Section I

Aquatic Resources Are Still Declining

DESPITE DECADES of efforts intended to protect water resources, and some success against certain forms of chemical and organic contamination, the nation's waters continue to decline, and the Clean Water Act's call for protecting integrity remains unanswered. The problem has been a failure to see rivers as living systems and a failure to take biology seriously in management programs. We need a new approach, one that integrates and informs us of the ways our rivers, landscapes, and society interact.

Water resources are losing their living components

Despite strong legal mandates and massive expenditures, signs of continuing degradation in biological systems are pervasive—in individual rivers (Karr et al. 1985b), U.S. states (Moyle and Williams 1990; Jenkins and Burkhead 1994), North America (Williams et al. 1989; Frissell 1993; Wilcove and Bean 1994), and around the globe (Hughes and Noss 1992; Moyle and Leidy 1992; Williams and Neves 1992; Allan and Flecker 1993; Zakaria-Ismail 1994; McAllister et al. 1997). Aquatic systems have been impaired, and they continue to deteriorate as a result of human society's actions (Table 1).

Devastation is obvious, even to the untrained eye. River channels have been destroyed by straightening, dredging, damming, and water withdrawal for irrigation and industrial and domestic uses. Degradation of living systems inevitably follows. Biological diversity in aquatic habitats is threatened; aquatic biotas have become homogenized through local extinction, the introduction of alien species, and declining genetic diversity (Moyle and Williams 1990; Whittier et al., 1997a). As recently as a century ago, a commercial freshwater fishery second only to the one in the Columbia River flourished in the Illinois River, Illinois. Now it is gone, and the one in the Columbia is nearly gone. Since the turn of the twentieth century, commercial fish harvests in U.S. rivers have fallen by more than 95%.

Even where commercial and sport catches of fish and shellfish are permitted, one can no longer assume that those harvests are safe to eat (U.S. EPA 1996a). In 1996, fish consumption advisories were imposed on 5% of the river kilometers in the United States (*www.epa.gov/OST/fishadvice/index.html*). The number of fish advisories is rising. The 2193 advisories reported for U.S. water bodies in 1996 represent an increase of 26% over 1995 and a 72% increase over 1993. For millennia, humans have depended on the harvest from terrestrial (including agricultural), marine, and freshwater systems for food. But the supply of freshwater foods has collapsed. How would society respond if agricultural productivity declined by more

Table 1. Examples from United States rivers of degradation in aquatic biota (from Karr 1995b).

Proportionately more aquatic organisms are classed as rare to extinct (34% of fish, 75% of unionid mussels, and 65% of crayfish) than terrestrial organisms (from 11% to 14% of birds, mammals, and reptiles; Master 1990).
Twenty percent of native fishes of the western United States are extinct or endangered (Miller et al. 1989; Williams and Miller 1990).
Thirty-two percent of fish native to the Colorado River are extinct, endangered, or threatened (Carlson and Muth 1989).
In the Pacific Northwest, 214 native, naturally spawning Pacific salmon and steelhead stocks face "a high or moderate risk of extinction, or are of special concern" (Nehlsen et al. 1991).
Since 1933, 20% of molluscs in the Tennessee River system have been lost (Williams et al. 1993); 46% of the remaining molluscs are endangered or seriously depleted throughout their range.
Since 1910, naturally spawning salmon runs in the Columbia River have declined by more than 95% (Ebel et al. 1989).
During the twentieth century, the commercial fish harvests of major U.S. rivers have declined by more than 80% (Missouri and Delaware Rivers), more than 95% (Columbia River), and 100% (Illinois River) (Karr et al. 1985b; Ebel et al. 1989; Hesse et al. 1989; Patrick 1992).
In 1910, more than 2600 commercial mussel fishers operated on the Illinois River; virtually none remain today.
Since 1850, many fish species have declined or disappeared from rivers in the United States (Maumee River, Ohio: 45% [Karr et al. 1985b]; Illinois River, Illinois: 67% [Karr et al. 1985b]; California rivers: 67% [Moyle and Williams 1990]). This decline, combined with the introduction of alien species, has homogenized the aquatic biota of many regions (an average of 28% of the fish species in major drainages of Virginia are introduced; Jenkins and Burkhead 1994).
Native minnows have declined while alien littoral predators have spread throughout northeastern U.S. lakes (Whittier et al. 1997a).
The taxa richness and relative abundances of dominant benthic macroinvertebrate groups change with land use. Most species of mayflies, stoneflies, and caddisflies—numerous in forested watersheds—disappear in agricultural and urban watersheds. They are replaced by midges (chironomids) in agricultural areas and oligochaete worms in urban watersheds (Lenat and Crawford 1994).
Riparian corridors have been decimated (Swift 1984).
Thirty-eight states reported fish consumption closures, restrictions, or advisories in 1985; 47 states did so in 1991. The 2193 advisories reported for U.S. water bodies in 1996 represent a 26% increase over 1995 and a 72% increase over 1993 (U.S. EPA 1996a). Contaminated fish pose health threats to wildlife and people (Colborn et al. 1990, 1996), including intergenerational consequences such as impaired cognitive functioning in infants born to women who consume contaminated fish (Jacobson et al. 1990; Jacobson and Jacobson 1996).

