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Sustaining Healthy Freshwater Ecosystems

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SUMMARY

Fresh water is vital to human life and economic well-being, and societies extract vast quantities of water from rivers, lakes, wetlands, and underground aquifers to supply the requirements of cities, farms, and industries. Our need for fresh water has long caused us to overlook equally vital benefits of water that remains in stream to sustain healthy aquatic ecosystems. There is growing recognition, however, that functionally intact and biologically complex freshwater ecosystems provide many economically valuable commodities and services to society. These services 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. Over the long term, intact ecosystems are more likely to retain the adaptive capacity to sustain production of these goods and services in the face of future environmental disruptions such as climate change. These ecosystem benefits are costly and often impossible to replace when aquatic systems are degraded. For this reason, deliberations about water allocation should always include provisions for maintaining the integrity of freshwater ecosystems.

Scientific evidence indicates that aquatic ecosystems can be protected or restored by recognizing the following:

- Rivers, lakes, wetlands, and their connecting ground waters are literally the “sinks” into which landscapes drain. Far from being isolated bodies or conduits, freshwater ecosystems are tightly linked to the watersheds or catchments of which each is a part, and they are greatly influenced by human uses or modifications of land as well as water. The stream network itself is important to the continuum of river processes.
- Dynamic patterns of flow that are maintained within the natural range of variation will promote the integrity and sustainability of freshwater aquatic systems.
- Aquatic ecosystems additionally require that sediments and shorelines, heat and light properties, chemical and nutrient inputs, and plant and animal populations fluctuate within natural ranges, neither experiencing excessive swings beyond their natural ranges nor being held at constant levels.

Failure to provide for these natural requirements results in loss of species and ecosystem services in wetlands, rivers, and lakes. Scientifically defining requirements for protecting or restoring aquatic ecosystems, however, is only a first step. New policy and management approaches will also be required. Current piecemeal and consumption-oriented approaches to water policy cannot solve the problems confronting our increasingly degraded freshwater ecosystems. To begin to redress how water is viewed and managed in the United States, we recommend:

1) Framing national, regional, and local water management policies to explicitly incorporate freshwater ecosystem needs.
2) Defining water resources to include watersheds, so that fresh waters are viewed within a landscape or ecosystem context instead of by political jurisdiction or in geographic isolation.
3) Increasing communication and education across disciplines, especially among engineers, hydrologists, economists, and ecologists, to facilitate an integrated view of freshwater resources.
4) Increasing restoration efforts using well-grounded ecological principles as guidelines.
5) Maintaining and protecting remaining freshwater ecosystems that have high integrity.
6) And recognizing human society’s dependence on naturally functioning ecosystems.

Cover—(1) Rio Grande at Bandelier National Monument, New Mexico. Photo courtesy Jim Thibault, University of New Mexico Biology Department; (2) Rio Grande near Bernalillo, New Mexico. Photo courtesy Anders Molles, son of Manuel C. Molles, Jr., University of New Mexico Biology Department; (3) Dry Rio Grande at Bosque del Apache National Wildlife Refuge, July 17, 2002. Photo courtesy Jennifer Schuetz, University of New Mexico Biology Department.

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by Jill S. Baron, N. LeRoy Poff, Paul L. Angermeier, Clifford N. Dahm, Peter H. Gleick, Nelson G. Hairston, Jr., Robert B. Jackson, Carol A. Johnston, Brian D. Richter, Alan D. Steinman

INTRODUCTION

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 sustain healthy aquatic ecosystems. There is growing recognition that functionally intact and biologically complex freshwater ecosystems provide many economically valuable commodities and services to society (Figure 1). 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 what ecologists call ecological services, defined as “the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life.” 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.

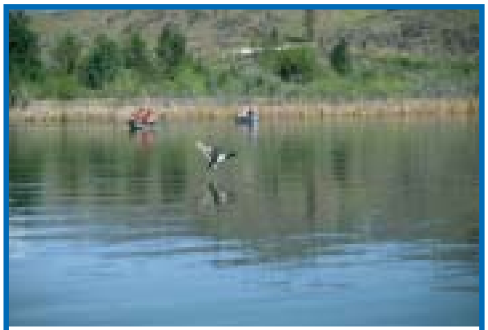

Figure 1—Freshwater ecosystems provide economically valuable commodities and services to humans (drinking water, irrigation, transportation, recreation, etc.), as well as habitat for plants and animals.

Ecological services are costly and often impossible to replace when aquatic ecosystems are degraded. 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. Debates involving sustainable allocation of water resources should recognize that maintenance of freshwater ecosystem integrity is a legitimate goal that must be considered among the competing demands for fresh water. Coherent policies are required that more equitably allocate water resources between natural ecosystem functioning and society’s extractive needs.

Current water management policies in the United States are clearly unable to meet this goal. Literally dozens of different government entities have a say in what wastes can be discharged into water or how water is used and redistributed, and the goals of one agency are often at cross-purposes with those of others. U. S. laws and regulations concerning water are implemented in a management context that focuses primarily on maintaining the lowest acceptable water quality and minimal flows, and protecting single species rather than aquatic communities. A fundamental change in water management policies is needed, one that embraces a much broader view of the dynamic nature of freshwater resources and the short- and long-term benefits they provide.

