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Seven Foundations of Biological Monitoring and Assessment

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ABSTRACT
Pressure on nature from the impact of 6 billion humans is taking its toll. Living systems in water bodies illustrate this toll much as blood-cell counts and blood chemistry illustrate the health of a human body. For most of the twentieth century, society remained largely unaware of the collapse of aquatic ecosystems because we saw water narrowly, as a fluid to be consumed or used as a raw material in agriculture or industry. When attempted, monitoring focused on the presence of chemical contaminants rather than the character of the aquatic biota. Direct biological monitoring and assessment, an antidote to that lack of awareness, has gained substantial ground in the last decade because they provide a mechanism to directly assess the condition of water bodies, diagnose the causes of degradation, define actions to attain conservation and restoration goals, and evaluate the effectiveness of management decisions. Seven foundations of modern bioassessment programs are crucial to the development and use of a new generation of indicators to reverse the erosion of aquatic living systems.

KEY WORDS: Bioassessment / biological integrity / IBI / monitoring / water law

Sette principi fondamentali per il biomonitoraggio e la valutazione dell'integrità ecologica
La pressione di una popolazione di 6 miliardi di uomini esercita un forte impatto sulla natura. Le comunità degli organismi acquatici riflettono questo impatto come le analisi ematochimiche riflettono lo stato della salute umana. Per gran parte del XX secolo la consapevolezza del collasso degli ecosistemi acquatici è stata largamente carente, a causa delle nostre vedute ristrette che concepiscono l'acqua come un fluido da consumare o da utilizzare come materia prima nell'agricoltura e nell'industria. Anche quando è stato attivato, il monitoraggio si è focalizzato sulla presenza di contaminanti chimici, anziché sulle comunità acquatiche. Nell'ultimo decennio il monitoraggio e la valutazione biologica, un antidoto a tale mancanza di consapevolezza, hanno registrato sostanziali progressi poiché permettono di stimare direttamente lo stato dei corpi idrici, diagnosticare le cause del loro degrado, individuare le azioni necessarie per raggiungere gli obiettivi di conservazione e restauro ambientale e valutare l'efficacia delle misure adottate. Vengono presentati sette principi fondamentali di moderni programmi di biomonitoraggio, di importanza cruciale per l'individuazione e l'utilizzo di una nuova generazione di indicatori, finalizzata ad invertire il progressivo degrado degli ecosistemi acquatici.

PAROLE CHIAVE: valutazione biologica / integrità biologica / IBI / monitoraggio / legislazione sulle acque

INTRODUCTION

From drinking to bathing, from industry to agriculture, from supplying food (e.g., fish, shellfish) to feeding the human spirit, water is essential to human existence. Despite the diverse contributions of water and associated resources to the well-being of human society, water managers have long focused on the quality and quantity of water—the fluid. Because water and rivers have been viewed and taught as if they were plumbing instead of as living or life-supporting, water resources have been progressively degraded by the actions of human society. Success in halting and reversing this degradation requires a new approach. Society needs to view its goal of sustaining water supplies not as a plumbing issue but as a biological issue.

For more than a century in the United States, federal laws have been in place to protect water resources. Although its common name has evolved since the 1960s [Water Pollution Control Act, Water Quality Act, and Clean Water Act (CWA)], successive reauthorizations have broadened and strengthened the CWA. The most important language in that law, and the clause that stimulated my interest, was its powerful objective: "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters."

More recently, Australia and New Zealand's water quality guidelines (ANZEEC, 1992), Australia's 2004 National Water Initiative, Japan's River Law (Tamai, 2000), and the European Water Framework Directive (European Commission, 2000) have focused attention on the biology of waters as well. As the focus on biology spreads to new regions, demand for more effective biological monitoring (sampling the biota of a place) and biological assessment (using samples of living organisms to evaluate the biological condition or health of places) expands as well.

Transitions to new legislative vision are often resisted by state and national agencies and institutions (Dörner, 1996). In the United States, the biological mandate was neglected for years (Karr, 1991; Adler, 2003), and resistance to a biological focus continues despite substantial inroads being made at local (Clallam County, 2004), state (Ohio EPA, 1989a,b), and national (USEPA, 2005) levels. As a result, underreporting of levels of water body impairment is not tolerated as much as in the past. More and more agencies are incorporating biological monitoring and assessment into their water quality programs, as required by USEPA some years ago.