than 80% or if eating "farm-fresh" products threatened our health? Why then do we continue to ignore such changes in "wild-caught" aquatic resources?

Current programs are not protecting rivers or their biological resources because the Clean Water Act has been implemented as if crystal-clear distilled water running down concrete conduits were the ultimate goal (Karr 1995b). For example, at least $473 billion was spent to build, operate, and administer water-pollution control facilities between 1970 and 1989 (Water Quality 2000 1991). Yet the decline continues, and money is wasted on inadequate or inappropriate treatment facilities (Karr et al. 1985a; Box 1).

Box 1. Narrow use of chemical criteria can damage water resources and waste money. Use of biological criteria can do the opposite.

Most U.S. cities have spent decades installing wastewater treatment plants to protect water bodies from raw sewage. In primary treatment, wastes that float to the top or sink to the bottom of settling tanks are physically removed. The effluent passes into secondary treatment, where microorganisms digest the fine organic particles that remain. Neither primary nor secondary treatment removes chemicals from the effluent; compounds may include toxic industrial chemicals, pesticides, nitrates, and even pharmaceuticals excreted in human wastes (Raloff 1998). Tertiary treatment, the most expensive treatment level, is targeted at removing these chemicals. Wastewater treatment managers typically use chemical criteria to determine if the effluent they release into water bodies is safe after treatment. But those chemical criteria may still not protect regional waters.

Chlorine is added to secondary sewage effluent because it kills microorganisms that cause human disease. But the effects of this chlorine continue after the effluent is released into streams or other water bodies (Colborn and Clement 1992; Jacobson and Jacobson 1996). In three Illinois streams receiving water from a secondary treatment plant, an IBI based on fish declined significantly as residual chlorine concentration increased (Karr et al. 1985a; Figure 1); the biological effects of chlorine appeared in fish assemblages downstream of the effluent inflow (Figure 2). With chlorination (treatment phase I), IBIs were much lower downstream than upstream. In contrast, when chlorine was removed from secondary effluent (phase II), downstream and upstream IBIs did not differ significantly. Chlorine added to wastewater effluent continues to kill organisms long after the water is released. Furthermore, biological condition did not improve when expensive tertiary denitrification was added (phase III), even though this treatment brought the plant into compliance with chemical water quality standards for nitrates.

This example illustrates three important points. First, biological integrity may be damaged by too narrow a focus on chemical criteria. Second, such a narrow focus can waste money. Third, many current management approaches and policies are, in essence, untested hypotheses. Managers do not always make the effort to look for broader effects or to test beyond their initial criteria. Had managers looked for bio-

(continues)

logical effects or reconsidered the levels of chlorine in the effluent instead of assuming that their chlorine criteria worked, the biota of these Illinois streams might have suffered less.

The Taylor Creek watershed in nearby Ohio underwent a different experience (S. Malone, Ohio EPA, and W. C. High, Wolpert LLP, unpubl. manuscript). Plans to build a traditionally planned and engineered sewer system to meet chemical criteria—with pipes dug into stream channels and laid along riparian corridors to take advantage of gravity flow—were rejected by the state, which enforced biological as well as chemical criteria. State water managers recognized that the proposed sewer system would damage aquatic life. The engineers went back to their drawing boards and, working with biologists and others, came up with a plan that placed their sewer lines along existing rights of way such as roads. The new plan minimized stream crossings, designing them perpendicular to stream channels; it left buffer zones between the stream and construction activity and made erosion control, bioengineering, and environmental inspectors an integral part of the construction plan. As a result, 17 miles of stream were saved, and project planners discovered that they had also saved money. In fact, the contractors took the new methods to other projects as a way to save both money and time. Narrow pursuit of chemical criteria would have destroyed this stream and riparian corridor. But the presence—and enforcement—of biological criteria protected the stream and led to better engineering designs as well.

