Indices of Marine Degradation: Their Utility

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ABSTRACT / Improved definition of pollutant effects in coastal marine environments is needed for two principal reasons. First, we need better understanding of how much pollutant degradation exists. Then we need more agreement on its social importance. Only then can society decide more consistently and equitably how much pollutant impact is tolerable and how much is too much. Scientists alone cannot define "unreasonable degradation" in a social sense, of course, but we can define quantitative scales of degradation and (together with nonscientists) specify ranges on these scales of "warning" and "alarm." Rationales are presented for the urgency of these improvements.

A strategy is described for indexing the socially relevant features of coastal environments at greatest risk from pollutants. The strategy differs from most existing environmental indices in several respects. Each of the 11 indices proposed is constrained by the following design criteria: (1) socially relevant, (2) simple and easily understood by laymen, (3) scientifically defensible, (4) quantitative and expressed probabilistically, and (5) acceptable in terms of cost.

Evaluations of the draft indices are being completed by more than 50 collaborating scientists. One index is described to illustrate the utility of simple, socially relevant measures of marine degradation.

The optimism of scientists and engineers over their ability to help ameliorate environmental conflicts (generally in the future, "with better data") contrasts with the perceptions of others (Bell 1985, Feyerabend 1978, Cooper 1982). Less widespread optimism exists with regard to conflicts over acid precipitation, increased concentrations of atmospheric carbon dioxide, and other persistent issues. Many are disappointed with what can be done with data alone. Hope for much less disappointment in the future is hardly a solid basis for environmental management. In addition to making "better" measurements, we need more managerially reliable and relevant interpretations of the data if we are to have more useful measures of environmental quality (Limburg and others 1984).

It is important that the scientific community develop better consensus on the most useful measures of ecosystem degradation. The need is felt by decision makers (Ruckelshaus 1983, Levin and Kimball 1984) and by scientists (Cooper 1982, White 1984). To achieve better consensus scientists need to define measures of environmental impact that are more reliable, socially important, and understandable to the laity. For this purpose, we suggest indices of degradation, to complement useful measures of environmental status and trend already in use.

KEY WORDS: Indices; Environmental quality; Indicators, marine; Indicators, coastal and estuarine; Indicators, techniques; Measures; Monitoring

Several technical and nontechnical collaborators have helped develop, improve, and test 11 such indices. These activities began in December 1981. Tests of the resulting indices of coastal degradation are now (August 1985) being reviewed for publication as NOAA reports.

Why Are Indices Needed?

Why emphasize indices? Why not continue to rely upon direct measures of degradation, inferences from controlled measurements, and other indicators of environmental quality? While many available indicators, both empirical and theoretical, are useful in pollution assessment, simple indices are often most advantageous from the decision-maker's perspective (for example, Train 1972 and 1973). A related need is the commonly expressed imperative for more consistent and reliable criteria of ecologically important impact (for example, Ruckelshaus 1983, Levin and Kimball 1984). Governments have long needed indices of their economic conditions. For many of the same needs, including the need to understand influences of environmental quality on economics (for example, Soule and Walsh 1983), we expect marine environmental quality to be monitored more thoughtfully and reliably in the near future.

Indices, unlike direct measurements, can provide the important benefit of being more readily interpret-

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able, by the scientist and particularly by the layman (ACMRR/IABO 1976, Ott 1978, Train 1973 [cited in Ott 1978:3], Thomas 1972). The indices we discuss are tangible. They can be interpreted readily, without reference to additional standards or reference values. Additional information may be needed for full interpretation, but each index is intrinsically informative. Direct measures alone of most features (say, average annual hatchlings per nest of a coastal bird) are marginally interpretable in managerial contexts. However, the index of reproductive success in marine birds uses this same measure relative to a standard and is directly interpretable (see below). Indices of this form are used commonly in decision making, but they are often defined in haste without reflection upon their statistical properties or ecological consistency.

We also wish to minimize false alarms. Direct measures of environmental change are often variable enough to seem man-dominated. These indices, however, require that spatial and temporal variance in the variables indexed be estimated adequately to distinguish the pollutant signal; inadequate estimates of these variances preclude use of the indices. Consequently the indices specify adequate data sets, and the probabilistic structure of each index guards against spurious interpretations.