Our current educational practices are as inadequate as management policies to the challenge of sustainable water resource management. Hydrologists, engineers, and water managers, the people who design and manage the nation’s water resource systems, are rarely taught about the ecological consequences of management policies. Likewise, ecologists are rarely trained to consider the critical role of water in human society or to understand the institutions that manage water. Economists, developers, and politicians seldom project far enough into the future to fully account for the potential ecological costs of short-term plans. Few Americans are aware of the infrastructure that brings them pure tap water or carries their wastes away, and fewer still understand the ecological tradeoffs that are made to allow these conveniences.

Although the requirements of healthy freshwater ecosystems are often at odds with human activity, this conflict need not be inevitable. 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. Current scientific understanding makes it possible to outline here in general terms the requirements for adequate quantity, quality, and timing of water flow to sustain the functioning of freshwater ecosystems. A critical next step will be communication of these requirements to a broader community. The American public, when given information about management alternatives, supports ecologically based management approaches, particularly toward fresh water.

Several previous studies that have addressed the overall condition of freshwater resources have recognized that

- water movement through the biosphere is highly altered by human activities;
- water is intensively used by humans;
- poor water quality is pervasive;

Table 1— Changes in hydrologic flow, water quality, wetland area, and species viability in U.S. rivers, lakes, and wetlands since Euro-American settlement.

U. S. Freshwater Resources	Pre-settlement Condition	Current Conditions	Source
Undammed rivers (in 48 contiguous states)	5.1 million km	4.7 million km	Echeverria et al. 1989
Free-flowing rivers that qualify for wild and scenic status (in 48 contiguous states)	5.1 million km	0.0001 million km	US DOI 1982
Number of dams >2m	0	75,000	CEQ 1995
Volume of water diverted from surface waters	0	10 million m^3 day^{-1}(1985)	Solley et al. 1998
Total daily U. S. water use	Unknown	1.5 million m^3 day^{-1}(1995)	Solley et al. 1998
Sediment inputs to reservoirs	not applicable	1,200 million m^3/year	Stallard 1998
River water quality*(1.1 million km surveyed)	Unimpaired	402,000 km impaired*	EPA 1998
Lake water quality*(6.8 million ha surveyed)	Unimpaired	2.7 million ha impaired*	EPA 1998
Wetland acreage (in 48 contiguous states)	87 million ha	35 million ha	van der Leeden et al. 1990
Number of native freshwater fish species	822 species	202 imperiled or extinct	Stein and Flack 1997
Number of native freshwater mussel species	305 species	157 imperiled or extinct	Stein and Flack 1997
Number of native crayfish species	330 species	111 imperiled or extinct	Stein and Flack 1997
Number of native amphibian species	242 species	64 imperiled or extinct	Stein and Flack 1997

*Only 19% (1,116,500 km) of total river km in U. S. were surveyed out of a total of 5,792,400 km. Only 40% (6.8 million ha) of total lake area (16.9 million ha) were surveyed.

- and freshwater plant and animal species are at greater risk of extinction from human activities compared with all other species.

These and other analyses indicate that freshwater ecosystems are under stress and at risk (Table 1).

Clearly, new management approaches are needed. In this paper we describe the requirements for water of sufficient quality, amount, timing, and flow variability in freshwater ecosystems to maintain the natural dynamics that produce ecosystem goods and services. We suggest steps to be taken toward restoration and conclude with recommendations for protecting and maintaining freshwater ecosystems.

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 both season to season and year to year, for example, are needed to support plant and animal communities and maintain natural habitat dynamics that support production and survival of species. Variability in the timing and rate of water flow strongly influence the sizes of native plant and animal populations and their age structures, the presence of rare or highly specialized species, the interactions of species with each other and with their environments, and many ecosystem processes. Periodic and episodic water flow patterns also influence water quality, physical habitat conditions and connections, and energy sources in aquatic ecosystems. Freshwater ecosystems, therefore, have evolved to the rhythms of natural hydrologic variability.

The structure and functioning of freshwater ecosystems are also 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. Materials generated across the landscape ultimately make their way into rivers, lakes, and other freshwater ecosystems. Thus these systems are greatly influenced by what happens on the land, including human activities.

We have identified 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 (Figure 2). 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 circulate within 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, refugia, substrates, and spawning grounds and supply 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. *Chemical and nutrient 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 biological diversity, particularly for rivers. These aspects include base flow, annual or frequent floods, rare and extreme flood events, seasonality of flows, and annual variability (BOX 1). 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. 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.

