Reemergence of the Importance of Biology in Water Quality Assessments

by
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Introduction

In recent decades, water quality has been defined primarily in chemical terms. Over the past decade, however, there has been growing recognition in water management agencies of the need to bring biology back into the water quality equation. It is now recognized that in certain cases chemical monitoring abilities have outstripped the ability to detect biological impacts of chemical contaminants. As a result, the nation sometimes spends large sums of money removing contaminants that are not affecting aquatic organisms. However, the reliance on chemical criteria or laboratory-derived toxicological information, out of context of the entire environmental milieu to which organisms are exposed in nature, also has resulted in permitted levels of toxicants that exceed an aquatic population's (or community's) ability to survive.

The reinstitution of biology in real-world environmental settings has brought with it a resurgence in the need for knowledge of systematics, basic life history information, population dynamics, and similar areas of whole-organism biology that have been neglected over the past several decades. At the same time, exciting developments in fields ranging from molecular biology to landscape ecology are emerging for fruitful application in the monitoring and management of inland aquatic resources. This paper examines these developments and opportunities in terms of the historical background, particularly in areas related to water quality assessment.

Historical Background

Three major federal legislative actions ultimately are responsible for current efforts to interject direct biological measures and more meaningful ecological perspective into the assessment of the well-being of inland aquatic ecosystems: (1) Water Quality Act, (2) National Environmental Policy Act, and (3) Endangered Species Act.

The Water Quality Act of 1965 and its offshoot the Clean Water Act (Federal Water Pollution Control Act Amendments of 1972, Clean Water Act of 1977, Water Quality Act of 1987) were enacted in response to widespread surface water degradation and a growing public environmental awareness and concern. The Water Quality Act amendments of 1972 formalized the term "biological integrity" under the directive to restore and maintain the "chemical, physical, and biological integrity of the nation's waters." However, following enactment of the initial legislation, the primary focus was on evaluation of chemical and physical criteria and on single-factor (and single-species) toxicity tests. Only recently has the idea been clarified and expanded in response to needs in conservation and resource management (USEPA 1990).

The National Environmental Policy Act of 1969 (NEPA) was responsible for interjecting an ecological perspective into Federal legislation and actions, particularly to natural resource projects. Increasingly, NEPA and its legal interpretations have had far reaching implications for the management of inland aquatic resources at the ecosystem and landscape scales. Recent examples include the Colorado River between Lakes Powell and Mead and the Columbia River Basin.

The endangered species Act of 1973 protects all species of animals, not deemed an insect pest, in danger of extinction. Twelve percent of all animal species live in inland waters and many species are restricted to limited biogeographic ranges. As freshwater habitats have become destroyed, altered, or polluted, biodiversity and ecosystem integrity have declined in a wide range of locations. The listing of federally recognized, endangered, freshwater species is an important means of tracking total biological integrity (Covich 1993).

Several large federal monitoring and assessment programs are being instituted that emphasize the measurement of water quality in biological rather than solely chemical/physical terms. These include the Environmental Monitoring and Assessment Program of the U.S. Environmental Protection Agency (EMAP) and the National Water Quality Assessment Program of the U.S. Geological Survey (NAWQA). Presumably, the newly instituted National Biological Service also will have a strong emphasis on biological assessments through wetlands surveys, inventories of biological resources, and the like.

In addition, the states are required to institute narrative biological criteria into state water quality standards during the FY 1991-1993 triennium; numeric criteria and full implementation are scheduled to occur a few years later (USEPA 1990). These requirements also apply to agencies responsible for the management of large tracts of Federal land (e.g., U.S. Forest Service and Bureau of Land Management), especially in the West.

Ecological Integrity

The concept of biological integrity has provided the major impetus for bringing biology back into water quality assessments. The idea of biological, and subsequently ecological, integrity is traceable at least as far back as the writings of Aldo Leopold (Leopold 1949) but its emergence as a formal ecosystem property did not occur until the mid 1970's (e.g., Cairns 1977).

