GOALS FOR RESTORING A HEALTHY ESTUARY

Wim Kimmerer
September 25, 1995

Introduction

A workshop on restoration goals for the San Francisco Bay-Delta Estuary will be held in Tiburon on 2 October 1995. The purpose of the workshop is to begin to resolve technical issues regarding achievable goals for the restoration of a "healthy" estuary. Participants will include many of the scientists most active in research and management activities in the Bay-Delta. Output of the workshop will be presented for use in the CALFED process under the assumption that to achieve restoration of the ecosystem requires a clear statement of restoration goals.

This white paper has been prepared to summarize some of the technical issues regarding restoration goals and ecosystem health. The concept of ecosystem "health" is more than mere "ecobabble" and, as discussed below, understanding the concepts is essential for setting achievable goals. This paper is my attempt to set the stage for the discussion at the workshop; I hope that it will stimulate critical thinking of the conceptual and practical bases of goals for the ecosystem. This paper is necessarily subjective, and incorporates my biases: for example, my ignorance and therefore neglect of how these concepts apply to wetlands.

A great deal of effort has been expended by a variety of agencies and individuals in attempting to protect, restore, enhance, and analyze the San Francisco Bay-Delta estuarine ecosystem. The ultimate goals of all this activity have never been stated very clearly. Most of the planning and regulatory documents on restoration activities give goals that are either quite concrete but limited (e.g. to reverse the decline in abundance of certain species of fish) or rather vague. Terms such as "ecosystem health", "ecosystem integrity", "ecosystem function", "biodiversity", and "balanced indigenous ecosystem" are used frequently in written material on ecosystem restoration; none of these terms is sufficiently well-defined for this ecosystem to be useful in setting achievable goals.

To establish a clear direction for restoration of the Bay-Delta ecosystem, clear goals are necessary. The principal purpose of this workshop is to provide the technical basis for those goals, and for indicators or "performance measures" that can be used to determine progress toward these goals..

We must keep in mind that bringing the estuary to some desired state in the future cannot be the same as restoring it to some near-pristine condition in terms of species composition or structure: the estuary has already be irreversibly altered. Instead we need to define what we, as biologists, think the desired state or set of states should be, and what should or should not be included in a description of those states. In future workshops, other societal values will presumably be added to the definition. For example, a vision of the estuary constructed by biologists may include its use for rearing by large numbers of juvenile chinook salmon, while a vision created by a another group may not include rearing juvenile salmon at all. Since it will be possible to have a "healthy, functioning" ecosystem either way, the pathways to defining the desirable estuarine state(s) will necessarily involve difficult choices based as much on aesthetics or human use as on science.

Problem statement When we use the term "ecosystem health", what do we mean? The underlying problem is largely semantic, resulting from the extension of the concept of health from an individual to an ecosystem. Human health is fairly unambiguous and, in the twentieth century, based on a clear body of theory about the homeostatic properties of an organism. Ecosystem theory is not nearly as well developed, nor does it include a mechanism for homeostasis. Instead of a homeostatic mechanism, an ecosystem is believed to have one or possibly many alternative set points or region (i.e. sets of values of all state variables) toward which it moves, even as the set points themselves change because of changing physical conditions. This differs from homeostasis in that there is no ideal or target set point; instead, the set point is a consequence of the various interacting feedbacks in the system.

Although the concept of ecosystem health is not yet well defined, most ecologists would agree on the relative health of, say, the East River and Tomales Bay. Most of us would define a "healthy" estuary as one in which a full complement of estuarine species flourishes, with thriving, diverse wetlands, clear water, plenty of oxygen, numerous fish of many species and a variety of sizes, and if there is a significant human population nearby, thriving commercial and recreational fisheries supported by natural production.

In an attempt to cut through semantic problems, I assume that the goal of restoration is a "healthy", "functioning" ecosystem with plenty of "integrity", a "balanced, indigenous community", and an appropriate degree of "biodiversity". These various terms about the status of the ecosystem are made synonymous with each other and with restoration goals. In addition, "restoration" is used here to mean restoration of the ecosystem to a healthy state, not to some previous state. Hereafter I use the term "ecosystem health" to mean the status of the Bay-Delta ecosystem along a continuum with our ultimately desired ecosystem as an endpoint (or one of a number of interchangeable endpoints) toward which we hope to move the current, less than desirable, ecosystem. The other endpoint need not be defined.