Here I provide a brief overview of seven foundations of biological monitoring and assessment as I have come to understand them in the past 35 years.

Foundation 1. RIVERS ARE NOT HEALTHY

For thousands of years, humans have been attracted to rivers. Rivers bring a continuous supply of naturally clean water, provide fish and shellfish, and serve as important transportation corridors. As human populations have expanded, humans have withdrawn and polluted water, overharvested fish and shellfish, and altered river channels and riparian corridors. Decades and even centuries of living along a river inevitably change the river to such an extent that it may no longer supply its normal array of goods and services.

Many scientists, governments, and environmental groups have reported on these changes and called for programs to change and even reverse these trends (Karr, 1991; Karr and Chu, 1999; Boon *et al.*, 2000; Benke and Cushing, 2005; European Commission, 2000; USEPA, 2005, 2006; Petts *et al.*, 2006; Vugteveen *et al.*, 2006). But as environmental attorney and law professor William Rodgers has noted, "The most disturbing reality is that we [in the United States] have not succeeded in maintaining the biological productivity of our surface waters despite enormous investments" (Rodgers, 1994).

Five realities emerge from these collective observations:

- rivers and other waters are not healthy;
- the natural landscapes of rivers have been distorted by the action of humans;
- the institutional "landscapes" designed to protect river health have all too often been inadequate, even dysfunctional;
- all humans are responsible;
- decisions made in the past to extract value from rivers have used the wrong indicators, thereby making it possible for society to continue to degrade rivers.

Foundation 2. LEGISLATIVE MANDATES TO CORRECT THE SITUATION ARE CLEAR

The European Water Framework Directive demands an integrative ecosystem approach that connects rivers, their landscapes, and the uses humans make of water and associated resources (European Commission, 2000). The U.S. Clean Water Act calls for making the waters of the nation "fishable and swimmable" and to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters." Like a number of writings and laws, these water initiatives call for protecting the integrity of water resources (Tab. I). I define integrity as the characteristics embodied in the parts (genetic diversity, species, communities) and processes (hydrology, demography, interspecific interactions, energy flow, nutrient dynamics) of nature's legacy in a region. Protecting integrity involves protecting the living systems capacity to regenerate, reproduce, sustain, adapt, develop, and evolve (Westra *et al.*, 2000) in a way that protects the temporal and spatial dynamics of the river ecosystem, including the diverse factors that are valued and valuable to human society. Such protection requires tools (see Foundation 4) to measure biological condition as a divergence from integrity, which represents minimally altered natural condition as a standard or benchmark.

Tab. I. Sample of writings establishing integrity as a goal.

1948	*Sand County Almanac*, Aldo Leopold
1972	Water Pollution Control Act Amendments
1972	Great Lakes Water Quality Agreement
1988	Canadian National Park Act
1989	Kissimmee River (Florida) Restoration Project
1997	National Wildlife Refuge System Improvement Act
1998	National Parks Omnibus Management Act
2001	European Union Water Framework Directive

Foundation 3.
NEITHER CLEAN WATER NOR HABITAT ALONE ARE ENOUGH

Although degradation in the ability of water resources to support human and non-human living systems was a primary stimulus for water legislation, regulatory and incentive programs at state and federal levels rarely emphasized biological goals and endpoints (KARR, 1991). Managing narrowly for clean water or for some conception of "optimal habitat" has neither halted degradation nor recovered damaged water resources.

First, water management was dominated by narrow reductionist and engineering viewpoints. Early management, for example, emphasized control of chemical pollutants [substances or materials added to waters by human activity; CWA 502(6); 33 U.S.C. § 1362(6)] rather than a broader framework of pollution construed as human-induced alteration of the chemical, physical, biological, and radiological integrity of water [CWA 502(19); 33 U.S.C. § 1362(19)]. Factors beyond chemical pollutants responsible for biological degradation include altered flows, loss of riparian zone, physical alteration of stream channels, and introduction of alien species. Furthermore, CWA implementation emphasized rules and standards for effluents defined by available technology, rather than by measuring biological effects in the receiving waters (KARR, 1991). When a biological perspective was taken, the emphasis was on acute and chronic effects of chemical pollutants on laboratory organisms.

Second, water management in the United States involves a patchwork of local, state, and national agencies; in border regions, international compacts also affect management programs. Water law within the American legal system is a complex of federal and state constitutions (fundamental law), statutes and ordinances (acts at state or federal and local levels), administrative regulations (formulated and implemented by agencies), executive orders (orders by state and federal chief executives), and common-law court decisions (GOLDFARB, 1988). This complexity makes integrated decision making almost impossible.