Ecological integrity concerns both ecosystem structure and function (Cairns 1977, Karr 1991). For a full, objective determination of system integrity, both structure and function must be evaluated together. **Structural integrity** involves the basic building blocks of aquatic communities and the ways they are arranged. An unusual change in one or more structural characteristics is interpreted as evidence of stress. Fundamental measurements are: (1) the number of species present, (2) the number (or mass) of individuals per species, and (3) the kinds of species present. Historically, aquatic ecologists have done a fairly good job of measuring structural aspects, probably because study of structure is less time-consuming, better understood, and requires less effort than study of function. However, such work is hampered by the lack of accurate, up-to-date taxonomic keys and comprehensive systematic works at the species level. **Functional integrity** involves processes such as photosynthesis and community respiration, nutrient transfer, energy flow, and decomposition. Abnormal rates of activity or accumulation or depletion of materials are indications of disruptions of the functional integrity of ecosystems.

Importance of Scale (Space and Time)

Ecological integrity is a scale-dependent concept (King 1993). The scale of an ecological system refers to its spatial and temporal dimensions (Allen and Hoekstra 1992). Maintenance of ecological integrity implies maintenance of some normal state or norm of operation. Measuring or observing ecosystem integrity, or its loss, thus requires observations over sufficient time to identify the range of variation (King 1993).

Inland aquatic ecologists must deal more effectively with the spatial and temporal dimensions of their science. Aquatic ecosystems require certain spatial and temporal bounds for maintenance of their structure and function. A minimum extent may be required for an ecological process to operate or interaction to take place. Failure to observe the system at these scales can hamper study and understanding of system structure and function and make inferences about ecosystem integrity difficult or impossible.

Ecosystems in particular must be defined simultaneously in terms of space and time, and ecological dynamics occur over a broad spectrum of space-time scales (O'Neill et al. 1986). For example, stream ecosystem responses occur at scales ranging from millimeters and minutes to hundreds of kilometers and millions of years (Minshall 1988). Small scale events recur with relatively high frequency while larger scale events are progressively more rare. Extensive dam construction and the demise of salmonid populations in the Pacific Northwest is symptomatic of a region- or basin-wide loss of ecological integrity.

Ecosystem Health, Management, and Sustainability

The integrity of inland aquatic ecosystems is being assaulted in many ways. Major anthropogenic disturbances that impact inland waters and associated riparian ecosystems include livestock grazing, forestry and logging practices, mining, beaver introduction and removal, sewage discharge, agricultural practices (sediments, nutrients, toxicants, dewatering, etc.), manufacturing and processing operations, and fish management practices (e.g., use of poisons to remove unwanted species, introduction of exotic species) (e.g., Resh et al. 1988). Other important influences involve dam building, diking, channelization, removal of woody debris,, irrigation, and generation of electricity (Power et al. 1988, Covich 1993). Not only may each of these activities be important to the integrity of inland aquatic ecosystems, but the effects of each type of disturbance may be cumulative or even synergistic.

Some large-scale disturbances affecting aquatic ecosystems, whether natural or human-induced, are rapid and dramatic. Examples include massive deforestation, forest fires, plant disease outbreaks, or insect infestations. Other disturbances occur gradually over extended periods of time and are not recognized until the situation becomes extremely difficult or impossible to reverse. These include acidification, some types of logging and mining, livestock grazing, fire suppression, irrigation, and, potentially, global climate change.

Fast or slow, disturbances of aquatic/riparian ecosystems may result in changes in water temperature or runoff, channel straightening, scouring/sedimentation, loss of physical habitat, alteration of food base, and waterlogging or drying of riparian soils. Additional factors of concern include protection of threatened and endangered species, maintenance of biodiversity and ecosystem function, and development of productive capacity. These impacts represent some of the major areas of concern to resource managers charged with protecting "ecological health" or improving conditions for aquatic/riparian ecosystems and they represent major challenges for the future. **Ecological health** is a condition of a system in which natural ecosystemic properties are not severely constrained, the ability for progressive self-organization is present, the capacity for self repair when perturbed is preserved, and minimal external support for management is needed (Steedman and Regier 1990).