Tenets for the workshop

1. Time moves in one direction only; therefore, many of the changes that have occurred in the estuary are either irreversible (e.g. introduced species) or practically so (e.g. dams).

2. Therefore, past states of the ecosystem will not be used as goals for restoration of the estuary; but rather as a guide to system response

3. Natural change in an ecosystem is not oriented toward a goal

4. The ecosystem under consideration comprises the San Francisco Bay-Delta estuary from approximately the Golden Gate to the upper limit of tidal action, including its open waters and tidal marshes.

Questions for the workshop

The principal issues to be addressed at the workshops are:

1. What should be the scientific basis for goals and objectives for restoration of the estuary?
2. What are the most useful indicators of ecosystem health for this estuary?
3. How do indicators of ecosystem health vary between wetlands and open water?
4. Are there any properties of the whole ecosystem (as opposed to populations or physical or chemical variables) that can be used to describe ecosystem health in a scientifically defensible way?
5. Are specific numerical objectives for population abundance or other variables warranted on a technical basis?

Secondary issues include:

6. Should goals be set in terms of habitat explicitly, or in terms of the populations expected to occupy that habitat (more a concern for open water than for wetlands)?
7. How should we account for future risks to the ecosystem such as sea level rise or the increasing human population and attendant increase in demands?

I anticipate that these issues will be addressed using a triage approach, in which we sort the issues into:

1. Issues on which consensus is or has been achieved

2. Issues that are not amendable to consensus because data are lacking, the issue is intractable, or interpretations are too divergent.

3. Issues for which consensus could be achieved following a well-structured program of investigation

Existing Information

There is a serious risk in this workshop of "re-inventing the wheel". Many people have addressed the issue of ecosystem health, some as it applies to estuaries. In this section I examine some of these efforts to glean from them ideas useful in our effort.

A brief literature review Ecology is considered a young science; the sub-discipline that addresses ecosystem health is in its infancy and growing rapidly. As with any young science, much of the literature concerns definitions. Here I review briefly the general tone of this literature as it relates to the San Francisco Bay-Delta estuary. Key references are in the Bibliography.

The literature on ecosystem health mostly falls into two categories: discussions of what constitutes ecosystem health and how one might measure it, and scientific articles analyzing human influences on ecosystems that result in specific instances of degradation (e.g. metal pollution). The latter class of articles does not offer much in terms of definition. Many articles in the former class suffer from excessive generality, or they offer indicators of ecosystem health that cannot be applied to this estuary, mostly because they are not pertinent to the problems faced here.

The analogy to human health is weak, as discussed above. There is no optimum state for the ecosystem, so goals must be subjective. Therefore, how can the status of the ecosystem be interpreted as either healthy or unhealthy? Several common themes run through the literature on ecosystem health or integrity; these are listed below at the beginning of each paragraph in italics.

Use of poorly defined terminology. The terminology of this branch of ecology is rather weak and poorly defined. Terms such as "balanced ecosystem" tend to be used without definition or critical appraisal. Using the terminology suggested above should prevent difficulties with semantics.

The concept of ecosystem integrity. Ecosystem "integrity" is closely related to (or indistinguishable from) that of "health". Regier (1993) listed about 40 attributes of an ecosystem with integrity, based on discussions in a conference on that topic (Woodley et al. 1993). With only one exception, these attributes could apply equally well (or poorly) to an ecosystem in any state, however degraded. For example, an ecosystem with integrity ...

- "has as its primary nexus a set of living organisms, each unique but always changing, within adapting populations of different evolving species or taxa...
- is a self-organizing dissipative system which may represent a compromise between the thermodynamic imperative of energy destruction...and the biological imperative of survival." (Regier 1993)

The sole exception is that an ecosystem with integrity is said to contain "some relatively large, longer-lived plant and animal organisms..." with various functions. Thus, despite the growing literature on this topic, this concept appears to have little to offer for developing a working definition of ecosystem health.

The concept of sustainability. Much of the literature on this topic uses terms like "self-sustaining" as an indicator of health. However, any ecosystem is self-sustaining provided its energy supply is adequate and conditions do not preclude life. What this term apparently means is that ecosystem components *desired by humans* occur in self-sustaining populations.

