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Sustaining Healthy Freshwater Ecosystems

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Functionally intact and biologically complex freshwater ecosystems provide many economically valuable commodities and services to society. The services supplied by freshwater ecosystems include flood control, transportation, recreation, purification of human and industrial wastes, habitat for plants and animals, and production of fish and other foods and marketable goods. These human benefits are called ecological services, defined as "the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life" (Daily 1997). Over the long term, healthy freshwater ecosystems are likely to retain the adaptive capacity to sustain production of these ecological services in the face of future environmental disruptions such as climate change.

Ecological services are costly and often impossible to replace when aquatic ecosystems are degraded (NRC 1992; Baron et al. 2002). Yet today, aquatic ecosystems are being severely altered or destroyed at a greater rate than at any other time in human history, and far faster than they are being restored. This is due largely to the fact that fresh water is vital to human life and economic well-being, and societies draw heavily on rivers, lakes, wetlands, and underground aquifers to supply water for drinking, irrigating crops, and running industrial processes. The benefits of these extractive uses of fresh water have traditionally overshadowed the equally vital benefits of water that remains in stream to support healthy aquatic ecosystems.

Sustainability, defined in *Our Common Future* (WCED 1987) as the ability to meet the needs of the present without compromising the ability of future generations to meet their own needs, has become a rallying cry for environmentalists, planners, and even some engineers. Yet too often only *human* uses are considered under the rubric of "water sustainability." Water use is historically defined as water used for agricultural, municipal, and industrial activities. Although there are increasing numbers of examples in the United States of legislated in-stream flows to meet a variety of environmental needs, a common complaint from water managers is that those needs are vaguely described and ill-defined. How much water does an aquatic ecosystem need? The following essay is an attempt to answer this question, but the answer is not simply water volume. Freshwater ecosystems are dynamic, and we describe the requirements for water of sufficient quality, timing, and flow variability, in addition to volume, to maintain the natural dynamics that produce ecosystem goods and services.

As goods and services provided by freshwater ecosystems become increasingly understood and valued, a framework for allocating water supply for ecological needs as well as societal needs to be developed. The challenge is to determine how society can extract the water resources it needs while protecting the important natural complexity and adaptive capacity of freshwater ecosystems. In this respect, scientific understanding of freshwater ecosystem requirements is necessary to the debate over sustainable water uses, but insufficient.

Coherent policies are required that more equitably allocate water resources between natural ecosystem functioning and society's extractive needs.

Requirements for Freshwater Ecosystem Integrity

Freshwater ecosystems differ greatly from one another depending on type, location, and climate, but they nevertheless share important features. For one, lakes, wetlands, rivers, and their connected ground waters share a common need for water within a certain range of quantity and quality. In addition, because freshwater ecosystems are dynamic, all require a range of natural variation or disturbance to maintain viability or resilience. Water flows that vary from season to season or year to year, for example, are needed to support diverse plant and animal communities and promote critical ecosystem processes. Periodic and episodic extremes in water flow also influence water quality, physical habitat conditions and connections, and energy sources in aquatic ecosystems. Freshwater ecosystems, therefore, are defined by the rhythms of natural hydrologic variability.

The structure and functioning of freshwater ecosystems are tightly linked to the watersheds, or catchments, of which they are a part. Water flowing through the landscape on its way to the sea moves in three dimensions, linking upstream to downstream, stream channels to floodplains and riparian wetlands, and surface waters to ground water. Terrestrial landscapes ultimately drain into rivers, lakes, and other freshwater ecosystems, making these systems directly influenced by what happens on the land, including human activities.