Third, Clean Water Act implementing regulations were not developed after careful consideration of the newly defined integrity goal, a reality that crippled those wanting to focus on biological endpoints, because it favored perspectives focused on chemical endpoints, or worse, technology-based goals. Fourth, neither cost-effective approaches to biological monitoring and assessment nor tools to measure biological condition (divergence from integrity) were available. Fifth, no mechanism was available to link field measurements to enforceable management options. Because of the extensive work of hundreds of academic and agency scientists in the past 25 years, all of these challenges have been substantially overcome.

While agencies charged with Clean Water Act enforcement focused on clean water rather than biological goals, fish and wildlife agencies emphasized protecting "the habitat" of a few species important to sport, commercial, or subsistence harvesters. As a result, primary management actions, such as supplementation of wild fish by hatchery fish and habitat enhancement by, for example, removal of woody debris to speed fish passage, often damaged wild fish populations. Here again, narrow conceptions dominated management actions when a broader approach to protection or restoration was needed.

Human actions (e.g., grazing, logging, point source effluent, agriculture, construction of transportation corridors, and urbanization) have altered one or more of five major sets of factors (water quality, habitat structure, flow regime, energy sources, and biotic interactions; KARR, 1991; KARR and CHU, 1999) with numerous biological consequences (Fig. 1).

Foundation 4.
BIOLOGICAL MEASURES MAKE THE BEST PRIMARY ENDPOINTS

Monitoring and assessment using the resident biota of a stream provides both an integrative view of the effects of human influences and a rich variety of signals that can be used to diagnose the causes of degradation. To implement effective biological monitoring, however, managers need formal methods for sampling the biota, evaluating the resulting data, and clearly describing the condition of sampled areas. But managers have long emphasized measurement of chem-

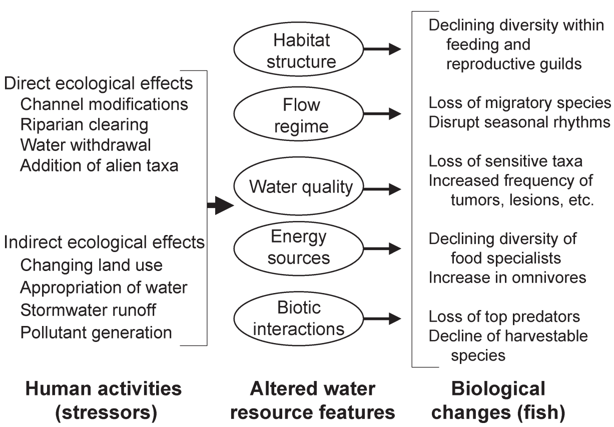

Fig. 1. Human activities alter five water resource features, resulting in specific changes in fish assemblages. (Modified from KARR and YODER, 2004)

ical pollutants in water, so water resource agencies hired few ecologists.

The five-factor concept (see Fig. 1) implies that spending infinite time and money on one factor while ignoring the others is unlikely to succeed in maintaining stream health. Neverthless, measuring the diverse conditions for all five sets of factors will likely be prohibitively expensive. A carefully formulated program of biological monitoring is more cost-effective because organisms are the integrators of all that happens in a watershed, from the briefest pollutant event to the chronic alteration of flow associated with urbanization, water withdrawals, or dams. Recognition of these facts is not enough, however; the crucial step must then be the development of a measurement system to track biological condition.

I developed such a measurement system, called the index of biological integrity (IBI), to fill this need (KARR, 1981, 1991; KARR *et al*., 1986; KARR and CHU, 1999). Any bioassessment program that hopes to capture the complexity of biological systems and the varied impacts humans have on them requires a multidimensional approach that integrates biological signals from individual, population, assemblage, and landscape levels. The core components of a robust biological monitoring program are (KARR and CHU, 2000): a focus on biological endpoints; use of a minimally disturbed reference condition as a benchmark; organization of sites into classes with similar environmental characteristics; assessment of change caused by human actions; standardized sampling, laboratory, and analytical procedures; numerical and verbal scoring of sites to reflect site condition; and defined condition classes, representing degrees of degradation. When done properly, the result will be an improved ability to select high-quality areas for acquisition and conservation; to diagnose likely causes of degradation; and to define management actions to halt degradation or restore degraded areas.