Presented this way, this attribute of ecosystem health is redundant to the general description of a healthy ecosystem given above. A related topic is the sustainability of human use of an ecosystem for harvest, recreation, or other purposes. The ecosystem need not sustain such uses without intervention; genetic considerations aside, using hatcheries to support a major fishery does not necessarily impair the attributes that make the ecosystem otherwise healthy.

Anthropogenic disturbance contrasted with "natural" disturbance. The literature generally distinguishes anthropogenic disturbance from the "natural" ebb and flow of events in an ecosystem. This distinction under-represents the capacity of nature for catastrophe. Natural disturbances of a severity equal to the most severe human interference have occurred in geological time if not in historical time. Anthropogenic effects differ from natural disturbance less in their severity than in their frequency and therefore capacity for cumulative effects, although some anthropogenic insults have no close parallel in nature.

"Holistic" approaches. The recent trend toward solutions of problems in ecosystems instead of populations extends into the concept of ecosystem health. The idea of examining the entire ecosystem has attractive parallels in medicine. However, it is not clear that there are emergent properties of ecosystems that can be used in such a way. Furthermore, ecologists construct ecosystems from their observed parts: for example, measures of ecosystem properties like diversity or energy flow can only be determined by detailed sampling of individual components. Interestingly, the use of the "fish-X2" relationships to support a management measure for the Bay-Delta is a rare example in of applying a remedy to many parts of an ecosystem at once. Note that in this case the mechanisms behind the relationships are not well understood, recalling the analogy to early medicine in which physiological understanding was lacking.

Goals of restoration vs. indicator variables. If the goal of restoration is to produce a "healthy" estuarine ecosystem, then the objectives of restoration actions should be to improve the status of the ecosystem in terms of indicators of "health". Therefore these indicators need to be attributes that are measurable, scientifically defensible, and interpretable. This may seem obvious, but many proposed measures of ecosystem health do not meet some or all of these criteria.

Comparison of reference and stressed systems. Most of the recommendations for measures of ecosystem health include comparisons with more-or-less pristine reference sites. This works reasonably well for the ecosystems discussed by the existing literature, which include terrestrial sites, lakes, and rivers, but only rarely estuaries. Comparison among large numbers of systems differing in relatively few ways is the basis for the EPA's Environmental Management and Assessment Program (EMAP), which has been applied to estuaries of the east and Gulf coasts (see below). It is not clear that Pacific coast estuaries can be similarly compared, given tremendous difference in size, watersheds, topography, flow, tides, and other characteristics. However, this comparative technique might be possible for tidal wetlands, for which at least functional (if not structural) comparisons might be useful (e.g. primary production).

D-021891

Use of relative abundance of sensitive and tolerant species. Sensitive species can be used as indicators of stressed conditions if the identity of the species and its response to the particular stress under consideration are reasonably certain. Estuarine and marine systems, because of their open exchange with the sea, may be inappropriate systems for the application of this approach. For example, the marine polychaete *Capitella capitata* has long been considered an indicator of sewage stress, but recently it has been shown to be a complex of perhaps 10 or so species with different degrees of tolerance for organic enrichment. To use the differential response of sensitive and tolerant species as an index of stress requires either certainty about these species' relative tolerances to the relevant stress, or comparison between stressed and unstressed locations.

Parallel efforts in this estuary There are several efforts now underway in the form of other workshops and activities aimed at defining goals or ecosystem health. Important activities include:

1. The Bay Area Wetlands Ecosystem Goals Project, which will hold a meeting of its Resource Managers Group on Monday, September 25.

2. A workshop on "Creating Sustainable Landscapes in the San Francisco Bay Region" to be held on September 30 by the Institute for Ecological Health, San Francisco State University

Although the purposes of these activities and the mix of disciplines is different from those of the October 2 workshop, useful outputs of these workshops should be incorporated to the greatest extent possible.

EMAP The EPA's Environmental Management and Assessment Program (EMAP) is intended to assess the status of the nation's ecosystems. Emphasis has been on estuarine ecosystems on the Gulf and east coasts. This program is designed to examine populations of ecosystems rather than individual systems, so the overall approach is different from ours. However, the underlying goals should be similar. Material on EMAP was obtained from various Internet sites.