We describe five dynamic environmental factors that regulate much of the structure and functioning of any aquatic ecosystem, although their relative importance varies among aquatic ecosystem types. The interaction of these drivers in space and time defines the dynamic nature of freshwater ecosystems:

1. The *flow pattern* defines the rates and pathways by which rainfall and snowmelt enter and move through river channels, lakes, wetlands, and connecting ground waters, and also determines how long water is stored in these ecosystems.
2. *Sediment and organic matter inputs* provide raw materials that create physical habitat structure for completion of organisms' life cycles, as well as supply energy sources and store nutrients that sustain aquatic plants and animals.
3. *Temperature and light characteristics* regulate the metabolic processes, activity levels, and productivity of aquatic organisms.
4. *Nutrient and other chemical conditions* regulate pH, plant and animal productivity, and water quality.
5. The *plant and animal assemblage* influences ecosystem process rates and community structure.

In naturally functioning freshwater ecosystems, all five of these factors vary within defined ranges throughout the year, tracking seasonal changes in climate and day length. Species have evolved and ecosystems have adjusted to accommodate these annual cycles. They have also developed strategies for surviving—and often requiring—periodic hydrologic extremes caused by floods and droughts that exceed the normal annual highs or lows in flows, temperature, and other factors.

Focusing on one factor at a time will not yield a true picture of ecosystem functioning. Evaluating freshwater ecosystem integrity requires that all five of these dynamic environmental factors be integrated and considered jointly.

Flow Patterns

An evaluation of the characteristics required for healthy functioning can begin with a description of the natural or historical flow patterns for streams, rivers, wetlands and lakes. Certain aspects of these patterns are critical for regulating biological productivity (that is, the growth of algae or phytoplankton that form the base of aquatic food webs and the higher organisms in the food web such as invertebrates and fish) and biological diversity, particularly for rivers and their associated floodplain wetlands (Poff et al. 1997). These aspects include base flow, annual or frequent floods, rare and extreme flood events, seasonality of flows, and annual variability. Such factors are also relevant for evaluating the integrity of lakes and wetlands because flow patterns and hydroperiod (that is, seasonal fluctuations in water levels) influence water circulation patterns and renewal rates, as well as types and abundances of aquatic vegetation such as reeds, grasses, and flowering plants as well as associated animals. Furthermore, the characteristic flow pattern of a lake, wetland, or stream critically influences algal productivity and is an important factor to be considered when determining acceptable levels of nutrient (nitrogen and phosphorus) runoff from the surrounding landscape. Human alterations of river flow have seldom taken into account the ecological consequences of flow alteration; however, it is increasingly understood that modifying natural hydrologic patterns can dramatically alter the productivity and diversity of freshwater ecosystems (Baron et al. 2002).

Sediment and Organic Matter Inputs

In river systems, the movement of sediments and influxes of organic matter are important components of habitat structure and dynamics (Palmer et al. 2000). Natural organic matter inputs include seasonal runoff and debris such as leaves and decaying material from terrestrial plants. Especially in smaller rivers and streams, the organic matter that arrives from the land is a particularly important source of energy and nutrients, and tree trunks and other woody materials that fall into the water provide important habitat structure for aquatic organisms. Natural sediment movements are those that accompany natural variations in water flows. In lakes and wetlands, all but the finest inflowing sediment falls permanently to the bottom, so that over time these systems fill. The plants, microbes, and animals, including many fish species that populate the bottoms of freshwater systems are highly adapted to the specific sediment and organic matter conditions of their environment, and do not persist if changes in the type, size, or frequency of sediment inputs occur. The fate of these organisms is critical to sustaining freshwater ecosystems since they are responsible for much of the work of water purification, decomposition, and nutrient cycling.

Humans have severely altered the natural rates of sediment and organic matter supply to aquatic systems, increasing some inputs while decreasing others. Poor agricultural, logging, or construction practices promote high rates of soil erosion. The U.S. Environmental Protection Agency reports that sediment from non-point sources is the cause of substandard water quality in one quarter of all lakes (EPA 1998). Dams alter sediment flows both for the reservoirs behind them and the streams below, silting up the former while starving the latter. By one estimate, 1.2 billion cubic meters of sediment builds up each year in U.S. reservoirs (Stallard 1998). This sediment capture in turn cuts off normal sand, silt, and gravel supplies to downstream reaches, causing streambed erosion that both degrades in-channel habitat and isolates floodplain and riparian wetlands from the channel during high flows. Channel straightening, overgrazing of river and stream banks, and clearing of streamside vegetation reduce organic matter inputs and often increase erosion.