The concept of **ecosystem sustainability** is a long forgotten aspect of resource management, but it is implicit in the idea of ecosystem health described above. Ecosystem sustainability is "the ability to sustain diversity, productivity, resilience to stress, health, renewability, and/or yields of desired values, resource uses, products, or services from an ecosystem while maintaining the integrity of the ecosystem over time" (Overbay 1992). Its reinstitution into the resource management equation has come about through NEPA, the Endangered Species Act, and numerous other Federal laws enacted during the 1960's and 1970's.

Emerging Issues

Population-/Community-level Concerns

As noted above, there is a spectrum of the kinds of biological information that one can use to evaluate water quality. Studies at the population and community levels of organization emphasize species populations and interactions within and among them, such as competition. In this approach the physical environment is seen as external to the system of biota and biotic interactions (King 1993). Population and community studies emphasize biotic interactions, whereas ecosystem studies emphasize fluxes of matter and energy (O'Neill et al. 1986).

At the population level, the presence and abundance of one or more key species or "indicator organisms" may be used to indicate the condition of the aquatic environment. However, this approach has been effective only in the rare cases where the monitored species responded clearly to specific types of water quality. Other measures at the population level may be more responsive to ecological dynamics than simply abundance. These are built on the properties of individuals (size, growth rate, content of particular components like fats or certain enzymes) or populations (birth and death rates, population growth rate, age-frequency distribution). For planktonic animals that carry their eggs, the egg-ratio method of measuring reproductive rate can be used and from it a mortality rate derived (Edmondson (1993). A decline in birth rate appears to signal a significant change in environmental conditions and therefore may provide a possible assessment approach for detecting human-induced impacts (W.T. Edmondson personal communication). Similar methods could be applied to insects and other macroinvertebrates in streams.

Toxicity has been widely studied under artificial (laboratory) conditions. The application of toxicity tests to intact or partially isolated systems in nature is less common but needed. Mortality generally is the criterion in such tests, but a sublethal condition is just as important in controlling populations because properties of organisms other than death also vary with toxicity and toxicity may affect reproduction, behavior, morphology, and physiological responses without causing direct mortality.

Population guilds and subcommunities have proven more satisfactory as measures of biotic stress than measures involving single species. Algae, invertebrates, and fish are the groups most commonly used. Each has its advantages and disadvantages (Plafkin et al. 1989). For example, paleolimnologists interested in inferring the effects of acid rain in lakes have been able to estimate the pH of lakes based on groups of diatoms found in bottom sediments. Bioassessment procedures that incorporate multiple measures (metrics) of the responses of population-aggregates ("communities") are recommended on the assumption that different measures are sensitive to different types of water quality impairment and that a collective "signal" is more easy to discern than individual ones (Plafkin 1989, Karr 1991, 1993). However, some metrics respond in opposite ways; many are biased toward a particular type of pollution (e.g., organic wastes); and not all types of pollution are represented or adequately determined. Therefore, summing individual scores to obtain a single total score, as is commonly done, tends to conceal valuable information and produce equivocal results. Additional work is needed to remove uninformative redundancy and develop metrics specific to difference types of degradation.

Ecosystem-/Landscape-level Concerns

The study of ecosystems focuses on the processing and transfer of matter and energy in which the environment is an integral (as opposed to external) part of the system (King 1993). Study of landscapes commonly addresses patterns of distributions within and among ecosystems and thus with spatial scales of relatively broad extent. Geology and climate provide major factors influencing the characteristics of a river basin or watershed ecosystem (e.g., Minshall et al. 1985) and thus act at the scale of the landscape. The occurrence of natural geographic variation in the ecological features of undisturbed aquatic systems thus must be recognized in any effort to assess ecosystem responses at the landscape scale (Hughes et al. 1986, Karr 1991).

Patterns of disturbances, both natural and human-induced, may be superimposed on the natural pattern of variability resulting in a mosaic of patches of different ages and composition (White and Pickett 1985). For example, the River Continuum concept proposes that there are features of even pristine stream/riparian ecosystems that change progressively throughout a river basin and that therefore require a landscape perspective for proper interpretation (Vannote et al. 1980). The influence of riparian vegetation, annual amount of terrestrial leaf litter in the channel, availability of dissolved organic matter, and the modal size of particulate organic matter all generally decrease with distance from the headwaters of a stream system. The relative contributions of photosynthesis and community metabolism and the composition of functional feeding groups also change gradually and in a predictable fashion along the so-called river continuum. The effects of disturbances also vary along a river system; the effects of some (especially if widely dispersed) become dissipated with increasing stream size while other disturbances may act cumulatively.