Identifying values and the associated questions is an important first step in the EMAP process. Values desired for ecological resources typically fall into three categories:

1. *Sustainability*: maintaining the desired uses of these resources over time.
2. *Productivity*: net accumulation of plant and animal matter, for example, food, timber, natural production.
3. *Aesthetics*: retaining the natural beauty of the landscape.

Examples of questions to be addressed by EMAP:

- What proportion of estuarine area in large estuaries, tidal rivers, and small estuaries has fish with gross pathologies?

- What proportion of lakes are eutrophic, mesotrophic, and oligotrophic?
- What proportion of wetlands have less than the expected number and composition of native plant species?
- What proportion of forests have vegetative structure and functions to sustain forest biodiversity?
- What proportion of the surficial sediments in harbors and embayments are toxic to aquatic organisms?

Indicators for EMAP are chosen using societal values as a basis. These indicators fall into two classes: *condition* indicators, which provide a quantitative estimate of the state of a resource, and *stressor* indicators, which display the magnitude of an anthropogenic or natural stressor, provided these stressors are believed to affect ecosystem condition. For estuaries, the indicators being used are:

- Dissolved oxygen
- Quantity of marine debris
- Water clarity
- Sediments: toxicity, quality
- Benthos: condition, abundance, diversity
- Fish: condition, abundance, diversity

EMAP is based on a comparison among numerous sites, so these indicators can be used in a comparative sense. However, some of them (e.g. percent saturation of dissolved oxygen) can be used as absolute measures. The biological indicators are based on the Index of Biotic Integrity (IBI; Karr et al. 1986), which is determined from samples of the species composition of fish in lakes. Metrics included in the IBI include the numbers of species and individuals, number in several different taxonomic groups, percent in various trophic groups, percent tolerant and intolerant species, percent hybrids, and percent with disease. Use of this index requires comparison among various sites, so it is suitable only where a large number of stressed and unstressed sites are available for comparison.

Biodiversity initiatives Numerous initiatives are aimed at maintaining or otherwise addressing biodiversity. This term is not generally very clearly defined or differentiated from the more traditional term "diversity". For example, biodiversity is "...defined as the collection of genomes, species, and ecosystems occurring in a geographically defined region" (Ocean Studies Board 1995). This definition is a generalization of the traditional term, which refers to some measure of the number of species within a larger taxonomic or functional grouping, and the degree to which the species composition is dominated by one or a few species. Thus, "biodiversity" by this definition is vaguer and therefore less useful for measurement, regardless of its utility as a rallying point for reducing the global rate of extinction.

CALFED requirements CALFED (a consortium of California and Federal resource agencies) is attempting to identify the problems in the estuary and the tradeoffs that need to be made to reduce the impacts of water development. They have developed a problem

D-021893

statement that explicitly shifts the definition of the problems of the Bay-Delta ecosystem from variables of societal interest (i.e. abundance of species of recreational or commercial value or whose existence is in jeopardy) to their habitat, stating "...better habitat generally leads to more abundance of species." However, the indicators selected by CALFED are described as "the health and sustainability of individual species and species communities...'[1]. The terms "health" and "sustainability" are not defined in the document.

Characteristics of health indicators

This section describes several characteristics that might apply to health indicators. The next section lists a variety of potential indicators and discusses their characteristics. These and other characteristics are discussed in detail by Cairns et al. (1993). The characteristics are given numerical scores between 1 and 5: a score of 1 means that the indicator is most useful from the perspective of that characteristic, and 5 means that it has severe weaknesses. Scores of 3 would not eliminate an indicator if it were useful on the basis of other considerations. Some of the characteristics have a maximum of 3.

Primary or derived Health indicators can be primary or derived, where primary indicators are monotonically related to an ecosystem property that most scientists would agree is "good" or "valuable", and derived indicators are variables that are assumed to be related to some primary indicator that itself may not be measurable or interpretable.

1. Primary:
   Abundance of an endangered or recreationally important species
3. Derived
   Quantity of certain kinds of habitat (e.g. shallow-water low-salinity)

Interpretable Some indices of "health" may be as readily interpretable as is body temperature for human health (at least in principle). Others require value judgments as to what value of the index is enough and what is too little. Still others may be completely uninterpretable, in that the direction of change going from an "unhealthy" to a "healthy" ecosystem is unclear, or knowledge of the topic is insufficient to form a basis for interpretation. The interpretation is made on the basis of relevance to ecological considerations or societal values:

1. Interpretable
   Oxygen percent saturation
3. Require value judgments
   Abundance indices of ecologically important species

---

[1] CALFED Problem Definition Package, draft of 1 September 1995. Sacramento.