Temperature and Light

Water temperature directly regulates oxygen concentrations, the metabolic rate of aquatic organisms, and associated life processes such as growth, maturation, and reproduction. In lakes particularly, the absorption of solar energy and its dissipation as heat are critical to the development of temperature gradients between surface and deeper water layers and also to water circulation patterns. Circulation patterns and temperature gradients in turn influence nutrient cycling, distribution of dissolved oxygen, and both the distribution and behavior of organisms, including game fish. Streams and rivers are generally turbulent and somewhat turbid and change temperature in synchrony with the daily and seasonal atmospheric conditions. However, this natural pattern is often interrupted by dams, which often release cold and clear water, significantly altering biological processes in the downstream river reaches.

Nutrient and Chemical Conditions

Natural nutrient and chemical conditions are those that reflect local climate, bedrock, soil, vegetation type, and topography. Natural water conditions can range from clear, nutrient-poor rivers and lakes on crystalline bedrock to much more chemically enriched and algae-producing freshwaters in catchments with organic matter-rich soils or limestone bedrock. This natural regional diversity in watershed characteristics, in turn, sustains high biological diversity.

Cultural eutrophication occurs when additional nutrients, chiefly nitrogen and phosphorus, from human activities enter freshwater ecosystems. The result is a decrease in biological diversity, although productivity of certain algal species can increase well beyond original levels. Among U.S. lakes identified by the EPA as impaired in 1996, excess nutrients contributed to more than half of the water quality problems (EPA 1998).

Man-made chemicals and toxins, ranging from herbicides and pesticides to personal care products and pharmaceuticals, are found in most waters of the United States and Europe (Kolpin et al. 2002; Buerge et al. 2003). More than half of agricultural and urban streams sampled by the U. S. Geological Survey were found to have pesticide concentrations that exceed guidelines for the protection of aquatic life (USGS 1999). While definitive understanding of their effects is yet unknown, studies have shown these agents can behave as endocrine disruptors, inhibit reproductive capability, affect population and community stability, and alter rates of primary productivity and decomposition.

Plant and Animal Assemblages

The community of species that lives in any given aquatic ecosystem reflects both the pool of species available in the region and the abilities of individual species to colonize and survive in that water body. The suitability of a freshwater ecosystem for any particular species is dictated by the environmental conditions—that is, water flow, sediment, temperature, light, and nutrient patterns—and the presence of, and interactions among, other species in the system. Thus, both the habitat and the biotic community provide controls and feedbacks that maintain a diverse range of species. The high degree of natural variation in environmental conditions in fresh waters across the United States promotes high biological diversity. In fact, North American freshwater habitats are unrivaled in diversity of fish, mussel, crayfish, amphibian, and aquatic reptile species compared with anywhere else in the world (Abell et al. 2000). The biota, in turn, shape critical ecological processes of primary production, decomposition, and nutrient cycling. Within a body of water, species often perform overlapping, apparently redundant roles in these processes, a factor that helps provide local ecosystems with a greater capacity to adapt to future environmental variation. High apparent redundancy (that is, a high number of functionally similar species) affords a kind of insurance that ecological functions will continue during environmental stress (Mulder et al. 2001). Critical to this is connectivity among water bodies, which allows species to move to more suitable habitat as environmental conditions change.

Human activities that alter freshwater environmental conditions can greatly change both the identity of the species in the community and the functioning of the ecosystem. Introduction of non-native species that can thrive under the existing or altered range of environmental variation can contribute to the extinction of native species, severely modify food webs, and alter ecological processes such as nutrient cycling in all types of freshwater ecosystems. Exotic species are often most successful in human-modified systems, where they can be difficult to eradicate.