IBI, like conventional economic indexes such as the index of leading economic indicators, is a multimetric index that provides a convenient measure of the status of a complex system. Both economic and biological indicators require a baseline state against which future conditions are assessed. For IBI, that baseline–biological integrity–is the condition at a site with a biota that is the product of evolutionary and biogeographic processes in the relative absence of the effects of modern human activity.

Multimetric indexes like IBI integrate multiple biological indicators to measure and communicate biological condition. Much as a physician relies on a battery of medical tests, not just one, to diagnose illness, anyone can use an IBI to diagnose the condition of a place. This robust measure of the biological dimensions of site condition has by now been applied to challenges in basic science, resource management, engineering, public policy, law, and community participation in developing as well as developed nations.

Initial work with biological indicators concentrated on streams, using fish as focal organisms, but the conceptual underpinnings of IBI have now been applied to diverse environments (streams, large rivers, wetlands, lakes, coastal areas, riparian corridors, sagebrush steppe, and others) and taxonomic groups (fishes, aquatic and terrestrial invertebrates, algae and diatoms, birds, and vascular plants: Appendix). A carefully designed program can provide important insight regardless of the taxonomic group(s) studied. The strong relationship between fish and benthic invertebrate IBIs in two watersheds in Japan demonstrates that point (Fig. 2).

Several states have incorporated biological criteria into state water quality standards (e.g., Ohio, Florida, Maine, Vermont; DAVIS *et al*., 1996; USEPA, 2002), and biological monitoring is now a key component of EPA water management guidelines to states (USEPA, 2005). IBI or conceptually similar multimetric indices are now used on six continents and in freshwater, marine, and terrestrial systems. The diverse biological monitoring and assessment literature (see Appendix) of the last 25 years demonstrates the power of biological approaches to protect living waters. That literature shows very clear shifts in focus: from physical and chemical variables to biological variables; from chemical stressors to all stressors; from a narrow single-factor view to a more integrative view; and from simple indicators to more complex multidimensional

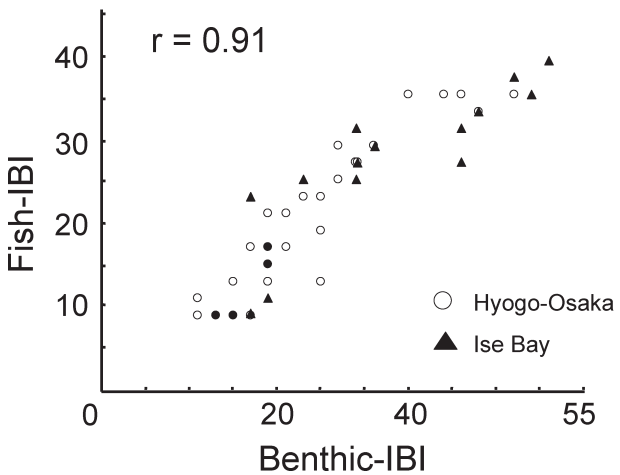

Fig. 2. Relationship of benthic invertebrate IBI and a fish IBI for two watersheds (Hyogo-Osaka and Ise Bay) in Japan. (From ROSSANO, 2002)

indicators of biological condition. All this evolution has required aquatic scientists and managers to deal with one simple question: How do we measure biological condition in a way that provides a better foundation for societal decision making?

Foundation 5. METRICS THAT PROVIDE CLEAR, EASILY INTERPRETED SIGNALS ARE KEY

Toxicologists use dose-response curves to understand the effects of a chemical on individual organisms. They might determine, for example, which of two compounds are most toxic to a species or identify differences in sensitivity of two species to the same compound. In effect, they work to understand how a species responds to increasing chemical concentrations.

Similarly, an ecological dose-response curve is crucial to successfully developing a multimetric biological index (Fig. 3). But instead of looking at the response of individuals in a laboratory situation, we evaluate how living systems change as human activity increases in a watershed. Living systems may be measured in a variety of ways: proportion of a population of a species showing an effect (e.g., external lesions), species richness of a taxonomic or ecological group, age structure of a population, or the relative abundance of a group such as predators. In effect we ask the question, how does the biology of a place change as a function of increasing human action?