5. Uninterpretable
Species diversity in open waters

Measurable or conceptual A health index can be measured directly, or (more frequently) calculated from a series of other measurements, subjectively determined, or conceptual. Conceptual indices could be determined in an experimental setting but are not generally measurable in the whole system.

1. Directly measurable or observable (no controversial assumptions needed to calculate a summary value such as an area-wide mean):
Oxygen percent saturation
2. Calculable (assumptions must be made such as method of averaging or interpolation, or about quantities that are not measured directly)
Abundance indices of fish
4. Subjectively determined:
Natural beauty
5. Conceptual:
Resilience

Quantitative vs. Qualitative Health measures could be quantitative, binary, or qualitative:

1. Quantitative:
Diversity or species richness (perhaps more useful in marshes)
2. Binary:
Presence or absence of toxic concentration of pollutants
3. Qualitative:
Quality of marsh or open-water habitat

Historically based Health indicators are interpretable either by comparison between stressed and unstressed locales, or through historical trends. Indicators with a long historical record are likely to be more useful than others. This is a qualitative index, with 1 indicating the presence of long data record, 2 indicating some historical data, and 3 indicating very little or no data.

Indicators for the San Francisco Bay-Delta Estuary

Table 1 lists indicators gleaned from the literature, from discussions with colleagues, or through consideration of the meaning(s) of ecosystem health. These indicators are grouped according to the variables to be measured, and rated according to the characteristics listed above.

D-021895

Relatively few of the indicators rate well on all of the characteristics listed above. Most of the indicators that might be associated with "health" in a theoretical sense (e.g. resistance to invasion) rate low on most of the characteristics; thus these are not valuable indicators of ecosystem health. Many of the indicators that are measurable and quantitative require considerable interpretation or value judgements before they can be used (e.g. abundance of recreationally important species).

Many of the indicators may be more valuable in marshes, where emphasis is on habitat (in the form of physical structure and plant life) rather than on the animals inhabiting the marsh. For example, plant species diversity may be related to the diversity of animal habitat. In open water, it is not clear that high diversity of plant life makes much difference.

No doubt there are indicators I have missed, and probably there would be disagreement over the classifications of many of those in Table 1. This forms the starting point for discussions at the October 2 workshop.

The section below briefly discusses each of these indices by groups and suggests ones that might be more or less useful as indicators.

Abundance Several groups of species are considered depending on societal interpretations of their value. Species that are threatened or endangered, or those that support a fishery, are given greater consideration than those that are environmentally sensitive or ecologically important. Only two of these indicators do not require a value judgement. The abundance of a threatened or endangered species can be interpreted (at least in principle) in terms of the numbers required to eliminate danger of extinction. The existence of a commercial fishery is evidence of sufficiency of stock size if stocks are not declining. All of these indicators might be useful to the extent that the necessary interpretations of numerical goals can be made. Abundance of sensitive species may be less desirable as an indicator because of the difficulty in defining them. For example, longfin smelt appear to be more sensitive than delta smelt to freshwater outflow, but are also in less danger of extinction, judging from the listing of delta smelt, but not longfin smelt, as threatened.

Species composition Diversity is probably not a useful indicator for open water because it is difficult to interpret, but diversity of marsh plants may be more helpful. The rate of extinction of species appears valuable based on the rankings, but is rather low and may require comparison with other ecosystems. Genetic diversity and the frequency of hybridization seem also to be difficult to interpret. The frequency of introductions or, conversely, resistance to invasion, is often cited as a measure of ecosystem health but again interpretation is problematic. Presence of undesirable species seems like a useful indicator but there may be little that can be done about it: for example, there seems to be little chance of eliminating the greatest nuisance species in the Great Lakes, the zebra mussel.

Population characteristics Several characteristics of populations have been suggested, including age and trophic structure, and morphology or behavior of individuals in

D-021896

populations. These share the drawback that it is unclear which direction a "healthy" population should go from the existing situation. Resilience of populations (as distinct from resilience of ecosystems) is informative about the potential effects of restoration but may not be controllable.