Improved indices are needed as indicators of pollutant degradation for monitoring programs. It is evident that major collaborative efforts would be necessary to monitor adequately on a national basis, that is, to monitor for compliance with laws and regulations, for trends in pollution and pollution effects, and so forth (Segar 1981).

Improved management guidance is needed in areas such as these: (a) Are the early-life stages of valued fish and shellfish stocks suffering excessive pollutant-induced mortality? (b) Can we afford more reliable standards for pathogens in shellfish? (c) What, if anything, should be done about hypoxia in particular regions? These and other issues commonly beget requests to quantify degradation and its warning signs. Consequently, it is important not only that useful indices of degradation provide reliable scales of degradation, but also that these scales should identify levels of warning or of ecologically important impact. (Ecologically important impacts, as defined by scientists, may or may not be socially acceptable as perceived by the decision maker, of course.)

Reliable figures on the national economic significance of over- and underregulation may not be available, but examples of costly regulatory decisions are abundant. For example, the municipalities of New York City and nearby New Jersey invested heavily in land-based alternatives to ocean dumping of sewage sludge. This heavy investment was supported primarily by about $100M in construction grants awarded by the US EPA under the Clean Water Act. This investment was required initially by an EPA policy that sewage sludge dumping be phased out by the end of 1981 (see 40 CFR 220.3[2]). In 1977, the US Congress amended the Marine Protection, Research and Sanctuary Act (more commonly referred to as the Ocean Dumping Act) to require that no permit be issued by the EPA that would allow the ocean dumping of sewage sludge after 1981. The amendment defined sewage sludge as municipal wastewater treatment sludge that might "unreasonably degrade or endanger human health, welfare, or amenities" of the marine environment. The Conference Committee Report indicated that sewage sludge that did not comply with EPA's marine environmental impact criteria could not be ocean dumped after this 1981 phase-out date. The EPA therefore continued to require the phasing out of sewage sludge dumping. New York City sued the EPA —*City of New York* v *EPA*, 543 F. suppl. 1084 (SDNY 1981)—arguing that the EPA, in determining whether sludge dumping unreasonably degrades the marine environment, must balance the impact of ocean dumping against the impact on the environment from alternative methods of sludge disposal. The court agreed that the term *unreasonable* calls for a balancing of potential impacts and allowed the city to continue dumping, even after 1981, until such time as the EPA did consider and weigh all the factors involved. Thus, much of the investment in planning, design of alternative disposal facilities, and purchase of equipment by the city and other municipalities to end ocean dumping has been lost.

This sort of costly regulatory decision, arising in large degree from uncertain interpretations of "unreasonable degradation," seems to be uncomfortably common. Other, substantial, opportunity costs can be incurred, for instance, when development proposals suffer prolonged delays due to regulatory indecision over projected impacts of uncertain social significance (Schramm and others 1979). Conversely, inadequate projections of risk from development can, as shown repeatedly over recent decades, lead to costly losses of resources, and so forth. Both pollution control costs and the dollar costs of environmental damage seem to be very sensitive to improved regulatory understanding of environmental impacts (Ridker and Watson 1981, Peskin and others 1981).

The words *unreasonable degradation* in the Ocean Dumping Act, and similar qualitative phrases in other environmental legislation, constituted a problem in the

Table 1. Proposed indices of coastal degradation.

Dietary risks from toxicants in marine foods
Pollutant stress in sediments
Pollutant stress in the water column
Human pathogen risks
Benthic species composition and abundance
Fish and shellfish diseases
Fecundity in fish and shellfish
Mortality in eggs and larvae of fish and shellfish—field measurements
Mortality in eggs and larvae of fish and shellfish—laboratory measurements
Reproductive success in marine birds
Oxygen depletion effects

New York City v *EPA* court case. Understandably, laws are not quantitative in their definitions of socially unreasonable degradation, but this difficulty in quantifying such key phrases extends even to the regulatory agencies responsible for implementing the laws. Disagreements over what constitutes unreasonable environmental degradation constrain governmental commitment to remedy degradation. If we cannot measure socially excessive impacts in agreed ways, how can governments decide to regulate or not, or encourage better waste management? Indices alone (that is, indices of oxygen depletion, of human pathogen risks, and so forth) could not resolve the impacts of sewage sludge dumping. But indices can quantify the combined impacts of the several pollutant sources, providing consistent bases for social determinations as to (aggregate) reasonableness. To the extent possible, allocation of blame among the several sources of pollution must rely upon various research and monitoring strategies.