We measure such change by comparing the value to what would be expected in a similar place without human influence (the natural baseline). Do selected sets of species change (e.g., do predators decline, omnivores or generalists increase) in taxa richness or relative abundance as human activity increases? By identifying which of a broad range of biological attributes change in consistent ways, we can identify which attributes are interpretable as indicators of the effects of human actions. Within the infinite variety of biological attributes that can be measured, only a small proportion vary systematically and reliabley across a gradient of human influence. Measures in that small subset are potential metrics for an IBI.

In contrast, when a biological attribute does not change in value with human influence, there is no dose-response curve, and the attribute is not appropriate for use as a metric in an assessment index. Use of biological measures that do not follow dose-response curves is one of the most common flaws in efforts to develop multimetric indexes.

Demonstrating an empirical relationship between human influence and biological change is only the first step in metric identification (KARR and CHU, 1999;

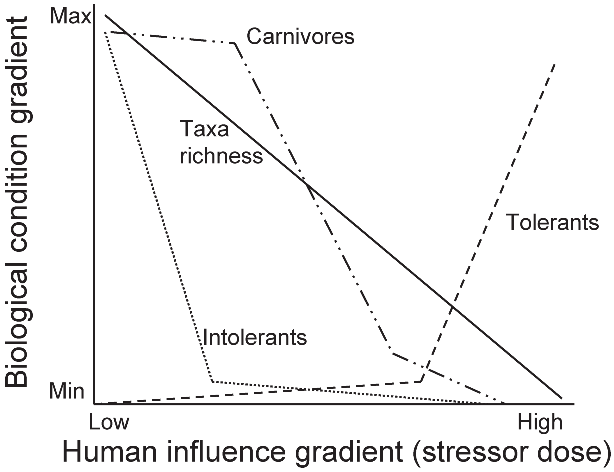

Fig. 3. An ecological dose-response curve showing the relationship between a human influence gradient (stressor dose) and selected biological attributes (e.g., native taxa richness, relative abundance of predators and other organisms).

KARR and KIMBERLING, 2003; FORE, 2003). Additional steps involve examining graphs to ensure that least- and most-disturbed sites do not overlap in their values of the biological attribute. Graphs should also be examined for outliers, points in graphical space that are outside the pattern of most points in the graph. What other human actions at outlier sites might explain their divergence in biological condition? For example, if biological condition (e.g., taxa richness) is unexpectedly low at a site, one might look for an unknown point source or runoff from a nearby highway.

Other factors are also relevant in metric selection. First, when two or more metrics measure essentially the same component of biology (e.g., both taxa richness and relative abundance of a taxonomic or ecological group), retain only one in the multimetric index. Second, avoid simplicistic use of correlation coefficients among metrics to discard metrics. The correlations among metrics should be high because all metrics are selected to reflect changes associated with human influence. That is, metric redundancy should be evaluated on the basis of biological, not statistical, criteria. Third, select metrics that have sensitivities that differ with position along the gradient (intolerant vs. tolerant taxa) and with different kinds of human influence (lesions or skeletal anomalies suggest the presence of toxic chemicals). Fourth, do not avoid potential metrics simply because they exhibit zero values across some proportion of the human influence gradient. Fifth, range and signal/noise tests are excellent for eliminating poorly performing candidate metrics (MCCORMICK *et al.*, 2001). For more detailed guidance on the metric selection process, consult the following references: KARR *et al.*, 1986; KARR, 1991;

HUGHES *et al.*, 1998; KARR and CHU, 1999; KARR and KIMBERLING, 2003; FORE, 2003; and HUGHES *et al.*, 2004. Proper selection of metrics is crucial to the development and successful use of a multimetric index.

For many years, biological data were viewed as too variable to be used in monitoring and assessment. When formulated and applied correctly, however, multimetric biological indexes substantially reduce this problem. Four key practices should be followed: compare ecologically similar sites (e.g., limited range of stream sizes included within a data set); select only the most reliable and responsive metrics; maintain high data-quality standards; and use the power derived from combining multiple metrics. Successful approaches to calibrate for stream size (FAUSCH *et al.*, 1984) and elevation, slope, flow regime, geology, and other factors (PONT *et al.*, 2006) are now available. A study of terrestrial invertebrates at five study sites in sagebrush steppe in eastern Washington, for example, illustrates the fourth point. Individual biological measures are often highly variable; the mean error variance for 8 metrics included in a terrestrial IBI there averaged a rather high 56%. But when those metrics were combined using standard procedures, the error variance of the 8-metric IBI was much smaller (17%; KIMBERLING *et al.*, 2001).