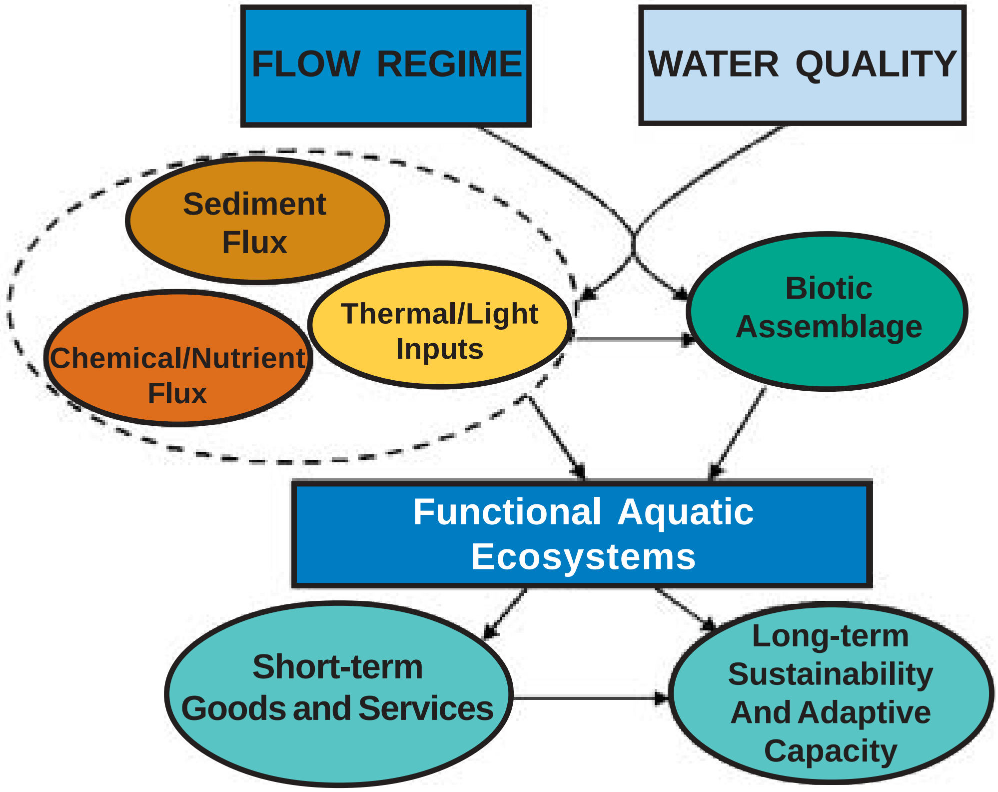

Figure 2— Conceptual model of major forces that influence freshwater ecosystems.

BOX 1— DEFINING FLOW CONDITIONS FOR RIVERS AND STREAMS

Base flow conditions characterize periods of low flow between storms. They define the minimum quantity of water in the channel, which directly influences habitat availability for aquatic organisms as well as the depth to saturated soil for riparian species. The magnitude and duration of base flow varies greatly among different rivers, reflecting differences in climate, geology, and vegetation in a watershed.

Frequent (that is, two-year return interval) floods reset the system by flushing fine materials from the streambed, thus promoting higher production during base flow periods. High flows may also facilitate dispersal of organisms both up- and downstream. In many cases moderately high flows inundate adjacent floodplains and maintain riparian vegetation dynamics.

Rare or extreme events such as 50- or 100-year floods represent important reformative events for river systems. They transport large amounts of sediment, often transferring it from the main channel to floodplains. Habitat diversity within the river is increased as channels are scoured and reformed and successional dynamics in riparian communities and floodplain wetlands are reset. Large flows can also remove species that are poorly adapted to dynamic river environments such as upland tree species or non-native fish species. The success of non-native invaders is often minimized by natural high flows, and the restriction of major floods by reservoirs plays an important role in the establishment and proliferation of exotic species in many river systems.

Seasonal timing of flows, especially high flows, is critical for maintaining many native species whose reproductive strategies are tied to such flows. For example, some fish use high flows to initiate spawning runs. Along western rivers, cottonwood trees release seeds during peak snowmelt to maximize the opportunity for seedling establishment on floodplains. Changing the seasonal timing of flows has severe negative consequences for aquatic and riparian communities.

Annual variation in flow is an important factor influencing river systems. For example, year-to-year variation in runoff volume can maintain high species diversity. Similarly, ecosystem productivity and foodweb structure can fluctuate in response to this year-to-year variation. This variation also ensures that various species benefit in different years, thus promoting high biological diversity.

Human alterations of river flow have seldom taken into account the ecological consequences. “Many rivers now resemble elaborate plumbing works, with the timing and amount of flow completely controlled, like water from a faucet, so as to maximize the rivers’ benefits for humans,” wrote water policy expert Sandra L. Postel. “But while modern engineering has been remarkably successful at getting water to people and farms when and where they need it, it has failed to protect the fundamental ecological function of rivers and aquatic systems.”

Rivers in the U.S. West are prime examples of how human manipulation of water flows can lead to multiple damages to riverbank and floodplain processes and communities. Damming rivers and dampening natural variations in flow rates by maintaining minimum flows year round have contributed to widespread loss of native fish species and regeneration failure of native cottonwood trees, which used to support diverse riparian communities (BOX 2).

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. Natural organic matter inputs include seasonal runoff and debris such as leaves and decaying plant material from land-based communities in the watershed. 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 substrates and habitats 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 invertebrates, algae, bryophytes,

Figure 3—Livestock use of streams can have impacts on the amount of sediment and nutrients inputs. Photo courtesy the U.S. Geological Survey, South Platte National Water Quality Assessment Program (NAWQA).

vascular plants, and bacteria that populate the bottoms of freshwater systems are highly adapted to the specific sediment and organic matter conditions of their environment, as are many fish species, 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 (Figure 3). Poor agricultural, logging, or construction practices, for example, promote high rates of soil erosion. In many areas small streams or wetlands have even been completely eliminated through filling, paving, or re-routing into artificial channels. The U.S. Environmental Protection Agency (EPA) reports that in one quarter of all lakes with sub-standard water quality, the cause of impairment is silt entering from agricultural, urban, construction, and other non-point (widely dispersed) sources. 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, another 1.2 billion cubic meters of sediment builds up each year in U. S. reservoirs (Table 1). 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 rejuvenating high flows. Channel straightening, overgrazing of river and stream banks, and clearing of streamside vegetation reduce organic matter inputs and often increase erosion.

Figure 4—Eutrophication from irrigation return flows. Photo courtesy the U.S. Geological Survey, South Platte National Water Quality Assessment Program (NAWQA).