Energy flow "Productivity" carries sufficient baggage to have a positive connotation when it is applied to ecosystems; yet, high primary production in an estuary may be a result of eutrophication. High secondary production or biomass of consumers (of desirable species) is probably useful as an indicator except that values must be selected, and there is very little historical basis. The same is true of growth rates in populations. The production: respiration ratio has been suggested as a measure of health, but many estuaries are probably net oxidizers of carbon except where primary production is stimulated by anthropogenic nutrient inputs.

Water quality The amount of debris per unit area of bottom or marsh is a useful indicator of the aesthetic value of the ecosystem more than its function; nevertheless it is easy to measure. Percent saturation of oxygen is probably the most commonly used indicator for estuaries, but since the reduction of sewage input with the Clean Water Act, oxygen concentration is not reduced except in the Stockton Ship Channel in late summer. Water clarity is also often cited as an indicator; it is very low in the Bay-Delta estuary because of retention of fine sediments produced by hydraulic mining in the last century. There may be opportunities for control of sediments over the long run, so this is a useful index. The size distribution of organic matter appears to be related to eutrophication in lakes, but is probably not useful here. Similarly, nutrients are rarely limiting in the Bay-Delta, so their loading rates are not of much use.

Toxicity and disease Several indicators relating to the physical health of aquatic organisms or humans are useful. It would be very desirable to have fish with a low incidence of lesions, tumors, or disease, and that can safely be consumed by people. In addition, concentrations of pollutants exceeding known thresholds for toxic effects, or bioassay results indicating toxic concentrations in water or sediments, are clear indicators that ecosystem health is degraded even in the absence of observable effects on populations. The amount of toxic material being discharged is more suitable as a means of controlling inputs than as an indicator of the status of the ecosystem.

Physical habitat The definition of habitat for open-water species is not necessarily clear, in that most species are known only from sampling in a subset of available habitat. In marshes, however, restoration efforts are directed at habitat (i.e. the marsh itself) rather than the animals that inhabit it. This fundamental difference means that aspects of marsh habitat such as fragmentation, heterogeneity, and the shape and physical structure of banks should be considered outright as indicators of health. For example, a marsh with little vegetation, lots of open mudflat, and straight channels would not be considered very healthy. Similarly, vegetative cover along river or slough channels is part of the natural landscape of these areas and can be valued without regard to the use of those areas by animals.

Flow variables All of the flow-related variables listed have been used either as standards for estuarine protection or as independent variables in analyses of abundance or survival patterns of valued species. Thus, these are useful in limiting operations to protect the ecosystem, but may not themselves be measures of ecosystem health.

Other characteristics Natural beauty, though subject to interpretation, underlies much of what people take as ecosystem "health" and should be included as an indicator in spite of its subjectivity. Resilience is an important property of ecosystems, but more useful in a theoretical context than in management because it is impossible to measure or interpret in a real ecosystem. Self-sustainability, as discussed above, is a property of any ecosystem and therefore suffers from the same problems as resilience.

Recommendations

The following indicators are suggested as the most useful.

Little or no interpretation required:

Abundance of threatened or endangered species
Existence of a viable commercial fishery
Percentage of native fishes with stable (or increasing) populations
Abundance of debris
High oxygen percent saturation
Water clarity
Frequency of tumors or disease in fish
Frequency of toxic effects
Suitability of fish and invertebrates as food for humans
Quantity of marsh habitat

Interpretation or additional information required:

Abundance of other species (native estuarine-dependent fish and crustaceans)
Abundance of striped bass
Abundance of undesirable species (e.g. water hyacinth)
Production of invertebrates and fish
Amount of open-water habitat (with appropriate characteristics)
Marsh habitat heterogeneity, channel fractal dimension
Riparian cover
Natural beauty

D-021898

Table 1. Potential indicators of ecosystem health grouped according to variables included, and ranked according to characteristics defined in the text