One final advantage of IBI should not be overlooked: because IBI is derived from analysis of empirical data, its use does not require resolution of all higher-order theoretical debates in contemporary ecology (bottom-up vs. top-down population regulation; relationships between diversity, stability, and resilience in ecological systems).

Foundation 6.
SUCCESSFUL BIOASESSMENT DEPENDS ON RIGOROUS SAMPLING DESIGN AND ANALYSIS

Choosing the right metrics is only the beginning, however. Collecting field data without developing a sampling design that will provide information relevant to specific scientific or policy goals is collecting data in a vacuum. Sampling design, the first step in developing a monitoring and assessment program, should combine biological insight and efforts to maximize statistical power.

First, monitoring and assessment programs must provide accurate information about a site's flora or fauna, with emphasis on those components of the biota most influenced by human actions. Regional biology and natural history should be the primary drivers of sampling design and analytical approach.

Second, sampling design and analysis should be planned to provide information at the most relevant spatial and temporal scale(s). For example, it is not necessary to document the magnitude and sources of all natural seasonal or successional variation in the study system. Rather, the sampling design should be planned to reveal how varying levels and kinds of human activity have influenced the biota at study sites. When the goal is to characterize the condition of a population of sites to reflect, for example, regional condition, a probabilistic sampling design is essential (LARSEN *et al.*, 2002). Because the definition of reference condition in effect drives the whole analytical process, great care should also be exercised in use of the reference concept. Within these broad objectives, sampling protocols will vary widely, depending on the type of system (stream, wetland, upland forest) and organisms (fish, birds, plants, invertebrates) examined.

Third, study design should also be informed by knowledge of how the data will be used and what analytical approaches will be applied in those analyses. Rather than solely searching for statistical relationships and significance, one can often learn much about biological pattern with simple graphical methods. Graphs reveal, better than strictly statistical tools, patterns of biological response, including "outliers," which may convey unique information that can help

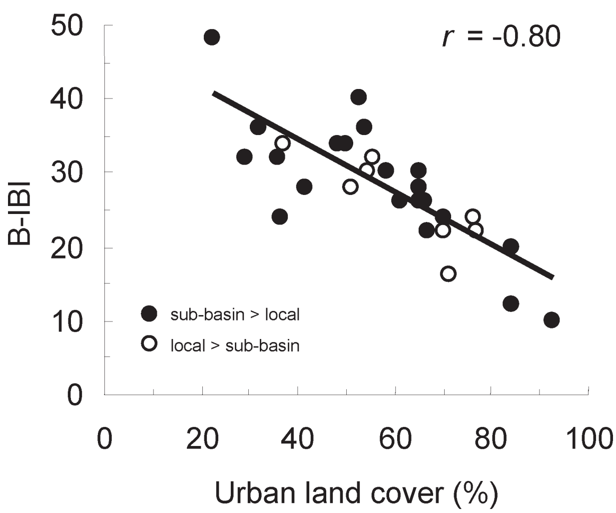

Fig. 4. Relationship of B-IBI (benthic index of biological integrity) to percentage of urban land cover for 31 lowland stream sites, Puget Sound, Washington, USA. The relationship is strong at both subbasin (r = -0.73, p < 0.001, n = 34) and local (r = -0.71, p < 0.001, n = 31) scales but is strongest (r = -0.80, n = 31, plotted here) when the highest value for each site, regardless of scale, is examined. Subbasin scale is the entire drainage upstream of sample site. Local scale is an area 200 m on each side of the stream and extending 1 km upstream from sample site. (Data from MORLEY and KARR, 2002)

diagnose particular problems or traits of a site (KARR and CHU, 1997, 1999). Graphical displays illustrate variation in behavior among taxa, such as in response to specific disturbances. They also reveal the direction and magnitude of change.

Combining graphical displays with statistical analyses can improve our understanding of the underlying factors responsible for patterns. One example of that comes from analysis of scale (from local to basin-wide), a subject explored by many researchers (STEEDMAN, 1988; RICHARDS *et al.*, 1996; ROTH *et al.*, 1996; ALLAN *et al.*, 1997; MORLEY and KARR, 2002). One lesson of these studies is that no single scale of analysis is adequate (Fig. 4).

Statistics should be used to validate metric choices and predictions while building a multimetric index. But excessive dependence on the outcome of statistical tests can obscure meaningful biological patterns when a narrow focus on *p*-values rather than biological consequences dominates decision making (KARR and CHU, 1997, 1999).