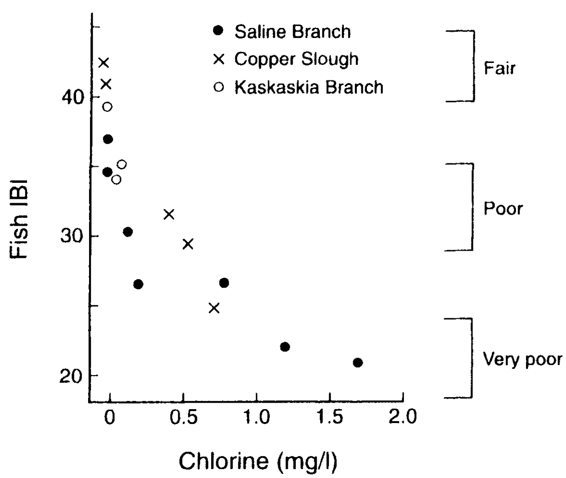

Figure 1. In three streams in east-central Illinois, the fish indexes of biological integrity (IBIs) declined significantly in response to wastewater inflow from secondary treatment with chlorination. Fish IBIs declined as residual chlorine concentration increased (from Karr et al. 1985a).

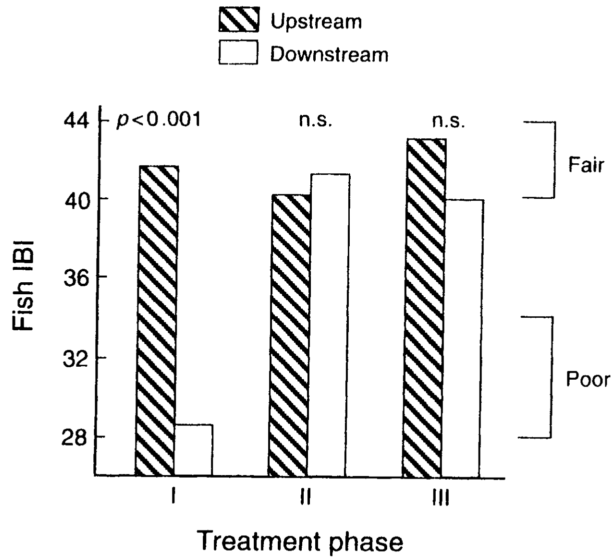

Figure 2. Fish IBIs for stations upstream and downstream of wastewater treatment effluent in Copper Slough, east-central Illinois. Phase I: standard secondary treatment; phase II: secondary treatment without chlorination; phase III: secondary treatment without chlorination but with tertiary denitrification. With chlorination (phase I), IBIs were much lower downstream than upstream of effluent inflow. Upstream and downstream sites did not differ statistically after removal of chlorine from secondary effluent (phase II). The addition of expensive tertiary denitrification (phase III) did not increase IBIs (from Karr et al. 1985a).

In many respects, society has been lulled into believing that our individual and collective interests in water resources are protected by national, state, and local laws and regulations. We have had faith in the outdated "prior appropriation doctrine" of American frontier water law, the implementation of the Clean Water Act, or "wild and scenic river" designation when, in fact, our habits as a society and the way we have implemented our laws have progressively compromised our fresh waters.

Premise 2

"Clean water" is not enough

Society relies on freshwater systems for drinking water, food, commerce, and recreation as well as waste removal, decomposition, and aesthetics. Yet in the Pacific Northwest alone, recent declines in salmon runs and closures of sport and commercial fisheries have led to economic losses of nearly $1 billion and 60,000 jobs per year (Pacific Rivers Council 1995). Retaining the biological elements of freshwater systems (populations, species, genes), as well as the processes sustaining them (mutation, selection, fish migration, biogeochemical cycles), is crucial to retaining the goods and services fresh waters provide (Table 2).