Temperature and Light

The light and heat properties of a body of water are influenced by climate and topography as well as by the characteristics of the water body itself: its chemical composition, suspended sediments, and algal productivity. Water temperature directly regulates oxygen concentrations, the metabolic rate of aquatic organisms, and associated life processes such as growth, maturation, and reproduction. The temperature cycle greatly influences the fitness of aquatic plants and animals and, by extension, where species are distributed in the system and how the living community in a body of water varies from season to season. In lakes particularly, the absorption of solar energy and its dissipation as heat are critical to development of temperature gradients between the 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 fishes. Water temperature can change dramatically downstream of dams (BOX 2). In Utah's Green River, mean monthly water temperatures ranged between 2 degrees Celsius (C) in winter and 18 degrees C in summer before completion of the Flaming Gorge Dam in 1962. After dam closure, the annual range of mean monthly water temperatures below the dam was greatly narrowed, to between 4 C and 9 C. As a result, species richness declined and 18 genera (that is, groups of related species) of insects were lost; other species, notably freshwater shrimp, came to dominate the ranks of invertebrate animals. Aquatic insects have not recovered despite 20 years of partial temperature restoration achieved by releasing water from warmer reservoir water layers. Water temperature also dropped in the Colorado River after closure of the Glen Canyon Dam in 1963, and there was a dramatic increase in water clarity. Water clarity now routinely allows visibility to greater than 7 meters, whereas prior to dam closure, the water column was opaque with suspended sediments. The colder, clearer waters have allowed a non-native trout population to flourish, at the top of an unusual food web more commonly found much further north.

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 biodiversity.

A condition known as cultural eutrophication occurs when additional nutrients, chiefly nitrogen and phosphorus, from human activities enter freshwater ecosystems (Figure 4). The result is a decrease in biodiversity, although productivity of certain algal species can increase well beyond original levels. Midwestern and Eastern lakes such as Lakes Michigan, Huron, Erie, and

Ontario demonstrate the consequences of excess inputs of nutrients and toxic contaminants, as well as non-native species introductions and over-fishing (BOX 3). Onondaga Lake, New York, which was polluted with salt brine effluent from a soda ash industry, likewise responded with marked changes in the plankton and fish communities, including invasions by non-native fish species. Among U.S. lakes identified by the EPA as impaired in 1996, excess nutrients contributed to more than half of the water quality problems. 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.

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 virtually unrivaled in diversity of fish, mussel, crayfish, amphibian, and aquatic reptile species compared with anywhere else in the world. The biota, in turn, are involved in shaping the 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, species richness or biodiversity) affords a kind of insurance that ecological functions will continue during environmental stress. Critical to this is connectivity among water bodies, which allows species to move to more suitable habitat as environmental conditions change.

Figure 5—Freshwater ecosystems provide habitats to plants and animals. Human activities and water use place many of these freshwater species at risk of extinction. Photo courtesy the U.S. Geological Survey, South Platte National Water Quality Assessment Program (NAWQA).

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 (Figure 5). Excessive stress or simplification of natural complexity has the potential to push functionally intact freshwater ecosystems beyond the bounds of resilience or sustainability, threatening their ability to provide important goods and services on both short and long time scales. Further, 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. Exotic species are often successful in 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 restore these systems to a more natural and sustainable state and prevent continued loss of biodiversity, 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. New statistical approaches to setting management targets for streamflow variability over time have been applied to or proposed for several rivers, including the Flathead River in Montana, the Roanoke River in North Carolina, and the vast Colorado River system in the West. These variable streamflow techniques seek a balance between water delivery needs for power generation or irrigation, and in-stream ecological needs for flow variability that displays a certain timing, frequency, duration, and rate of change characteristic of the natural system (Figure 6). Restoring this flow variability 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. In some situations, best management practices have succeeded in reducing runoff of agricultural pollutants. These practices include erosion control and moderate applications of fertilizers, pesticides and herbicides. Best management practices require willing farmers, however, and willingness is often a response either to economic incentives or to stringent

BOX 2 — THE COLORADO RIVER

The Colorado River is one of the most highly regulated and heavily used river systems in the world. Two principal reservoirs, Lakes Powell and Mead, along with 12 other large reservoirs store and release water according to complicated equations designed to maximize both hydroelectric generation and water supplies for agricultural, domestic, and industrial use in seven states across the Western United States and Mexico. More than 30 million people depend on Colorado River water. The original Colorado River Compact of 1928 allocated all water for societal use. (Actually it over-allocated because typical water volumes were overestimated while year-to-year variability was ignored.)

Physical changes to the river below the dams have been profound. Flow in the Colorado River is snowmelt driven, and pre-dam flow patterns were dominated by large discharges from April through July, followed by low flows in late summer and fall. The river carried tremendous amounts of sediment from the highly erodible Colorado Plateau, and river temperatures were seasonally warm. Today, river flow is nearly decoupled from natural snowmelt, and peak discharges can occur in any month, often November to January. Daily changes in water releases as great as 566 cubic meters per second occur regularly for hydropower generation. Alluvial sediment, which once played a vital role in creating in-channel habitat, is now trapped behind the dams, and the waters below are clear and sediment-starved. Also, because water is released from the bottom waters of most reservoirs, water temperatures for hundreds of kilometers below the dams are very cold throughout the summer and relatively warm during the winter, a reversal of the natural seasonal cycle. (An exception is Flaming Gorge Reservoir on the Green River in the upper Colorado basin, where water is released from multiple reservoir layers.)