Inordinate dependence on rote statistical testing can be very misleading. Three errors are common. First, scientists and managers err in using a local data set to extrapolate patterns to a much larger universe. It is unlikely that a simple numeric description of relationships from a single, inevitably idiosyncratic data set can be used to provide general rules for a range of landscapes. That kind of inappropriate interpretation is especially tempting when the output of statistical analysis suggests that a large proportion of the variance in a data set is extracted; too often the word *explained* is used in this situation with the, in my view, inappropriate suggestion of a cause-and-effect relationship.

Second, scientists use location-specific patterns with each region-specific data set, rather than looking for general principles and patterns across multiple data sets and regions. The selection of metrics for the benthic IBI (KARR, 1998), for example, came not from a detailed analysis of one data set but from knowledge of dose-response curves for about 60 benthic invertebrate measures influenced by a variety of human actions in areas across North America and in Japan. The terrestrial invertebrate IBI for sagebrush steppe was not formalized until data from Washington and Oregon study sites were evaluated and integrated (KARR and KIMBERLING, 2003).

Third, not enough effort is made to understand the effects of natural spatial and temporal variance and variation introduced by the measurement process (LARSEN *et al.*, 2001). Trend detection may be impossible without an effort to understand the sources of variation in a monitoring program.

In short, collecting data should begin only after specific program goals are defined, sampling methods and efforts are determined, and analytical procedures are planned.

Tab. II. Twenty-year pattern of change in number of U.S. states* with bioassessment programs applying multiple biological metrics for streams and wadeable rivers. The first multimetric IBI for stream bioassessment was published in 1981 (KARR, 1981). (From USEPA, 2002.)

Year	States with biological assessment in place	States with biological assessment under development
1981	0	0
1989	3	11
1995	42	6
2001	50	1

* Includes 50 states, the District of Columbia, and one interstate commission

Foundation 7.
COMMUNICATION WITH THE PUBLIC AND POLICYMAKERS COMPLETES THE CYCLE

Communicating the biological consequences of human activities to citizens, political leaders, and decision makers is a core goal of biological monitoring and assessment. Effective communication can transform biological monitoring from a largely scientific exercise to an effective tool for environmental decision making.

When members of the public are aware of patterns and trends in living systems, they are more likely to hold political leaders accountable for natural resource protection. They can also appreciate why biological assessment is more powerful than conventional chemical assessments. A biological focus can detect degradation caused by the full array of human influences on living systems, not just the direct effects of chemical pollutants. Because of this strength, many state and federal agencies and citizen groups are developing programs that directly monitor and assess the condition of living systems (Tab. II; DAVIS *et al.*, 1996; KARR *et al.*, 2000; CLALLAM COUNTY, 2004; USEPA, 2002, 2005).

By more effectively engaging citizens, scientists can shift the regulatory and incentive focus of government actions from measuring of chemical pollutants in water to measuring of the biological condition of a water body.

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APPENDIX

Key references published since 1981 on biological monitoring and assessment with brief annotations, in five-year increments. This list emphasizes works on the development and use of multimetric indexes, such as IBI. To compile the list, I invited three other scientists (Robert Hughes, Corvallis, Oregon; Chris Yoder, Columbus, Ohio; and Leska Fore, Seattle, Washington) to send me a list of what they consider to be the 10 to 20 most influential biological monitoring papers published since 1981. All responded with thoughtful compilations (from 17 to 68 papers). I also prepared a list. The following is my effort to capture the breadth of papers the four of us cited. Note that several edited books and special issues of journals are listed without noting all papers in those sources.

1981–1985

Karr 1981: Proposed IBI conceptual model; integrated multiple metrics into index
Karr and Dudley 1981: Popularized definition of biological integrity; defined multifaceted aspects of human influence on streams
Fausch *et al*. 1984: Regional testing and application of IBI principles

1986–1990

Angermeier and Karr 1986: Early exploration of sampling and analysis
Hughes *et al*. 1986: Formalized regional reference site concept
Karr *et al*. 1986: Early IBI how-to manual
Hilsenhoff 1987: First useful US benthic index; organic enrichment focus
Hughes and Gammon 1987: Applied IBI to large, boatable river
Moss *et al*. 1987: First “predictive” model for benthic assemblages
Ohio EPA 1987-1989: First state to define rigorous bioassessment framework; included fish and invertebrate assessments
Omernik 1987: Described aquatic ecoregions for the United States
Miller *et al*. 1988: Adaptation of IBI concepts to regions throughout United States
Steedman 1988: Extended fish IBI to Canadian streams
Plafkin *et al*. 1989: First detailed USEPA guidance for bioassessment