It often is assumed that ecosystems are resilient to alternation of structure due to compensatory functional responses. But this assumption has never been adequately tested for aquatic ecosystems. Measurement of ecosystem function has been avoided because methods dealing with it have been lacking or are more difficult and time consuming to employ. However, freshwater ecologists now have the fundamental tools needed to begin assessing some functional aspects of ecosystem integrity (e.g., metabolism chambers, nutrient uptake techniques, leaf litter decomposition). Further efforts are needed to develop practical, cost-effective techniques for use in routine bioassessment.

In addition, measurement of functional integrity should include genetic and evolutionary aspects. Biological systems are in a continual state of evolution, and the scales of their response can be expected to be the product of selection by long term evolution. Failure to appropriately and adequately address evolutionary aspects has been an important shortcoming in ecosytem ecology because it has led to major misconceptions regarding ecosystem properties and processes such as succession (Colinvaux 1993). The dilution, isolation, and extinction of genetic pools are bound to be major problems in inland waters now and in the future; awareness of the problem is just becoming widespread and is restricted mainly to fish and molluscs (Williams and Miller 1990, Nehlsen et al. 1992, Bogan 1993) but effects on other aquatic groups are expected to be equally severe (e.g., Zwick 1992). Measurement of this aspect of integrity is more problematic than for other types of processes and the approach is still being defined. Nonetheless, it is important that the need be recognized and steps taken to address genetic and evolutionary components in assessing the ecological integrity of inland waters.

Importance of Seasonality

Seasonal variations in activity, condition, distribution, and abundance (hence, recruitment and/or mortality) of aquatic organisms are common. This is to be expected in strongly seasonal environments but is found even in the tropics. Therefore, temporal variation must be accounted for in biological assessments of environmental conditions or determinations of change but frequently it is not. Failure to consider seasonal differences is especially important when comparing data from difference locations or for the same area over time. For assessment of long term trends, samples must be collected at ecologically equivalent times each year.

Nonequilibrium Nature of Aquatic Systems and the Role of Disturbance

In recent times, understanding of the development of complex systems has changed significantly, as a result of a paradigm shift from a belief in the dominance of equilibrium processes in ecology to one that emphasizes the importance of nonequilibrium processes (see e.g. Botkin 1990, Reice 1994). Formerly, the dynamics within ecological levels of organization, from populations through ecosystems, were viewed as being controlled primarily by processes which were density-dependent and tended toward equilibrium conditions. For example, in this view, populations were seen as tending toward a quasi-steady state balance between natality and mortality and ecosystems as tending toward a monotypic "climax" state. The present view, whose implications have yet to be fully appreciated by most ecologists, is that the dynamics of the various levels of organization are controlled largely by random processes, such as disturbance, which are density-independent and of a nonequilibrium type. Though reality probably lies somewhere between the two extremes of these views, the latter currently dominates ecological thinking.

Whether aquatic ecosystems are perceived as equilibrium or nonequilibrium actually may depend on the spatiotemporal scale being considered (O'Neill et al. 1986) and on the magnitude and time since disturbance. For example, in a year-to-year and section-by-section context, most natural stream ecosystems may be perceived to be nonequilibrium in character. They receive substantial environmental influences from outside their boundaries and exert comparable influences on adjacent ecosystems. They also are dynamic and continually changing. Many lakes possess similar features but usually to a lesser extent. However, when viewed in broader contexts, aquatic systems may exhibit several levels of stable behavior and show substantial spatial homogeneity (e.g., Frost et al. 1988, Minshall 1988).