Ecological responses to the dams have been equally profound. The clear, cold tail waters below the dams, in conjunction with widespread introduction of non-native species, have promoted food webs that are alien to the Colorado River. Prior to regulation, the organic matter that fueled the river food web primarily originated on land and was carried into the river during large runoff events. Now, organic matter is supplied largely by luxuriant mats of algae that grow on the bottom of the river. The algae are consumed by insects and other invertebrates that historically occurred only in the much colder tributaries of the Colorado; these insects and invertebrates are in turn eaten by non-native rainbow and brown trout. Below the Glen Canyon Dam that holds Lake Powell, only four out of eight indigenous fish species remain, along with 22 non-native fishes, many of which either compete with or directly feed on the endangered native fish. Native cottonwood trees and the animal community they support are declining because the trees are unable to take root under variable flows. Also, upstream reservoirs that reduce the magnitude of annual floods prevent the establishment of cottonwoods higher on the riverbanks. Other shrubs and trees that are more tolerant of these modified conditions have grown profusely, including non-natives such as tamarisk.

The effects of 14 major dams and hundreds of water diversions have been felt all the way to the river mouth. Since completion of the Glen Canyon Dam in 1963, measurable flows from the Colorado River into the Sea of Cortez have occurred only infrequently. The wetland area at the mouth of the river has decreased from a historical average of 250,000 hectares to 5,800 to 63,000 hectares (depending on the year). In the Sea of Cortez, the lack of freshwater inflows has contributed to the endangerment of a large number of species, and the loss of algal productivity has caused the abundance of bivalve mollusk populations to drop 94 percent from 1950 values.

To reduce the impact of dam operations on the river’s ecological resources, Congress passed the Grand Canyon Protection Act of 1992. A large group of Colorado River stakeholders now work with a Department of Interior sponsored Grand Canyon Monitoring and Research Center to attempt through adaptive management to protect and restore riparian areas and native fishes, several of which are threatened or endangered. In 1996, after nearly 15 years of study, a large experimental flood was generated to help scientists and managers investigate the effects of high flows on sediment transport and biological, cultural, and socioeconomic resources. Another set of experimental floods is planned, along with aggressive efforts to reduce non-native trout populations. There is also discussion of installing a thermal control device on Glen Canyon Dam to raise water temperatures below it. Partial restoration of historic temperatures below Flaming Gorge Dam on the Green River, however, have not improved conditions for aquatic insects directly below the dam. More than 20 years later, the number of species is as low or lower than before the restoration efforts began. Further downstream, the number of insect taxa did increase, but only because warmer summer temperatures occurred in combination with periodic floods and sediment inputs from a tributary.

Is it possible to manage a river as highly regulated as the Colorado in ways that protect and improve environmental conditions for the native biota? Only time will tell, but an important first step is recognizing that key processes and conditions must be allowed to fluctuate within a range of natural variability.

Photo credits, clockwise from top center: Green River, 22 May 1871: John Wesley Powell Photographs / # 17234, Grand Canyon National Park Museum Collection; Loch Vale Watershed, CO: J. Baron; Colorado River: K. Henry; Grand Canyon ca. 1872, John Wesley Powell Photographs / # 17248, Grand Canyon National Park Museum Collection; Colorado River delta: Jennifer Pitt, Environmental Defense; Lake Mead: National Park Service; Hoover Dam, 2002: P. Nagler; Glen Canyon Dam: Bureau of Reclamation, Upper Colorado Region.

regulations. To help in determining 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. 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. To allow for natural variation, 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 (Figure 7). 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 nitrogen and other contaminants that fall as acid rain or dry pollutants. These could be