Indicator	Primary	Interp table	Measu- rable	Quanti- tative	Historical
Abundance					
Abundance of a species qualifying as threatened or endangered	1	1	2	1	1
Abundance or indices of environmentally sensitive species	1	3	2	1	1
Abundance or indices of recreationally important fish	1	3	2	1	1
Existence of a viable commercial fishery	1	1	1	2	1
Abundance or indices of ecologically important species	1	3	2	1	1
Long-term declines in abundance of species	1	3	2	1	1
Percentage of native species with stable populations	1	1	1	1	1
Species composition					
Diversity or species richness (open water)	3	5	2	1	2
Diversity or species richness (marsh)	3	3	2	1	2
Community trophic structure	3	3	2	3	2
Rate of extinction	1	1	1	1	2
Frequency of introductions	3	3	1	1	1
Resistance to invasion	3	3	5	3	1
Degree of genetic diversity within populations	3	3	1	1	3
Frequency of hybridization	3	3	1	1	3
Presence of undesirable species	1	1	1	2	1
Noxious algal blooms	1	1	1	2	1
Abundance of opportunistic species	3	3	2	1	2
Population characteristics					
Population age structure	3	3	1	1	2
Gross morphology	3	1	2	3	2
Population resilience	1	3	2	1	2
Behavior	3	3	2	3	3
Energy flow					
Primary production (open water)	3	5	2	1	2
Fish or invertebrate biomass (mass)	1	3	2	1	2
Fish or invertebrate production (mass/time)	1	3	2	1	3
Growth rates	3	3	1	1	2

Production:respiration ratio	3	3	1	1	3
Water quality					
Abundance of debris	1	1	1	1	3
Oxygen percent saturation in water or sediment	1	1	1	1	1
Water clarity	1	3	1	1	1
Size distribution of organic matter	3	5	1	1	3
Frequency or intensity of nutrient loading	3	3	2	1	2
Toxicity and disease					
Frequency of lesions, tumors, or disease in aquatic organisms	1	3	1	1	2
Suitability of fish for consumption	1	1	1	1	2
Concentrations of pollutants in reference to thresholds	1	1	2	1	2
Frequency or intensity of toxicant discharge	3	3	2	1	2
Results of toxicity bioassays indicative of pollutant effects	1	1	2	1	2
Physical habitat					
Quantity of certain kinds of habitat	1	3	2	1	2
Quality of marsh or open-water habitat	1	1	2	3	2
Instream/riparian cover	1	3	2	1	1
Habitat fragmentation or linkage	3	3	2	1	2
Habitat heterogeneity	3	3	1	1	2
Channel sinuosity	3	3	1	1	1
Fractal dimension of banks	3	3	1	1	2
Physical stability of substrate and banks	3	3	1	3	2
Flow variables					
X2	3	3	2	1	1
Net delta outflow	3	3	2	1	1
Variability of freshwater flow	3	3	1	1	1
Percent freshwater flow diverted	3	3	2	1	1
Diversion flow or frequency	3	3	2	1	1
Other characteristics					
Natural beauty	1	3	4	3	1
Resilience	3	5	5	3	3

References

Cairns, J. Jr., P.V. McCormich, and B.R. Niederlehner. 1993. A proposed framework for developing indicators of ecosytem health. Hydrobiologia 263:1-44

Calow, P. 1992. Can ecosystems be healthy? Critical consideration of concepts. Journal of Aquatic Ecosystem Health 1:1-5 (And other articles in this journal volumes 1 and 2)

Costanza, R., B.G. Norton, and B.D. Haskell. 1992. Ecosystem health. Island Press, Washington. 269 pp.

Karr, J.R. 1991. Biological integrity: a long-neglected aspect of water resource management. EcologicalApplications 1:66-84

Karr, J.R., K.D. Fausch, P.L. Angermeier, P.R. Yant, and I.J. Schlosser. 1986. Assessing bioligical integrity in runnin watersL a method and its rationale. Illinois Natural History Survey, Champagne IL, Special Publication 5.

Kay, J.J. 1991. A nonequilibrium thermodynamic framework for discussing ecosytem integrity. Environmental Management 15:483-495

Ocean Studies Board, Commission on Geosciences, Environment, and Resources; Board on Biology, Commission of Life Sciences, National Research Council. 1995. Understanding Marine Biodiversity. National Academy of Sciences, Washington

Munkittrick, K.R. and D.G. Dixon. 1989. A holistic approach to ecosystem health assessment using fish population characteristics. Hydrobiologia 188/189:123-135.

Regier, H.A. 1 1993. The notion of natural and cultural integrity. Pp. 3-18 in Woodley et al. 1993.

Woodley, S., J. Kay, and G. Francis. 1993. Ecological integrity and the management of ecosystems. St. Lucie Press. 220 pp.