Measurement and interpretation of environmental quality entail their own costs, of course. While it would be "nice to know" many facets of marine environmental quality (see, for instance, Table 1), governments must consider the costs of monitoring.

What Sorts of Indices Are Needed?

Several workshops and individual authors have grappled with the notion of what constitutes ecologically important (sometimes called significant) impact (Ott 1978, Thomas 1972, Buffington and others 1980). We prefer to use *important* rather than *significant* ecological impact. *Significant* has the generally understood connotation of statistical significance.

Judging from some of the literature, the view seems to be prevalent that ecologically important impact can be defined on the basis of ecological insight and rules of scientific evidence alone; that is, *ecologically important impact* can be defined independently of social values. The issue of ecologically important impact is clarified by considering it under two questions: (a) Is it important enough to justify scientists' warnings to decision makers? or (b) Is it important enough to justify action by decison makers? We are concerned here with the first, and we aim to catalyze consensus among scientists as to which environmental impacts are important enough to justify warnings. Criteria for such justification must be based not only upon data analysis but on professional interpretation—interpretation in the context of judgments about social issues.

Kesteven (1969) was one of the first to summarize the central issue clearly and articulately, with specific reference to ecology. He emphasized the ethical balance required of ecologists, the obligation to inform public policy while avoiding the impression of more certain knowledge than exists. Ecologists' professional judgments about important impacts can be compared to engineers' inclusion of social norms in deciding upon safe engineering features in aircraft. Criteria for increasingly rigorous assessment and management of environmental risk can evolve in a manner similar to the historical improvements outlined by Starr (1983) for risk management in aircraft. Assessment of environmental risk is appropriately influenced by social norms, somewhat in the same manner that acceptable engineering risks in aviation were influenced by norms of excess incidence of deaths from flying accidents.

For our purposes, we see no utility in distinguishing between *ecologically important* and *socially important* impacts. We conclude that ecologists may recommend "important" levels of warning on index scales of degradation, but such suggestions inescapably require social judgments. Such suggestions are no less value laden than environmental decisions typically and appropriately considered by broader segments of society.

We suggest that more emphasis upon field-based scales of degradation can improve upon the reliability of existing laboratory-based scales for management and policy definition of *unreasonable degradation.* The principal reason for this is the clear tendency for laboratory-based assessments of pollution impact to over- or underestimate impact and to bias consequent regulation (White and Champ 1983, Kimball and Levin 1985). This leads to waste in government and industry and to waste of natural resources.

Criteria for Useful Indices

Although criteria for measuring ecologically important impact cannot be derived from science alone, four of the most useful criteria for defining such impacts are close to those already given by Buffington (1976) and Buffington and others (1980):

1) Measureable changes, differing with specified degrees of confidence from the distribution of normal ecological states
2) Changes that persist or will predictably persist over several years
3) Changes reliably attributable to man's activity
4) Changes at the population, community, or ecosystem levels

Rationales for these criteria and for the degree of scientific consensus on them are summarized by Sharma and others (1976), Eberhardt (1978), US Council on Environmental Quality and US Fish and Wildlife Service (1980), and Beanlands and Duinker (1983).

While we agree with these criteria, they do not seem to be sufficient, as they raise additional questions. First, should some effects at levels of ecological organization below populations be considered important? Is, for instance, persistent, pollutant-induced mortality in early-life stages of fishes not important only because we have not yet resolved the stock-recruit problem? That is, we can measure early-life pollutant-induced mortality in fish eggs and larvae, but with rare exceptions we cannot assess quantitatively the population consequences. A prudent decision maker might wish to consider ameliorating early-life mortality in fishes even prior to quantitative evidence of declining stocks.