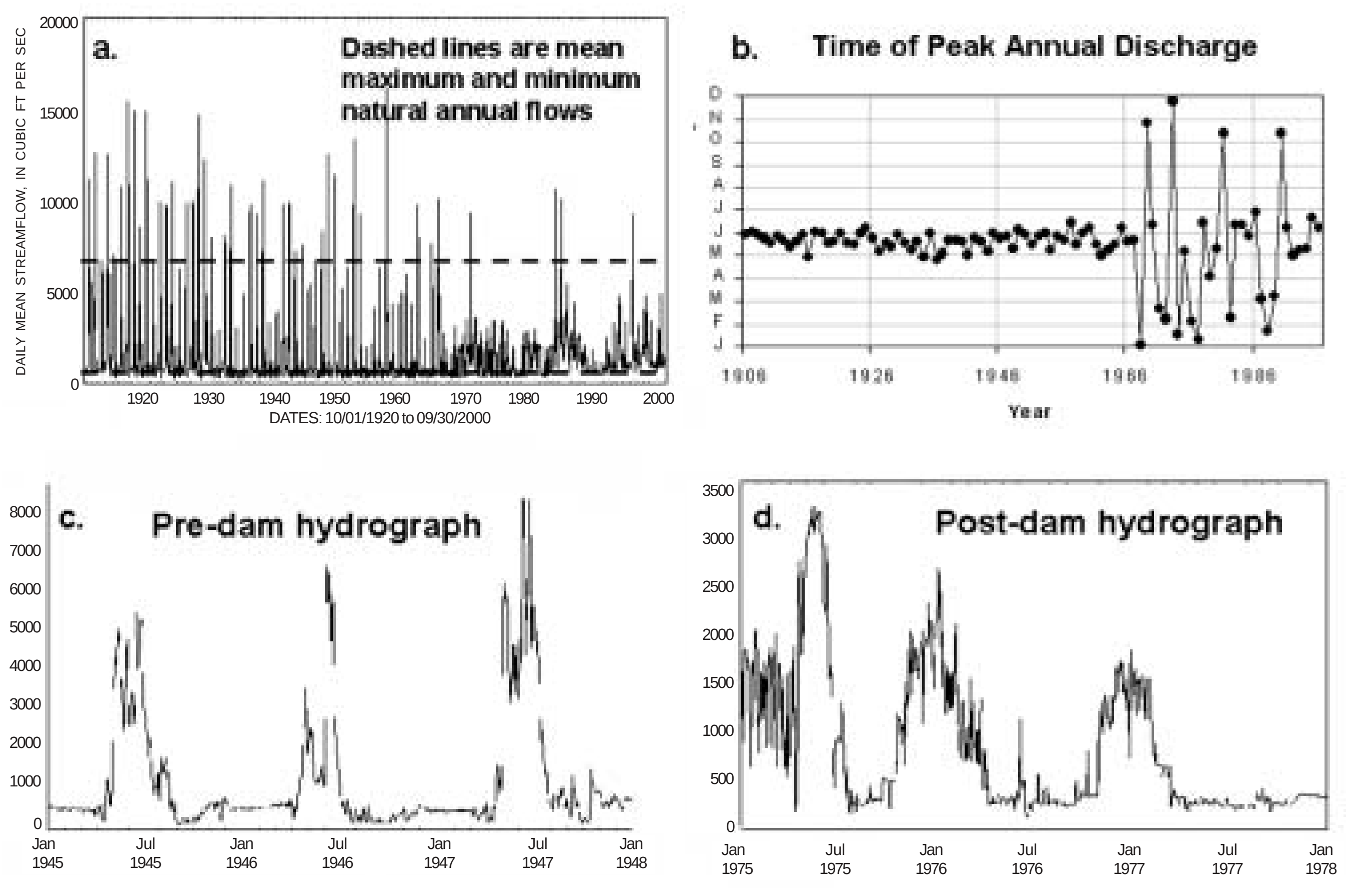

Figure 6 — Hydrologic characteristics for the Gunnison River, Colorado (site #09128000; USGS Water Resources Data of USA: http://water.usgs.gov/nwis). a) Daily mean streamflow (cubic feet per second) for the period 1906-1996. Dashed lines show mean maximum and minimum pre-dam construction annual flows; b) Time of year for peak annual discharge in the Gunnison River, showing April through June snowmelt-driven discharge until dam closure in 1968, when discharge maxima switched to the period October to March, reflecting water releases for hydroelectric power generation; c) Daily hydrograph for pre-dam period 1945-1957; d) Daily hydrograph for post-dam period 1975-1977. One method of restoring a more natural flow pattern calls for establishing a new range for maximum and minimum flows and timing of maximum flows that falls within the range of natural variation.

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. Several government programs, such as the EPA Clean Lakes Program, the Wetlands Restoration Act, and even the Endangered Species Act, mandate actions to prevent specific aspects of ecosystem degradation. But these programs are narrow in focus, effectively addressing symptoms rather than root causes of aquatic ecosystem decline. 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 (BOX 4). Other restoration projects around the nation also show promise.

The ecological consequences that arise when freshwater ecosystems are deprived of adequate water, proper timing of flows, and suitable water quality often become

BOX 3: THE GREAT LAKES ECOSYSTEMS

The Great Lakes – Superior, Michigan, Huron, Erie, and Ontario – hold 20 trillion cubic meters of fresh water, approximately 18 percent of the planet's fresh water supply. The overall basin is home to 35 million people, including 10 percent of the U.S. population and 25 percent of the Canadian population. Nearly 25 percent of agricultural production in Canada, and 7 percent of the agricultural production in the United States occurs in the basin. In addition, the Great Lakes provide drinking water for 40 million people and supply 210 million cubic meters of water per day for municipal, agricultural, and industrial use.

Poor water quality caused by excessive inputs of phosphorus and nitrogen is one of many serious problems affecting the Great Lakes. Some basins of the lakes also contain exceedingly high concentrations of toxic chemicals; habitat destruction has been significant and is increasing; native fisheries have been greatly altered or intentionally replaced; invasive species have altered native food webs and water quality and also damaged human infrastructure; and climate change is expected to alter lake levels. Although freshwater environments the world over share many of the same problems, their significance is heightened by the sheer size of the Great Lakes and the quantity and quality of their waters.

Water Quality. Water quality in the Great Lakes has improved dramatically from the eutrophic conditions that prevailed prior to the 1980s. This has been achieved through greater regulation of point-source pollution. However, water quality has not been restored to "natural condition." Years of phosphorus enrichment in Lake Michigan, for example, increased the growth of diatoms and depleted lake silica concentrations (silica is a necessary nutrient for diatoms and sinks to the lake bottom when diatoms die). Without enough silica, natural algal assemblages and the zooplankton that feed upon them have been severely altered. Today, cultural eutrophication may actually be masked by the filtering activity of zebra mussels, which increases water clarity by shifting nutrients from the water column to the lake sediments. Nonpoint source pollutants, including fertilizers, pesticides, sediment, and bacteria, still significantly impair Great Lakes water quality.

Invasive Species. Non-native species have modified habitats, reduced native biodiversity, and altered food webs. An estimated 162 exotic species now reside in the Great Lakes, including introduced sport fish. Although the zebra mussel and sea lamprey have received the most attention, many other less apparent species profoundly affect the ecosystem, including quagga mussels, predatory zooplankton such as *Cercopagis pengoi* and *Bythotrephes cederstroemi*, the benthic amphipod *Echinogammarus ischnus*, and the round and tubenose gobies. In addition to their ecological impacts, lamprey cost $10 million in control efforts each year, and zebra mussel control has totaled some $4 billion as of 2001.