Tools Available for Restoration

Despite widespread degradation of freshwater ecosystems, management techniques are available that can help restore these systems to a more natural and sustainable state and prevent continued loss of biological diversity, ecosystem functioning, and ecological integrity. One technique, for example, involves restoring some of the natural variations in stream flow, based on the understanding that river systems are naturally dynamic (Poff et al. 2003; Richter et al. 2003). Variable streamflow techniques seek a balance between water delivery needs for power generation or irrigation, and instream ecological needs for patterns of flow variability characteristic of the natural system, which vary regionally. Restoring flow variability provides the range of habitat conditions needed by a diverse biological community and helps to reconnect dynamic riparian and groundwater systems with surface flows, enabling water to move more naturally through all the spatial dimensions that are essential to fully functional ecosystems.

Other restoration efforts target pollution, both from point sources such as effluent from industrial or sewage pipes and nonpoint sources such as fertilizer runoff from urban lawns and rural croplands. Point sources of water pollution are readily identified, and many have been controlled, thanks in large part to the federal Clean Water Act and Safe Drinking Water Act. Nonpoint sources of nutrients and toxins now supply the majority of pollutants to freshwater ecosystems (Carpenter et al. 1998). In some situations, best management practices of erosion control and moderate applications of fertilizers, pesticides and herbicides can reduce runoff of agricultural pollutants. Best management practices require willing farmers, however, and willingness is often a response either to economic incentives or to stringent regulations. To determine best management practices, the EPA has recently published guidelines for establishing acceptable nutrient runoff criteria for different regions of the United States, recognizing the inherent natural variability in local and regional availability of nutrients (EPA 1999, 2000). The guidelines are based on Total Maximum Daily Load (TMDL), a calculation of the maximum amount of a pollutant that a water body can receive and still meet water quality standards. Water quality standards for a pollutant are established within each ecoregion based on comparison with relatively unpolluted waters or—if few or no unpolluted waters remain in a region—on waters with the lowest pollution levels. Once a standard is set, management practices can be enacted to reduce inputs of unwanted pollutants.

Another large source of nonpoint pollution is atmospheric deposition of pollutants, including acid rain. These could be reduced through more stringent controls on emissions of sulfur, nitrogen, metals, and organic toxins, and through development and application of more efficient transportation and energy production technologies.

Challenges Ahead

The problems confronting freshwater ecosystems will be intractable if they continue to be approached piecemeal. Control of pollution is necessary, for instance, but insufficient for maintaining a native species community if adequate water flows are not available at the right time, if the channel has been severely degraded, or if invasive species have been allowed to take hold. The needs of aquatic ecosystems and the needs of society for water supplies must be addressed collectively if freshwater ecological integrity is to be maintained or restored. Politically, this requires that broad coalitions of water users must work together towards a mutually acceptable future.

The best time to develop such coalitions is before water is allocated and before ecological crises occur. In many parts of the world, this opportunity was missed long ago. The potential for full or partial restoration remains, however. An ambitious example is taking place in south Florida, where water control structures are being physically removed and nutrient inputs curtailed in an attempt to encourage a more natural system.

Balancing Human Use and Needs of Freshwater Ecosystems

Stating the requirements for aquatic ecosystem integrity, of course, is not the same as implementing them in the context of today's complicated society. Policies for maintenance of water quality and flow are primarily based on human health needs. U.S. water policy currently supports increased withdrawals of water supplies in order to meet human demands, however there are signs suggesting these policies are beginning to change. Secretary of the Interior Gale Norton has called for collaborative approaches, enhanced water conservation, and enhancement of existing, not new, water supply structures (Water 2025: Preventing Crises and Conflict in the West. http://www.doi.gov/water2025/Water2025-Exec.htm). We must begin to redefine water use based on the recognition that supplies are finite and that healthy freshwater ecosystems must be sustained or restored. For these reasons we offer the following recommendations for how water is viewed and managed:

1. Incorporate freshwater ecosystem needs, particularly naturally variable flow patterns, into national and regional water management policies along with concerns about water quality and quantity.