Waters and fish travel over vast distances in space and time. The integrity of water resources thus depends on processes spanning many spatial and temporal scales: from cellular mechanisms producing local and regional adaptations to a massive transfer of energy and materials as fish migrate between the open ocean and mountain streams. Protecting the elements and processes society values therefore demands a broad, all-encompassing view—one not yet encouraged by conventional management strategies and terminology.

In particular, the word *pollution* must take on broader connotations. In conventional usage and agency jargon, *pollution* refers to chemical contamination. A more appropriate, yet little-used, definition that more accurately represents what is at stake as water resources decline is the definition given by the 1987 reauthorization of the Clean Water Act: *pollution* is any "man-made or man-induced alteration of the physical, chemical, biological, or radiological integrity of water." Under this definition, humans degrade or "pollute" by many actions, from irrigation withdrawals to overharvesting, not merely by releasing chemical contaminants.

Table 2. Elements, processes, and potential indicators of biological condition for six levels or organization within three biological categories. Indicators from multiple levels are needed to assess the condition of a site comprehensively (modified from Angermeier and Karr 1994).

Biological category	Elements (levels)	Processes	Indicators
Taxonomic	Species	Range expansion or contraction Extinction Evolution	Range size Number of populations Population size Isolating mechanisms
Genetic	Gene	Mutation Recombination Selection	Number of alleles Degree of linkage Inbreeding or outbreeding depression
Ecological	Individual	Health	Disease Deformities Individual size and condition index Growth rates
	Population	Changes in abundance Colonization or extinction Evolution Migration	Age or size structure Dispersal behavior Presence of particular taxa (e.g., intolerants) Gene flow
	Assemblage	Competitive exclusion Predation or parasitism Energy flow Nutrient cycling	Number of species Dominance Number of trophic links Stream distance for one carbon molecule to complete passage through food chain (spiraling length)
	Landscape	Disturbance Succession Soil formation Metapopulation dynamics	Fragmentation Percentage of disturbed land Number of communities Sources and sinks Number and character of metapopulations

Biological monitoring is essential to protect biological resources

Despite their faith in and reliance on technology, humans are part of the biological world. Human life depends on biological systems for food, air, water, climate control, waste assimilation, and many other essential goods and services (Costanza et al. 1997; Daily 1997; Pimentel et al. 1997). It is therefore vital for us to assess resources in terms of their biological condition. The criteria and standards by which we judge whether an activity has an impact—the endpoints that we monitor—must be explicitly biological.

Degradation of water resources begins in upland areas of a watershed, or catchment, as human activity alters plant cover. These changes, combined with alteration of stream corridors, in turn modify the quality of water flowing in the stream channel as well as the structure and dynamics of the channel and its adjacent riparian environments. Biological evaluations focus on living systems, not on chemical criteria, as integrators of such riverine change. In contrast, exclusive reliance on chemical criteria assumes that water resource declines have been caused by chemical contamination alone. Yet in many waters, physical habitat loss and fragmentation, invasion by alien species, excessive water withdrawals, and overharvest by sport and commercial fishers harm as much if not more than chemicals.

Even measured according to chemical criteria, water resources throughout the United States are significantly degraded (U.S. EPA 1992a, 1995; see Table 1). In 1990 the states reported that 998 water bodies had fish advisories in effect, and 50 water bodies had fishing bans imposed. More than one-third of river miles assessed by chemical criteria did not fully support the "designated uses" defined under the Clean Water Act. More than half of assessed lakes, 98% of assessed Great Lakes shore miles, and 44% of assessed estuary area did not fully support designated uses (U.S. EPA 1992a).

By September 1994, the number of fish consumption advisories had grown to 1531 (U.S. EPA 1995). Seven states (Maine, Massachusetts, Michigan, Missouri, New Jersey, New York, and Florida) issued advisories against eating fish from state waters in 1994. Fish consumption advisories increased again in 1995, by 12%; the advisories covered 46 chemical pollutants (including mercury, PCBs, chlordane, dioxin, and DDT) and multiple fish species. Forty-seven states had advisories, representing 15% of the nation's total lake acres and 4% of total river miles. All the Great Lakes were under advisories. For the first time, EPA reported that 10 million Americans were at risk of exposure to microbial contaminants such as *Cryptosporidium* because their drinking water was not adequately filtered (U.S. EPA 1996c). For the same year, the Washington State Department of Ecology reported that "80 percent of the hundreds of river and stream segments and half of the lakes tested by the state don't measure up to water quality standards" (*Seattle Times* 1996). Outbreaks of *Pfiesteria piscicida,* the "cell from hell," have killed millions of fish and were also implicated in human illnesses from Maryland to North Carolina in 1997 (Hager and Reibstein 1997).

