lakes to all aquatic ecosystems.

For example, one improvement of the model suggested by EPA (Hem et al., 1981) to use chlorophyll a not nutrient levels as a basis for trophic classification fits directly into the functional component mechanism of the SIV index.

Multi-parameter indices also exist which attempt to measure higher trophic level productivity including that of fish. This is a measure of ecosystem "health". Such attempts range from pioneering concepts such as those of Thienemann (1927) and Rawson (1951) to complex but realistic simulation models (e. g., Steele, 1974; Powell, in press). A "rough indicator of edaphic (= nutrient) conditions" combined with lake bathymetry (morphological structure) was the morphoedaphic index (MEI) of Rawson (1955) and Ryder (1965) and Ryder et al. (1974).

The MEI uses mean depth and fish harvest statistics and was designed for use in lakes. Since the most productive systems (lakes, streams, estuaries and coastal ocean waters) are shallow and well-stirred this index has limited use when expanded from typical thermally stratified lakes to all aquatic ecosystems.

Complex simulation models of the planktonic community are not yet usable as indices even though multiple parameters are involved. A primary reason is that such models are not normally designed to work with the kind of pollution stress normally imposed by toxic wastewater. Typically, the models will be perterbed by nutrients or the introduction of a natural change such as increased predation. Most chemical poisoning or aquatic habitat structural alteration has few natural analogs and these are yet little studied. The few potential analogous systems natural springs with high acidity as toxic metals have been little studied for metal toxicity dynamics. Almost no examples of organic biocide accumulation are available in natural aquatic ecosystems. However, metal or organic toxicants are a prime cause of aquatic ecosystem degradation, second only to dissolved oxygen reduction and diversion of water.

The construction of a numerical SIV index with some of the properties mentioned previously cannot be easily formulated in the abstract (see e.g., Boesch, 1977). Thus the index must be built on a case study and then generalized if possible. The task is formidable but an equal problem is acquiring an adequate data base which would also be available for other ecosystems. Records of planktonic and other biological variables are often available in the open literature. In contrast, pollution loading values are hard to find over long periods -- although they are usually available somewhere in the files of individual dischargers (Russel and Home, 1977) or in the files of the local regulatory agency (Home, Fischer and Roth, 1982).

V. Summary

An index which will measure the health of aquatic ecosystems would be very useful in determining the amount of damage, or recovery from damage, in aquatic ecosystems. The index should ideally be robust, precise, and multi-dimensional and reflect changes due to either toxicity or biostimulation. An index of selected indicator variables--the SIV index--is proposed which builds on the existing EPA and other indices used to estimate "trophic state". The SIV index differs from the existing habitat evaluation indices in that the bias is towards aquatic ecosystems rather than terrestrial ones. This bias is needed since the damage caused by humans to the two habitats is of a different kind. The structure of aquatic ecosystems is dynamic and is maintained by short-term biological and chemical inputs. Terrestrial ecosystems depend much more on the physical structures such as trees and hills. Water pollution usually destroys the chemical and biological structure while terrestrial disruption, such as housing developments or dams, destroys the entire physical structure.

The SIV index follows recent trends to use functional components of the ecosystem rather than only taxonomic classification. The index is comprehensive in that it uses both types of information. A major difference from other indices is an emphasis on precision so that small changes in the health of the ecosystem can be detected with statistical confidence. In this way damage can be detected before it is too late and recovery techniques modified during restoration to maximize benefits. The only way to achieve precision and avoid both type 1 and type 2 errors is to make a large number of measurements. This can be done if the variables chosen are inexpensive to measure, and this concept drives the choice of variables in the SIV index.

Common, numerous, and functionally important variables would be chosen for the SIV index. In most open-water aquatic ecosystems the plankton provide a good source of information on the health of the ecosystem. The plankton include the young stages of most commercially and recreationally important fishes, their food, and the photosynthetic base of the entire food chain. The plankton are sufficiently numerous and homogeneous to sample at a reasonable cost and are most directly exposed to water-born pollutants. For wetlands and streams the same principles apply but the collection techniques must be modified by the use of analogs to achieve the same high precision at a comparable cost.

Future research should focus on long-term data sets from already damaged test ecosystems where data are readily available and easily supplemented. This concept is opposite of the NSF long-term research program which considers only pristine ecosystems. Thus data from various less accessible "grey" literature will be the principle source of information.

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