Because most land and water use decisions are made locally, we recommend empowering local groups and communities to implement sustainable water policies. A large and growing number of watershed groups is already moving in this direction with the support and guidance of state and federal agencies. Flexibility, innovation, and incentives such as tax breaks, development permits, conservation easements, and pollution credits are effective tools for achieving freshwater ecosystem sustainability goals.

2. Define water resources to include watersheds so that fresh waters are viewed within a landscape or systems context.

Many of the problems facing freshwater ecosystems come from outside the lakes, rivers, or wetlands themselves. Laws and agency regulations lag in their recognition of this fact. One place to initiate a change is through existing governmental permitting processes. Requests to the Federal Energy Regulatory Commission for hydropower dam renewals, permit requests to the Army Corps of Engineers for dredge and fill operations under the Clean Water Act Section 404, and land use and effluent discharge permit requests to state, county, and local entities present ideal opportunities to integrate ecosystem needs with traditional water uses. The EPA's TMDL program is an effort to address both point and nonpoint pollution from a watershed to a water body, although the program has not yet been fully implemented.

3. Increase communication and education across disciplines.

Interdisciplinary training and experience, particularly for engineers, hydrologists, economists, and ecologists, can foster a new generation of water managers and users who think about freshwaters as systems that provide ecological goods and services in addition to water supply.

4. Increase restoration efforts for wetlands, lakes, and rivers using ecological principles as guidelines.

While some restoration has occurred, a greater effort is required to restore the ecological integrity of the nation's water resources. The goal of restoration should be to reinstate natural variations in the fundamental environmental factors identified above. Yet many restoration projects, especially for wetlands, have focused only on replanting vegetation while ignoring underlying hydrologic, geomorphic, biological, and chemical processes. In any given freshwater system, the extent of restoration and protection that is eventually undertaken will be widely debated because active management is inherently a social process, although one ideally informed by science. Restoration efforts can encompass a spectrum of goals, from nearly full recovery of native species and environmental conditions to the management of dynamic, biologically diverse communities that do not necessarily resemble native ecosystems.

5. Maintain and protect remaining minimally impaired freshwater ecosystems.

Aldo Leopold said: "If the biota, in the course of aeons, has built something we like but do not understand, then who but a fool would discard seemingly useless parts? To keep every cog and wheel is the first precaution of intelligent tinkering." Many restoration projects fail to reestablish ecosystem functioning once major processes have been disturbed. It is far wiser and cheaper to conserve what we have. Moreover, our remaining functionally intact freshwater ecosystems can provide a source of plant and animal colonists for restoration projects elsewhere.

6. Bring the ecosystem concept home.

Achieving ecological sustainability requires that we come to recognize the interdependence of people and the environments of which they are a part. For fresh waters, this will require broad recognition of the sources and uses of water for societal and ecological needs. It will also require taking a much longer view of water processes. Water delivery systems and even dams are developed with life spans and management guidelines of decades to, at most, a century. Freshwater ecosystems have evolved over aeons, and their sustainability must be considered from a long-term perspective. Governmental policies, mass media, and a market-driven economy all focus on much shorter-term benefits. Educational programs at the kindergarten through high school level, individual initiatives to become informed, and efforts by local watershed groups interested in protecting their natural resources can provide good first steps toward enduring stewardship. These steps must be matched by state and national acknowledgment that fundamental human needs for water can be met in the future only through policies that preserve the integrity and functioning of freshwater ecosystems today.

Conclusion

Freshwater ecosystems have been described as "biological assets (that are) both disproportionately rich and disproportionately imperiled" (Abramovitz 1996). They need not be so threatened. By recognizing the need for naturally varying flows of water and sediment, and reduced pollution loads, we can maintain or restore freshwater ecosystems to a sustainable state that will continue to provide the amenities and services society has come to expect while helping native aquatic species to flourish.

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