Alarming as they are, these assessments still underestimate the magnitude of real damage to our waters because they generally do not incorporate biological criteria or indicators. When compared with strictly chemical assessments, those using biological criteria typically double the proportion of stream miles that violate state or federal water quality standards or designated uses (Yoder 1991b; Yoder and Rankin 1995a). The reasons for this result are simple. Although humans degrade aquatic systems in numerous ways, chemical measures focus on only one way. Some states rely on chemical surrogates to infer whether a water body supports the "designated use" of aquatic life; others measure biological condition directly (Davis et al. 1996). Only 25% of 392,353 evaluated river miles were judged impaired according to chemical standards intended to assess aquatic life. But when biological condition was assessed directly, 50% of the 64,790 miles evaluated in the United States showed impairment. In the Piedmont region of Delaware, for example, the physical habitat and biological quality of 90% of nontidal streams is impaired (Maxted 1997). Human-made dead-end canals in residential developments along coastal bays in Delaware and Maryland support only one-seventh to one-twentieth of the species richness, abundance, and biomass of natural coastal bays (Maxted et al. 1997).

Perhaps more important, these numbers suggest that we know more about the condition of water resources than we actually do. Sadly, despite massive expenditures and numerous efforts to report water resource trends, "Congress and the current administration are short on information about the true state of the nation's water quality and the factors affecting it" (Knopman and Smith 1993). Because assessments emphasize chemical contamination rather than biological endpoints, state and federal administrators are not well equipped to communicate to the public either the status of or the trends in resource condition. Further, because few miles of rivers are actually assessed, and because those that are assessed are often sampled inappropriately (e.g., without probability-based surveys; Larsen 1995, 1997; Olsen et al., in press), percentages of impaired river miles are extremely rough at best.

In short, despite explicit mandates to collect data to evaluate the condition of the nation's water resources, and the existence of a program intended to provide an inventory under section 305(b) of the Clean Water Act, no program has yet been designed or carried out to accomplish that goal (Karr 1991; Knopman and Smith 1993). Rather, for years most state agencies operated as if more chemical monitoring were better. They continued to amass extensive data files and voluminous but indigestible reports—despite evidence that their data had little effect on water resource programs (McCarron and Frydenborg 1997). Granting permits for specific water uses, judging compliance, enforcing regulations, and managing watersheds all depend on the availability of accurate information about water resource condition. Yet agencies persisted in "studying the system to death" (McCarron and Frydenborg 1997). In many cases, by the time proof came that aquatic system health had declined, it was too late for effective prevention efforts, and restoration was too costly.

Such problems are clearly an important force driving recent state actions; 42 states now use multimetric assessments of biological condition, and 6 states are developing them. Only 3 states were using multimetric biological approaches in 1989 (Davis et al. 1996), and none had them in 1981 when the first multimetric IBI article was published. Indeed, hardly any effective biological monitoring programs were in place before 1981. Most states still have a long way to go toward collecting and using biological data to improve the management of their waters.

Because they focus on living organisms—whose very existence represents the integration of conditions around them—biological evaluations can diagnose chemical, physical, and biological impacts as well as their cumulative effects. They can serve many kinds of environmental and regulatory programs when coupled with single-chemical toxicity testing in the laboratory. Furthermore, they are cost-effective. Chemical evaluations, in contrast, often underestimate overall degradation, and overreliance on chemical criteria can misdirect cleanup efforts, wasting both money and natural resources (see Box 1). Because they focus on what is at risk—biological systems—biological monitoring and assessment are less likely to underprotect aquatic systems or to waste resources.

Biological evaluations and criteria can redirect management programs toward restoring and maintaining "the chemical, physical, and biological integrity of the nation's waters." Assessments of species richness, species composition, relative abundances of species or groups of species, and feeding relationships among resident organisms are the most direct measure of whether a water body meets the Clean Water Act's biological standards for aquatic life (Karr 1993). To protect water resources, we should track the biological condition of water bodies the way we track local and national economies, personal health, and the chemical quality of drinking water.