Zebra mussel photo courtesy USGS.

Toxic Chemicals. The sediments in the Great Lakes store organic and inorganic contaminants coming from industrial, urban, and agricultural runoff as well as atmospheric deposition (including mercury and PCBs). Contaminants from sediments accumulate in aquatic species, affecting fish and wildfowl health and even the health of humans who eat contaminated fish. Contaminants also affect shipping, a major industry on the Great Lakes, because of potential restrictions on dredging of channels and harbors (which can release contaminants into the water column) and on disposal of dredged sediments.

Habitat Destruction. Land use changes have resulted in habitat loss throughout the Great Lakes basin. Urban sprawl continues to replace natural areas, farmland, and open space. The quality and quantity of coastal wetlands are declining; and the extent of hardened shorelines (that is, reinforced by sheet piling or rip rap) appears to be increasing, thus isolating wetlands from lakes, destroying habitat, and altering natural sediment movements.

Climate Change. Implications of future climate change in the Great Lakes region are profound. Some climate change models suggest conditions that will lead to lower lake levels, creating problems for the shipping industry as well as changes in water supply and environmental conditions in the lakes. Current climate models also suggest more extreme swings in climate, and unusually wet years may lead to periodic flooding. It is important to note that the 35 million people in the Great Lakes Basin are unprepared for large changes in lake level in either direction.

As an example of freshwater integrity, the Great Lakes fail on most accounts: shoreline hardening affects connectivity of the lakes with their wetlands; the current chemical and nutrient conditions represent a permanent change from natural conditions; and the plant and animal assemblages have been highly modified by human intervention. Constant effort and expense are now required to maintain water quality at acceptable levels, remove the legacies of past toxic inputs, control harmful non-native species, and restock valued recreational fisheries with exotic game fish that do not naturally reproduce in the lakes. Perhaps the Great Lakes can never be "restored" to the point where they are functionally self-sustaining, and therein lies a hard lesson. Many goods and services valued by society are no longer available (such as fisheries uncontaminated by toxins), and others are possible only through continuing expenditures of millions of dollars in remediation.

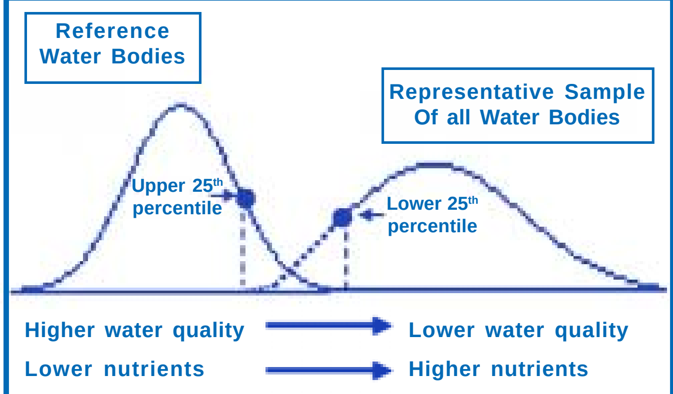

Figure 7—Two different approaches for establishing a standard or "reference condition value" for freshwaters. Reference condition values can be selected from waters that are representative of the most pristine, or least disturbed condition. If this goal is unrealistic, or if undisturbed water bodies no longer exist in the region, the reference condition value can be selected from among the least disturbed and polluted water bodies found in the region. Surveys of existing water quality from a broad range of water bodies are necessary in order to establish realistic water quality goals (Figure and text adapted from EPA 2000).

apparent to people only after the degradation begins to interfere with societal uses of fresh water. Nuisance algal blooms and loss of commercial or sport fisheries are examples of failures in ecosystem processes that were often years in the making. Some ecosystems naturally experience wide swings in environmental and ecological conditions from one year to the next that can mask gradual changes in physical and chemical factors. Most systems are inherently resilient to a particular pattern of disturbance, and their plant and animal communities will persist as long as conditions fluctuate within a certain range. Once a threshold is reached, however, these ecosystems may change rapidly to a new stable state that is very difficult to reverse. The collapse of a fishery and permanent cultural eutrophication from nutrient inputs are two examples of conditions that, once reached, make it difficult to restore the integrity of a freshwater system. Detecting such trends before problems become critical requires both monitoring the biological and physical conditions in freshwater ecosystems and understanding the natural ecological dynamics of these systems.

BALANCING HUMAN USE AND NEEDS OF FRESHWATER ECOSYSTEMS

The sustainability of aquatic ecosystems can best be ensured by maintaining naturally variable flows, adequate sediment and organic matter inputs, natural fluctuations in heat and light, clean water, and a naturally diverse plant and animal community. Failure to provide for these essential requirements results in loss of species and ecosystem services in wetlands, rivers, and lakes. Aquatic ecosystems can be protected or restored by recognizing the following:

1. Aquatic ecosystems are not simply isolated bodies or conduits but are tightly connected to terrestrial environments (Figure 8). Further, aquatic ecosystems are connected to each other and provide essential migration routes for species.

2. Dynamic patterns of flow that are maintained within the historical range of variation will promote the integrity and sustainability of freshwater systems.

3. Aquatic ecosystems additionally require that sediment loads, heat and light conditions, chemical and nutrient inputs, and plant and animal populations fluctuate within natural ranges, neither experiencing excessive swings beyond their natural ranges nor being held at constant, and therefore unnatural, levels.