1991–1995

Karr 1991: Overview of need for biological monitoring and assessment
Lyons 1992: Developed warmwater stream IBI for Wisconsin
Oberdorff and Hughes 1992: Extended IBI to European rivers
Fore *et al*. 1994: Explored statistical issues concerning IBI use
Kerans and Karr, 1994: Extended IBI to benthic macroinvertebrates
Minns *et al*. 1994: Extended IBI to Great Lakes littoral zones
Oberdorff and Porcher 1994: Used IBI to assess effects of salmon aquaculture
Davis and Simon, 1995: Major book on biomonitoring and bioassessment
Lyons *et al* 1995: Extended IBI to Mexico
Australian Journal of Ecology 1995 (special issue), **20**: 1-227.

1996–2000

Fore *et al*. 1996: Explored benthic IBI for Oregon streams
Hugueny *et al*. 1996: Extended fish IBI to West Africa
Keeler and McLemore 1996: Connected IBI to improved economic analysis
Lyons *et al*. 1996: Extended fish IBI to coldwater streams
Rossano 1996: Developed benthic IBI for Japan
Allan *et al*. 1997: Examined connections between land use and river health

Deegan *et al*. 1997: Applied IBI to estuaries
Thorne and Williams 1997: Bioassessment in several tropical regions
Bailey *et al*. 1998: Predictive modeling for Canadian streams
Ganasan and Hughes 1998: Extended fish IBI to India
Harig and Bain 1998: Developed IBI to assess northeastern U.S. lakes
Hughes *et al*. 1998: Used rigorous process to select metrics in western US streams
Karr 1998: Proposed benthic IBI (B-IBI) from work in United States and Japan
Miltner and Rankin 1998: Explored relationships between nutrients and IBI
Yoder and Rankin 1998: Uses of bioassessment in state programs
Barbour *et al*. 1999: Revised 1989 USEPA guidance document
Bryce *et al*. 1999: Examined human influence gradients and IBI
Hughes and Oberdorff 1999: Synthesis of IBI applications outside North America
Karr and Chu 1999: Comprehensive IBI review to date
Kleynhans 1999: Extended IBI concepts to South Africa
Simon 1999: Major book using fish to assess water body condition
Barbour and Yoder 2000: Review of multimetric uses in the United States
Canterbury *et al*. 2000: Birds as indicators of forest condition
Davies *et al*. 2000: Predictive models for Australian rivers
Hawkins *et al*. 2000: Explored RIVPACS models for U.S. streams
Norton *et al*. 2000: Used biomonitoring to discriminate causes of degradation
Human and Ecological Risk Assessment 1997 (special issue), **3**: 929-1016.
Environmental Monitoring and Assessment 1998 (special issue), **51**: 1-603.
Freshwater Biology 1999 (special issue), **41**: 197-479.
Hydrobiologia 2000 (special issue), **422/423**: 1-487.

2001–2006

Karr and Rossano 2001: Used public health lessons to protect river health
Jameson *et al*. 2001: Applied IBI concepts to coral reef assessment
McCormick *et al*. 2001: Used range and signal/noise tests to select metrics
Bryce *et al*. 2002: Applied IBI to riparian birds
Fore and Grafe 2002: Applied IBI to algal (diatom) assessment
Larsen *et al*. 2002: Statistics and study design in bioassessment
Oberdorff *et al*. 2002: Developed first rigorous predictive model using IBI
Emery *et al*. 2003: Developed IBI for great river
Karr and Kimberling 2003: Developed terrestrial invertebrate IBI for shrub-steppe
Simon 2003: Major book exploring biological response signatures
Yoder and Kulik 2003: IBI application in Canada
Bozzetti and Schulz 2004: Extended IBI to Brazilian streams
Karr and Yoder 2004: Application of bioassessment to diagnostics
Stoddard *et al*. 2005: Bioassessment in western United States
USEPA 2005: Developed and refined concept of tiered aquatic life uses
Davies and Jackson 2006: Refinement of the biological condition gradient
Pont *et al*. 2006: Predictive model IBI for all European streams
USEPA 2006: Report on benthic IBI and predictive bioassessment in U.S. wadeable streams
Ecological Applications, 2006 (special section), **16**: 1249-1310.