"Health" and "integrity" are meaningful for environmental management

Webster's dictionaries define *health* as a flourishing condition, well-being, vitality, or prosperity. A healthy person is free from physical disease or pain; a healthy person is sound in mind, body, and spirit. An organism is healthy when it performs all its vital functions normally and properly, when it is able to recover from normal stresses, when it requires minimal outside care. A country is healthy when a robust economy provides for the well-being of its citizens. An environment is healthy when the supply of goods and services required by both human and nonhuman residents is sustained. To be healthy is to be in good condition.

Despite—or perhaps because of—the simplicity and breadth of this concept, the intellectual literature is rife with arguments on whether it is appropriate to use *health* in an ecological context. Is it appropriate to speak of "ecological health" or "river health"?

The arguments mounted against health as an ecologically useful concept go something like the following. Suter (1993) insists that health is an inappropriate metaphor because it is not an observable ecological property. According to Suter, health is a property of organisms, a position that acknowledges only the first, and narrowest, of the dictionary's definitions. Scrimgeour and Wicklum (1996) believe that no objective ecosystem state can be defined that is preferable to alternative states. Calow (1992) asserts that the idea of health in organisms involves different principles from the concept "as applied to ecosystems." He distinguishes between applying the concept in a weak form to signal normality (an expected condition) and in a strong form to signal the existence of an active homeostatic process that returns disturbed systems to normality. The strong form, he suggests, requires a system-level control that does not exist in ecosystems. Neither does such a homeostatic control exist in any dictionary definition of health. Why, then, must this notion be central to health in an ecological context?

"Societal values" also enter the discussion, sometimes as an essential, sometimes as an inappropriate consideration. Policansky (1993) and Wicklum and Davies (1995) contend that health is a "value-laden concept" and therefore inappropriate in science. Yet Rapport (1989) suggests that efforts to protect ecological health must consider "the human uses and amenities derived from the system." Regier (1993) and Meyer (1997) agree with Rapport about the importance of societal values in defining and protecting health. Regier speaks of "integrity" rather than health, saying that the concept of integrity is "rooted in certain ecological concepts combined with certain sets of human values."

Other authors have searched for more objective or scientific arguments for referring to health in ecological contexts, often equating health with properties such as "self-organizing," "resilient," and "productive." Haskell et al. (1992) suggest that an ecosystem is healthy "if it is active and maintains its organization and autonomy over time and is resilient to stress." But resilience of biological systems is difficult to define and even more difficult to measure (Karr and Thomas 1996). Resilient to what? The term must be defined in the context of specific disturbances. A biota can sustain itself—it is very resilient—when faced with normal environmental variation, even when that variation is large (e.g., variation in river flow). But the same biota may not be able to withstand even the smallest disturbance outside the range of its evolutionary experience. Does this concept add any objectivity to our concept of health? In fact, highly disturbed systems tend to be resilient to stress. Does this observation mean that these systems are healthier?

Costanza (1992) goes one step further, proposing an ecosystem health index as the product of system vigor (primary production or metabolism), organization (species diversity or connectivity), and resilience (the ability to resist or recover from damage). But are these criteria scientifically defensible? Applying them, we would define lakes with limited plant nutrients as less healthy than highly productive lakes with abundant plant nutrients. Would an increase in primary production caused by the addition of excess nutrients, such as from sewage, therefore be considered still healthier? Using maximum production as a measure of ecological health is the analogue of using gross national product as a measure of economic vitality. By Costanza's second criterion, a tropical forest might be calculated as healthier (more diverse and connected) than a spruce-fir forest. By his third criterion, a community of sewage sludge worms (Tubificidae) at the outflow of a wastewater treatment plant would be healthy because it is very resilient to additional disturbance. These criteria all imply that "more is better" and can thus be turned too easily on their heads to justify human actions—from introducing species to adding fertilizers—that in fact degrade living systems.

Health as a word and concept in ecology is useful precisely because it is something people are familiar with. It is not a huge intuitive leap from "my health" to "ecological health." Cells; individual humans, animals, and plants; and complex ecological systems are all products of evolution. We understand that cells and individuals can be healthy or unhealthy; why is it unreasonable to extend the concept to ecosystems?