Another crucial criterion of importance is the geographic scale of impact. Intense but small-scale pollutant-induced impacts are numerous, but they are seldom considered important. However, the size of any particular impact that becomes socially important is sensitive enough to several other factors peculiar to the region affected that spatial scale is a very imperfect measure of importance. Examples of such factors include: numbers of people and uses affected, regional perceptions of monetary and other losses, overlap with other impacts, and scale of impacts on particular resources relative to their total distributions. We cannot envision how to quantify these and other regionally important determinants of "social importance." We do emphasize the value of mapping the severity of effects, as stressed by Mearns and O'Connor (1984), to facilitate accurate perceptions of importance in the broadest contexts.

Some authors have emphasized measures of ecosystem and community function as important indications of degradation (Kimball and Levin 1985, Beanlands and Duinker 1984, Cairns 1981). Indeed, some argue convincingly that pollutant influences on ecosystem structure and function are of primary concern (for example, Levin and Kimball 1984). We acknowledge the obvious importance of ecosystem functional states in general terms, but the findings of Wolfe and others (1982) in the New York Bight, Schindler (1983) and Schindler and others (1985) in artificially stressed lakes, and Ryder and Edwards (1985) in the Great Lakes support our perception that population-level impacts are generally measurable and socially interpretable prior to impacts on community and ecosystem function. We encourage further efforts to define useful measures of degraded ecosystem function, but have not found such measures that compete with the proposed indices (Table 1) in terms of the following criteria:

- Socially relevant or socially important. We should measure, directly or indirectly, those characteristics of ecosystems of interest to people and their governments.
- Simply and easily understood by laymen, that is, by the public and by managers and policy makers.
- Scientifically defensible, for the limited purposes intended. Causal relations between effects and pollutants, even combined pollutants, will seldom be evident from index values alone. Source–fate–effect relationships generally yield only to interdisciplinary research. Indices are useful (in consort with all other available assessment strategies) in relating impacts back to their major, causative pollutant sources.
- Quantitative, and expressed probabilistically in terms of excess prevalence or degree of impact.
- Acceptable in terms of cost.

No single index will be adequate to indicate unreasonable degradation in its many possible manifestations. Eleven indices of coastal and estuarine degradation (Table 1) strike some balance between detecting the most plausible kinds of important impacts vs the costs of measurement and interpretation. While we have developed formal rules for evaluating or testing the indices, the ultimate test will be the degree of their acceptance by the scientific community, by potential users, and by the decision makers.

The indices being tested are tangible indicators of excess prevalence, for example, excess prevalence of dietary risks from toxicants in marine foods, and of human pathogens in bathing waters. We avoid combining measures of dissimilar phenomena into "agglomerative" indices of, say, public health. Such agglomeration of particular measures leads to ambiguity as to what is indexed with what weight, and to the "eclipsing" of some measures indexed by other measures (Ott 1978). Eclipsing occurs when a measure of poor environmental quality is overshadowed or eclipsed by other measures, resulting in an overall index that fails to reflect impairment of quality (Inhaber 1976).

The scale for the indices ranges from zero to one, indicating no measurable pollutant degradation, to positive numbers corresponding to increasing degrees of degradation. This is illustrated in Figure 1. The warning range on the scale begins at 1, and 10 demarcates the "warning" and "alarm" ranges of the scale. The scale has no upper bound.

Data appropriate for this indexing approach must ensure reasonably powerful statistical tests; that is, unless the index can distinguish impacted regions or times from reference areas or times with power of 70% or greater, the index is not defined. Stated another way, the type-II or beta error must be less than 0.3 (for example, see Green 1979).

Table 2 shows the two generalized equations used for the indices. The structural form of all indices is similar: actual conditions are expressed as a proportion of critical or warning conditions. In a few cases existing regulatory standards (for example, dietary risks from PCBs) can be used as critical values for comparison with actual conditions. In most cases standards are lacking; ecological standards are then defined in probabilistic terms. The statistical standard for warning is exceptional departure from normal conditions (probability greater than 1 in 10) when departures are demonstrably pollutant-induced.

Illustrating an Index

In order to make the form of the indices explicit, one index is illustrated—the index of reproductive success in marine birds. This index relies upon field observations of fledgling success in marine birds, that is, upon survival from egg through fledgling stage.

The particular illustration of this index is based upon osprey (*Pandion haliaetus*) reproductive success between Boston and New York. (Ideally, this index should consider several bird species in the same region.) This population of ospreys has been studied extensively from 1969 to the present. Essentially, all osprey nests in this region have been censused over this 15-year period, which includes counts of successful fledglings.