Stating these requirements for maintaining aquatic ecosystem integrity, of course, is not the same as implementing them in the context of today's complicated society. U.S. water policy currently supports increased exploitation of water supplies in order to meet human demands. Policies for maintenance of water quality and flow are primarily based on human health needs. The age of ever-increasing exploitation is over, however. 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

Figure 8—Even isolated lakes are linked to the land and water around them through the flow of freshwater. Photo courtesy J. Boles, California Department of Water Resources

BOX 4: RESTORING FRESHWATER ECOSYSTEMS IN SOUTH FLORIDA

The south Florida ecosystem covers approximately 47,000 square kilometers and ranges from Orlando in the north to the Florida Keys at its southern extreme. It includes the Kissimmee River, Lake Okeechobee, The Everglades, and Florida Bay. The landscape is essentially flat; the elevation drop from Lake Okeechobee to Florida Bay, a distance of 160 kilometers, is less than 6 meters. South Florida has undergone enormous changes in population, land use, and hydrology over the past 100 years, resulting in profound changes to ecosystem structure and functioning. Starting in the early 1900s, efforts were made to drain the Everglades wetlands, which were viewed as wastelands and useless swamps. Hurricanes and floods prompted massive water management projects. There are now more than 2,500 kilometers of levees and canals, 150 gates and other water control structures, and 16 major pump stations. The flood control system has worked remarkably well, making the region less vulnerable to the extremes of flooding and drought by storing water for supply and moving it for flood control. These management projects were designed in the 1950s when it was anticipated the population in the region would reach 2 million by the year 2000. Today, however, the region is home to more than 6 million people. More significantly, the water projects were not designed with environmental protection or enhancement in mind.

Environmental problems unintentionally created by these water management projects include:

(1) Up to 6.4 billion liters per day of excess rainwater is channeled directly to the ocean to keep urban and agricultural lands from flooding, causing salinity imbalances in estuaries and influencing plant and animal communities.

(2) Lake Okeechobee is treated as a reservoir for water supply or flood control instead of as a natural lake.

(3) Water supply and periodicity for the Everglades has been altered, greatly harming the biota.

(4) And Water quality has deteriorated throughout the region.

Accelerated eutrophication of Lake Okeechobee from phosphorus runoff associated with dairy and beef cattle operations, for example, has shifted the composition of the algal, invertebrate, and higher plant community and thus, the food web. Phosphorus enrichment of the northern Everglades from sugar cane farms has changed the structure and biomass of the periphyton community (organisms attached to submerged substrates) while increasing cattails at the expense of sawgrass. Increases or decreases in the discharge of fresh water to estuaries have influenced the natural salinity patterns of these systems, affecting the abundance of seagrass, oyster, and fish communities. Channelization of the Kissimmee River caused the loss of 11,000 hectares of floodplain habitat.

Approximately half of the historic Everglades has been converted to agricultural or urban use. Populations of wading birds have been reduced 85 to 90 percent. Sixty-eight species of plants and animals in south Florida are threatened or endangered, and invasive species such as melaleuca, Brazilian pepper, Australian pine, torpedo grass, Old World climbing fern, and Asian swamp eel are threatening native habitats and species.

Although it is not possible to restore this region to its pristine condition, efforts are underway to redesign the south Florida aquatic environment to make it more compatible with the way the system formerly functioned. Congress has funded efforts to develop a Comprehensive Everglades Restoration Plan, an ambitious and innovative partnership that aims to enhance the region's ecological and economic values as well as the well-being of its human population. The objectives are to increase the amount of water available by storing it instead of sending it out to sea, ensure adequate water quality, and reconnect the parts of this ecosystem that have been disconnected and fractured. A multi-faceted approach has been proposed that may take 25 years or more to implement.

The ecological goals of the plan are to increase the extent of natural areas, improve habitat and functional quality, and improve native species richness and biodiversity. Success will be evaluated with quantitative criteria. For example, a goal for Lake Okeechobee is to reduce total phosphorus in the water column from a current concentration of 110 to 40 µg/L. Rigorous programs of scientific research will continue throughout project implementation in order to address major uncertainties. The information generated, combined with results from monitoring networks, will be used in adaptive management of the restoration plan.

The inflow and water distribution works for STA 1 (stormwater treatment area), which is a large constructed wetland that is treating runoff from sugar cane fields before entering the Everglades. Photo from the South Florida Water Management District archives.

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. It should also be refined to consider how flow variability influences the transport of pollutants.

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 fresh waters as systems with ecological purposes as well as water supply functions.

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. Highly visible yet ecologically incomplete restoration efforts such as these wetland revegetation projects may even foster complacency among the public. A recent Gallup Poll found that Americans are increasingly satisfied with the nation's environmental protection efforts, making them less likely to support the funding and political effort needed to enact genuine ecological restoration requirements. 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 (Figure 9). 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

Figure 9—Urban stream in Denver, Colorado. Photo courtesy the U.S. Geological Survey, South Platte National Water Quality Assessment Program (NAWQA).

state and national acknowledgment that fundamental human needs for water can only be met in the future 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." 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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SUGGESTIONS FOR FURTHER READING

This report summarizes the findings of our panel. Our full report, which is published in the journal Ecological Applications (Volume 12, Number 5: 1247-1260), discusses and cites extensive references to the primary scientific literature on this subject. From that list we have chosen those below as illustrative of the scientific publications and summaries upon which our report is based.

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