Of course we must "operationalize" the term—define it and find ways to measure it—but as a policy goal, protecting the health and integrity of our landscapes and rivers has a believable chance of engaging public interest and support. It is no accident that protecting biological or ecological "integrity" is the core principle of the Clean Water Act, Canada's National Park Act, and the Great Lakes Water Quality Agreement between the United States and Canada. Words like *health* and *integrity* are embedded in these laws because they are inspiring to citizens and a reminder to those who enforce the law to keep their minds on the big picture: the importance of living systems to the well-being of human society.

We contend that we can define *health* and *integrity* to make the terms useful in understanding humans' relationship with their surrounding ecological systems. Integrity applies to sites at one end of a continuum of human influence, sites that support a biota that is the product of evolutionary and biogeographic processes (Figure 3). This biota is a balanced, integrated, adaptive system having the full range of elements (genes, species, assemblages) and processes (mutation; demography; biotic interactions; nutrient and energy dynamics; and metapopulation, or fragmented population, processes) that are expected in the region's natural environment (Karr 1991; Angermeier and Karr 1994; Karr 1996). Adopting integrity as a management goal means aiming for a system that resembles this evolved state as much as possible (Angermeier 1997).

This definition of integrity takes into account three important principles: (1) a biota spans a variety of spatial and temporal scales; (2) a living system includes items one can count (the elements of biodiversity) plus the processes that generate and maintain them; and (3) living systems are embedded in dynamic evolutionary and biogeographic contexts. This breadth is important because human society depends on, and indeed values, both parts and processes—that is, both structure and function—in these systems (counter to Meyer's [1997] argument).

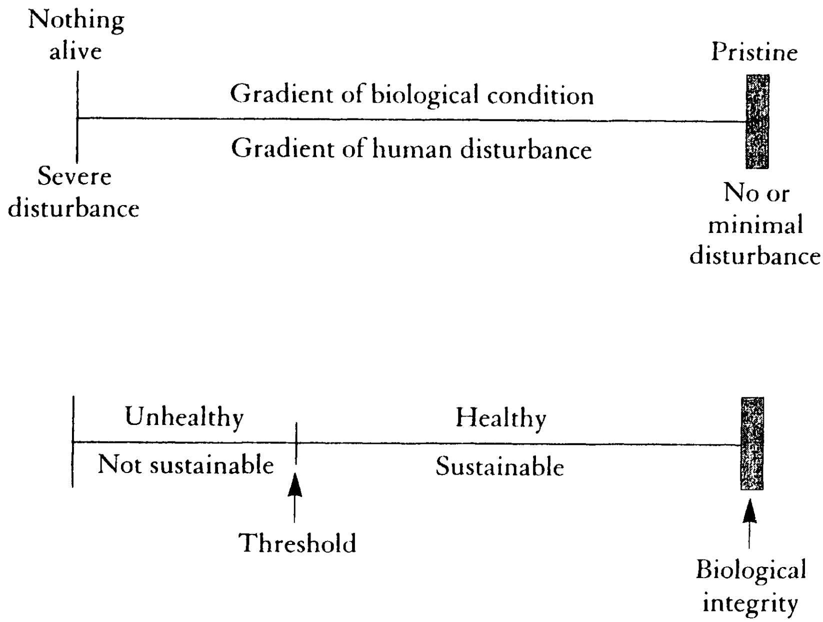

Figure 3. At one end of a continuum of human influence on biological condition, severe disturbance eliminates all life. At the other end of the gradient are "pristine," or minimally disturbed, living systems (*top*); these systems possess biological integrity. A parallel gradient (*bottom*) from integrity toward nothing alive passes through healthy, or sustainable, conditions or activities. Below a threshold defined by specific criteria (see text), the conditions or activities are no longer healthy or sustainable in terms of supporting living systems.

As human activity changes biological systems, they—and we along with them—move along a continuum, ultimately to a state where little or nothing is left alive (see Figure 3). Whether such a shift is acceptable to society is certainly a "value" decision—do we value the elements and processes that are lost?—but those decisions ought to be grounded in broad understanding of the consequences of loss, which include the loss of our own basis for existence (Westra 1998).

Two criteria would help set the thresholds for whether a loss is acceptable (Karr 1996). First, human activity should not alter the long-term ability of places to sustain the supply of goods and services those places provide. Second, human uses should not degrade off-site areas, a provision that requires a landscape-level perspective. Such criteria in decisions about environmental policy—from land use to fish harvest quotas—would avoid the depletion of living systems.