A convincing body of evidence relates gradual, erratic improvement in reproductive success (Figure 2) to declining environmental concentrations of DDT and its degradation products (Spitzer and Poole 1980). The natural variability from one year to another seems to result primarily from weather effects, food availability, and suitable nesting sites.

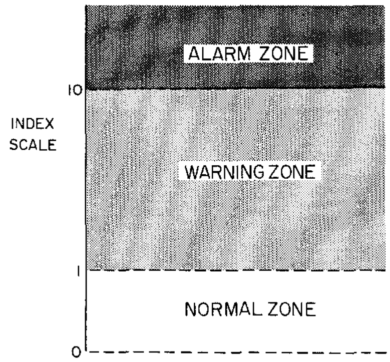

Figure 1. Interpretation of the index scale.

Table 3 shows the form of the index. The numerator is the lowest value of osprey productivity that would be expected under normal conditions once in ten years. The denominator is the mean productivity in recent years, that is, in one or more recent years with hypothesized pollutant impacts on reproduction. Only when current productivity declines to the lower 90% prediction limit of normal productivity will the index reach unity. More than 100 samples of osprey productivity were available for nearly every normal and test year. Consequently, the index test is robust with regard to nonnormality by virtue of the central limit theorem.

The index simply compares the lowest mean number of fledglings per nest expected in "normal" years (recent years without impact because DDE has mostly passed out of the system) to the means of fledglings during years of hypothesized impact. Mean productivity in normal years (1980–84) has been 1.3 fledglings per active nest. The lowest expected number of fledglings (1.1 per nest) is the low, one-tailed, 90% prediction limit on this normal productivity. The comparison is made with the four years (1969–72) during which DDT impacts appear to have been the greatest (Spitzer and others 1978). The average number of young fledged per active nest during 1969–72 was 0.59.

Calculation of the index is based upon the formula:

$$I = \left[\frac{\bar{X} - t_{(0.1)} S_X \sqrt{\frac{1}{n} \frac{1}{m}}}{\bar{Y}} \right]^b$$

where

$\bar{Y}$ = mean productivity in test area or time period, averaged over m years
$\bar{X}$ = mean productivity in reference area or time period, averaged over n years

Table 2. Indices are of two structural forms.

1) Regulatory standard: $\frac{\text{critical}}{\text{actual}}$, for example:
- Dietary risks from toxicants in marine foods
- Human pathogen risks from bathing

(both relative to Federal or State standards)

2) Ecological, statistical standard: $\frac{\text{1 in 10 worst bound of normal}}{\text{actual}}$, for example:
- Early-life reproductive mortality
- Oxygen depletion effects

Figure 2. Productivity of ospreys (fledglings per active nest) from Boston to New York. Courtesy of P. Spitzer, Center for Northern Studies, Wolcott, Vermont.

S_X = standard deviation of mean annual productivity in reference area
$t_{(0.1)}$ = one-tailed t statistic ($df = n - 1$)
b = scaling factor to ensure comparable scales for all indices in the series

Hence, the average index value during 1969–72 from Boston to New York was:

$$I = \left[\frac{1.284 - 0.2192}{0.5875}\right]^b = 1.813^b$$

The scaling factor, b, is determined by the degree of pollutant-induced reproductive inhibition that is considered "alarming." The scaling factor has the useful property of making the index take on reasonable values over its entire range that are also consistent with other indices in the series. The numeric index scale corresponds to three zones: a normal zone (0–1), a warning zone (>1–10), and an alarm zone (>10) (see Figure 1). The index proportion, critical/actual conditions or C/A (see Table 2), correctly yields unity for the lower bound of "warning" (Figure 1). However, if A falls just below the productivity rate necessary to maintain population size (the "replacement rate"), the ratio C/A rises to only 1.3 or so in this example. But pollutant-induced population declines of ospreys, and other susceptible birds, have already been considered socially alarming situations (US CEQ 1972). So it seems appropriate that osprey reproductive impairment persistently below their replacement rate of 0.8 fledglings per active nest (Spitzer 1980) be indexed as an "alarming" situation. This judgment is reinforced by the realization that productivity in several marine colonially nesting birds is similarly affected by persistent organic toxicants (Nisbet 1980). Recognizing that productivity of the most sensitive species may or may not be monitored at the right time and place, indexing this replacement rate as 10 may be an excessively relaxed definition of "alarm."