Disturbance and the resultant change in conditions has long been recognized as an important factor affecting the structure and dynamics of ecological systems at various levels of organization. More recently, emphasis has shifted from a viewpoint that disturbance is rare and unpredictable to treating it as a natural process that occurs at different spatial and temporal scales with varying degrees of predictability (e.g., Resh et al. 1989, Fisher 1990). Ecosystem development following disturbance should be expected to exhibit the characteristics of self-organizing, nonequilibrium systems (Kay 1991). The development of such systems is expected to proceed in irregular spurts from one steady state to another. Each spurt results in the system moving further from equilibrium and becoming more organized. For example, in ecosystem succession each of the serial stages corresponds to a transient steady state and the displacement of a previous serial stage by the next is a spurt which results in increased organization (Kay 1991). Because change (both natural and human-induced) is implicit in the modern, nonequilibrium view of ecosystems, its consideration is important in developing and applying the concept of ecosystem integrity to inland waters. Also, because ecosystem integrity is a scale-dependent concept, measuring or observing integrity or its loss in inland aquatic ecosystems requires observations over sufficient temporal extent to identify and characterize their patterns. (King 1993).

Implications For The Future

Modern water science encompasses a broad array of skills and areas of expertise. Future scientists, teachers, and resource managers will need to be broadly trained in these areas. However, in the future, the complexity and magnitude of the questions facing researchers and resource managers will increasingly require an interdisciplinary approach and the ability to work cooperatively.

The ecological integrity of inland waters is being assailed on many fronts. Direct assessment of the biota is crucial to the protection and management of aquatic resources. Sound understanding of basic biological (ecological) relationships is prerequisite to sound management (Jumars 1990, Edmondson 1993). Several large federal monitoring and assessment programs are being instituted that emphasize the measurement of water quality in biological rather than solely chemical-physical terms. Consequently, the need for training in the systematics and the basic biology and ecology of key groups of inland aquatic flora and fauna (e.g., diatom algae, macroinvertebrates, fish) will increase in the future. At the same time, many exciting developments, including genetic markers, molecular, morphological, and behavioral indicators of exposure to toxic substances, and molecular measures of function, are emerging in biology and are fertile fields for additional research. Computer-based geographical information systems, satellite imagery, and remote sensing are providing valuable techniques for addressing both research and management questions at various levels of resolution in the landscape. Rapid technological advances in these and other areas such as data logging and wireless transmission, radiotelemetry, geographical positioning systems, acoustical sounding, electronic surveying and distance measurers, pressure transducers for remote water level sensing, will provide powerful tools for addressing important questions relating to inland aquatic resources.

Explicit considerations of scale are increasingly a part of the process by which aquatic ecologists approach a variety of ecological issues and problems (King 1993). The many, coincident sources of natural and human-caused impacts on inland aquatic ecosystems will require consideration at multiple spatiotemporal scales that include adequate heterogeneity across landscapes (Covich 1993). Hierarchy theory commonly is used to address questions of scale (Allen and Hoekstra 1992). Thus, it is to be expected that issues of ecosystem integrity will need to address questions of scale and hierarchy. Various levels of organization and spatial-temporal scales need to be addressed; the approach will vary with the particular research questions or management problem. However, for the immediate future, the ecosystem-and landscape perspectives will be especially important, if sustainable biological aquatic resources are to be adequately protected in the face of continued pressures from human activities.

References

Allen, T.F.H. and T.W. Hoekstra. 1992. *Toward a Unified Ecolog*y. Columbia University Press, New York.

Bogan, A.E. 1993. Freshwater bivalve extinctions (mollusca: Unionoida): a search for causes. *Amer. Zool.* **33:**599-609.

Botkin, D. 1990. Discordant Harmonies: *A New Ecology for the Twenty-First Century.* Oxford University Press, New York.

Cairns, J. 1977. Aquatic ecosystem assimilative capacity. *Fisheries* **2**:5-7 & 24.

Colinvaux, P. 1993. *Ecology,* 2nd. ed. J. Wiley and Sons, Inc., New York.

Covich, A.P. 1993. Water and ecosystems, pp 41-55, in: P.H. Gleick (Ed.)*, Water in Crisis: A Guide to the World's Fresh Water Resources.* Oxford Univ. Press, New York.

Edmondson, W.T. 1993. Experiments and quasi-experiments in limnology. *Bull. of Mar. Sci.* **53**:65-83.