Like health and integrity generally, river health can take on multiple definitions. To irrigators, rivers are healthy if there is enough water for their fields. For a power utility, rivers are healthy if there is enough water to turn the turbines. For a drinking-water utility, rivers are healthy if there is enough pure or purifiable water throughout the year. To fishers, rivers are healthy if there are fish to harvest. For recreationists, rivers are healthy if swimming, water skiing, and boating do not sicken people. But every one of these viewpoints is only part of the picture. Each trivializes the other views of the river—not to mention nonhuman aspects of the river itself—while assigning value only to its own. To protect all river uses and values, we need broader definitions of river health.

Water bodies with integrity, especially rivers, have persisted in and shaped their region's physical and chemical environment over millennia. The very presence of their natural biota means that they are resilient to the normal variation in that environment. Still, the bounds over which the system changes as a result of most natural events are narrow in comparison with the changes caused by human actions such as row-crop agriculture, timber harvest, grazing, or urbanization. Normal, or expected, conditions constituting integrity vary geographically because each river's biota evolves in the context of local and regional geology and climate and within the biological constraints imposed by the organisms with access to that region (see Premise 6). Understanding this baseline must be the foundation for assessing change caused by humans. Only then can we make informed decisions in response to the question, Is this level of change acceptable?

When human activities within a watershed are minimal, the biota is determined by the interaction of biogeographic and evolutionary processes. As human populations increase and technology advances, landscapes are altered in a variety of ways. Those changes alter the river's biota and thus the entire biological context of the river, causing it to diverge from integrity. In some cases, the changes are minor. In others, they are substantial; they may even eliminate all or most of the plants and animals in a river. That much divergence from integrity is not healthy for humans or nonhumans.

Consideration of river health or integrity rarely entered decision making by societies bent on conquering some frontier. Water was simply there, a potable liquid to be used. It was there to be allocated, to be consumed, and to be discarded and, as likely as not, carried society's unwanted wastes with it. When the goal is to conquer, everything else is in the way. This attitude has threatened and continues to threaten the tenuous balance between water and human society, between rivers and the people who depend on rivers.

In some instances, water is at the center of, even a weapon in, age-old power struggles among humans: between the powerful and the weak in a single society—downstream populations of Hokoham in the arid American Southwest fortified themselves against upstream neighbors to retain control over the flow of water (Pringle 1998)—and between the societies of haves and of have-nots (Donahue and Johnston 1998). The consequences for human culture and values, as well as for human and ecological health, have been catastrophic.

Society—oblivious to either human-health or ecological risks of radically altering rivers—has chronically undervalued their biological components. We have behaved as if we could repair or replace any lost or broken parts of regional water resource systems, much as we replace toasters, cars, jobs, and even hearts or livers. This disregard has only worsened the lack of coherence in water law and in regulations regarding water use. The result is a body of federal, state, and local law that fails to make the connections between water quality and quantity, surface water and groundwater, headwater streams and large rivers, and the living and nonliving components of aquatic ecosystems. This disconnectedness was one thing when there were few people living on a vast North American continent; now it is quite another.

We need a new approach, one based on new conceptual models of how rivers, landscapes, and human society interact. Mental models guide much that we do. But models—whether conceptual, physical, or mathematical—can be wrong when they make inappropriate assumptions or focus on the wrong endpoint. They can mislead when they contain inappropriate levels of detail, or they can be irrelevant if they do not apply to the real world. The first rule of modeling is to recognize that "all models are wrong, but some models are useful" (Anderson and Woessner 1992). Models are most useful when they are routinely evaluated to determine if expectations are being met and if policies based on those models are accomplishing the goals of the society using those models.

A new model, with biological integrity and ecological health at its core, should inform society not only about the condition of rivers and the landscapes they run through, but also about the lives of people living in those landscapes. That model should focus on biological endpoints as the most integrative measures of river health. Because they can be defined on the basis of objective criteria (Karr 1996; Westra 1998) and used systematically to diagnose ecological condition (Rapport 1998), the concepts of biological integrity and ecological health can and should be central to that model (Rapport et al. 1998). Biological monitoring with these concepts at its core integrates the influence of all forms of degradation caused by human actions and can thus guide diagnostic, curative, restorative, and preventive management actions.