Reproductive impairment that barely, but persistently, prevents replacement of population deaths is therefore scaled as $I = 10$ (Figure 1). Using the lower bound of normal productivity calculated above and the replacement rate of 0.8, the scaling factor is:

$$10 = \left[\frac{1.0649}{0.8}\right]^b$$

$$b = 8.05$$

So the index value for the impacted period 1969–72 is:

$$I = 1.813^{8.05} = 120$$

Note that the scaling factor, b, does not alter the productivity ratios of 0 or 1, since these numbers to any power remain unchanged.

The importance of the impact is, of course, determined not only by the severity of reproductive impairment and its temporal persistence, but by the geographic extent of that impairment. In this case the Massachusetts to Virginia coastal region supported the largest breeding concentration of ospreys in the world during the 19th and 20th centuries (Spitzer and Poole 1980).

While this example indexes a prior impact, a similar index value might have been calculated in the early

Table 3. Index of reproductive success in marine birds.

$$I = \frac{\text{low, 90\% prediction limit on fledglings per nest in "normal" years}}{\text{fledglings per nest averaged over one to several recent years}}$$

Values of the index range:

<1	Indicating no detectible declines in reproductive success
1–10	Indicating reproductive success has declined, with ≥90% confidence; "warning" zone
>10	Indicating pronounced reproductive declines that will not sustain the population; "alarm" zone

1970s, since some prior data existed for estimating normal reproductive success and its annual variability.

Testing the Indices, and Their Limitations

It is important to assess the statistical power of the indices. It seems appropriately rigorous to require that indices of degradation detect real impacts with type II errors of 30% or less; that is, the indices should fail, on average, to detect only one in three important impacts. If we consider as real impacts persistent 50% declines in osprey productivity due to pesticides, what is the probability of detecting such impacts? In our example, the power is greater than 90%. In other terms, the β or type-II error is less than 10%. This is a more powerful test than ecologists typically have for hypothesized impacts. It demonstrates that some ecological impacts can be rigorously quantified in probabilistic terms.

In addition to testing the indices for scientific adequacy, managerial and policy testing is also needed. Environmental decision makers have commented upon the indices during development; their receptivity to calculated indices is obviously extremely important.

Utility of the indices is potentially similar to that of economic indices—they portray current status, but predict nothing about the future. Neither do indices provide insight into the dynamics of populations or ecosystems.

Caveats on the use of indices are similar to appropriate warnings about other indicators of environmental degradation. There are many such warnings about the traditional and ad hoc indicators in common use (for example, Beanlands and Duinker 1983, Segar 1981, White 1984). Perhaps the greatest limitation upon useful indices (and other indicators) is the paucity of appropriate data, now and in the foreseeable future.

Conclusions

Important impacts are, and must be, defined at least partially in social terms. Values of one and greater on proposed index scales, the "warning" and "alarm" ranges, are normative, suggested definitions of important impacts. Useful definitions of these ranges on the index scales require consensus among scientists and decision makers. Primarily field-based indices of marine degradation can contribute strongly to more rational, equitable, and less expensive pollutant regulations.

Experimental designs and monitoring strategies should explicitly define their risks of both type-I and type-II errors. The latter, often overlooked, risk of not detecting actual impacts should be demonstrably small (say β <0.3), thereby assuring that assessments would detect real effects with acceptable likelihood. Indices can help managers and policy makers commit the nation to avoiding "unreasonable degradation" in quantified terms. Indices could also constitute rigorously tested, socially relevant measures of pollution impact for use in monitoring. This is particularly important because the large costs of monitoring require great care in choosing useful measures of ecological state and function, and equal care in defining sampling designs.

A final conclusion is that the sparsity of appropriate data is a major limitation upon managerial uses of indices (and other indicators of environmental quality). This is particularly true of the few measurements over long time periods that reliably describe the distribution of normal environmental structure and rates of change. This limitation will persist, but it need not preclude more useful characterizations of environmental quality. However imprecise and arguable, socially important environmental impacts do exist. We have discussed only some steps toward scientific consensus on their recognition.

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