Fisher, S.G. 1990. Recovery processes in lotic ecosystems: limits of successional theory. *Environ. Manage.* **14**:725-736.

Frost, T.M., D. L. DeAngelis, S.M. Bartell, D.J. Hall, and S.H. Hurlbert. 1988. Scale in the design and interpretation of aquatic community research, pp. 229-258, in: S.R. Carpenter (Ed.), *Complex Interactions in Lake Communities*. Springer-Verlag, New York.

Jumars, P.A. 1990. W(h)ither limnology? *Limnol. Oceanogr.* **35**:1216-1218.

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

Kay, J.J. 1991. A nonequilibrium thermodynamic framework for discussing ecosystem integrity. *Environ. Managem*. **15**:483-495.

King, A.W. 1993. Considerations of scale and hierarchy, pp. 19-45, in: S. Woodley, J. Kay, and G. Francis (eds.), *Ecological Integrity and the Management of Ecosystems.* St. Lucie Press.

Leopold, A. 1949. *A Sand County Almanac: and Sketches Here and There*. Oxford Univ. Press, New York.

Minshall, G.W. 1988. Stream ecosystem theory: a global perspective. *J. N. Amer. Benthol. Soc*. **7**:263-288.

Nehlsen, W., J. E. Williams, and J.A. Lichatowich. 1992. pacific salmon at the crossroads: stocks at risk from California, Oregon, Idaho, and Washington. Trout(Winter): 24-51.

O'Neill, R.V., D.L. DeAngelis, J.B. Waide, and T.F.H. Allen. 1986. *A Hierarchical Concept of Ecosystems*. Princeton Univ. Press, Princeton, NJ.

Overbay, J.C. 1992. Ecosystem management, pp. 3-15, in Taking an Ecological Approach to Management; Proceedings of the National Workshop. U.S. Forest Service, Watershed and Air Management, Washington, DC. WO-WSA-3.

Plafkin, J.L., M.T. Barbour, K.D. Porter, S.K. Gross, and R.M. Hughes. 1989. Rapid bioassessment protocols for use in streams and rivers: benthic macroinvertebrates and fish. U.S. Environ. Prot. Ag., Washington, D.C. EPA/444/4-89-001.

Power, M.E., R.J. Stout, C.E. Cushing, P.P. Harper, F.R. Hauer, W.J. Matthews, P.B. Moyle, B. Statzner, and I.R. Wais de Badgen. 1988. Biotic and abiotic controls in river and stream communities. *J. N. Amer. Benthol. Soc.* **7**:456-479.

Reice, S.R. 1994. Nonequilibrium determinants of biological community structure. Amer. Sci. **82**:424-435.

Resh, V.H., A.V. Brown, A.P. Covich, M.E. Gurtz, H.W. Li, G.W. Minshall, S.R. Reice, A.L. Sheldon, J.B. Wallace, and R.C. Wissmar. 1988. The roll of disturbance in stream ecology. *J.N. Amer. Benthol. Soc*. **7:**433-455.

Steedman, R.J. and H.A. Regier. 1990. Ecological bases for an understanding of ecosystem integrity in the Great Lakes Basin. Great Lakes Fishery Commission and International Joint Commission.

U.S. Environmental Protection Agency. 1990. Biological criteria: national program guidance for surface waters. USEPA Office of Water Regulations and Standards, Washington, DC. EPA-440/5-90-004.

Vannote, R.L., G.W. Minshall, K.W. Cummins, J.R. Sedell, and C.E. Cushing. 1980. The river continuum concept. *Canad. J. Fish. Aquat. Sci.* **37**:130-137.

White, P.S. and S.T.A. Pickett. 1985. Natural disturbance and patch dynamics: an introduction, pp. 3-13, in: S.T.A. Pickett and P.S. White (Eds.), *The Ecology of Natural Disturbance and Patch Dynamics*. Academic Press, New York.

Williams, J.E. and R.R. Miller. 1990. Conservation status of the North American fish fauna in fresh water. *J. Fish Biol.* **37**(suppl. A):79-85.

Zwick, P. 1992. Stream habitat fragmentation - a threat to biodiversity. *Biodiversity and Conservation* **1**:80-97.

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