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MEETING ECOLOGICAL AND SOCIETAL NEEDS FOR FRESHWATER

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Abstract. Human society has used freshwater from rivers, lakes, groundwater, and wetlands for many different urban, agricultural, and industrial activities, but in doing so has overlooked its value in supporting ecosystems. Freshwater is vital to human life and societal well-being, and thus its utilization for consumption, irrigation, and transport has long taken precedence over other commodities and services provided by freshwater ecosystems. However, there is growing recognition that functionally intact and biologically complex aquatic ecosystems provide many economically valuable services and long-term benefits to society. The short-term benefits include ecosystem goods and services, such as food supply, flood control, purification of human and industrial wastes, and habitat for plant and animal life—and these are costly, if not impossible, to replace. Long-term benefits include the sustained provision of those goods and services, as well as the adaptive capacity of aquatic ecosystems to respond to future environmental alterations, such as climate change. Thus, maintenance of the processes and properties that support freshwater ecosystem integrity should be included in debates over sustainable water resource allocation.

The purpose of this report is to explain how the integrity of freshwater ecosystems depends upon adequate quantity, quality, timing, and temporal variability of water flow. Defining these requirements in a comprehensive but general manner provides a better foundation for their inclusion in current and future debates about allocation of water resources. In this way the needs of freshwater ecosystems can be legitimately recognized and addressed. We also recommend ways in which freshwater ecosystems can be protected, maintained, and restored.

Freshwater ecosystem structure and function are tightly linked to the watershed or catchment of which they are a part. Because riverine networks, lakes, wetlands, and their connecting groundwaters, are literally the ‘‘sinks’’ into which landscapes drain, they are greatly influenced by terrestrial processes, including many human uses or modifications of land and water. Freshwater ecosystems, whether lakes, wetlands, or rivers, have specific requirements in terms of quantity, quality, and seasonality of their water supplies. Sustainability normally requires these systems to fluctuate within a natural range of variation. Flow regime, sediment and organic matter inputs, thermal and light characteristics, chemical and nutrient characteristics, and biotic assemblages are fundamental defining attributes of freshwater ecosystems. These attributes impart relatively unique characteristics of productivity and biodiversity to each ecosystem. The natural range of variation in each of these attributes is critical to maintaining the integrity and dynamic potential of aquatic ecosys-

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tems; therefore, management should allow for dynamic change. Piecemeal approaches cannot solve the problems confronting freshwater ecosystems.

Scientific definitions of the requirements to protect and maintain aquatic ecosystems are necessary but insufficient for establishing the appropriate distribution between societal and ecosystem water needs. For scientific knowledge to be implemented science must be connected to a political agenda for sustainable development. We offer these recommendations as a beginning to redress how water is viewed and managed in the United States: (1) Frame national and regional water management policies to explicitly incorporate freshwater ecosystem needs, particularly those related to naturally variable flow regimes and to the linking of water quality with water quantity; (2) Define water resources to include watersheds, so that freshwaters are viewed within a landscape, or systems context; (3) Increase communication and education across disciplines, especially among engineers, hydrologists, economists, and ecologists to facilitate an integrated view of freshwater resources; (4) Increase restoration efforts, using well-grounded ecological principles as guidelines; (5) Maintain and protect the remaining freshwater ecosystems that have high integrity; and (6) Recognize the dependence of human society on naturally functioning ecosystems.

Key words: ecological education; ecological integrity; ecosystem protection; ecosystem services, freshwater; freshwater ecosystems; lakes; restoration; rivers; waterflow: quantity, quality, timing, seasonality; water management policy; watersheds; wetlands.

INTRODUCTION

Human society has used freshwater from rivers, lakes, groundwater, and wetlands for many different urban, agricultural, and industrial activities, but in doing so has overlooked its value in supporting ecosystems. 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 (NRC 1992). Freshwater is vital to human life and societal well-being, thus its utilization for consumption, irrigation, and transport has long taken precedence over other commodities and services provided by freshwater ecosystems. However, there is growing recognition that functionally intact and biologically complex aquatic ecosystems provide many economically valuable services and long-term benefits to society. Daily (1997:3) defines an ecosystem service as ‘‘the conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfill human life.’’ Short-term benefits include ecosystem goods and services, such as drinking water, food supply, flood control, purification of human and industrial wastes, and habitat for plant and animal life—all of which are costly, if not impossible, to replace (Wilson and Carpenter 1999, Daily 1997). Long-term benefits include the sustained provision of those goods and services, as well as the adaptive capacity of ecosystems to respond to future environmental alterations, such as climate change. Thus, maintenance of the processes and properties that support freshwater ecosystem integrity should be recognized as legitimate goals for freshwaters, worthy of consideration in debates over sustainable water resource allocation (NRC 1992, Karr 1991, Naiman et al., *in press*). Human society is served in the long term by ecosystem sustainability. We must develop a coherent policy that more equitably allocates water resources between natural ecosystem function and societal needs.

Current water management policies are clearly unable to meet this goal. United States laws and regulations for water are implemented in a management context that focuses primarily on the lowest acceptable water quality, minimal flows, and single-species protection. Literally dozens of different government entities in the United States have a say in what goes into water or how water is used and redistributed, and the goals of one agency are often at cross-purposes with those of others (van der Leeden et al. 1990). 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 educational practices are equally inadequate to the challenge of sustainable water resource management. Hydrologists, engineers, and water managers, the people who design and manage our nation’s water resource systems, are rarely taught about management consequences to ecosystems, nor are ecologists trained to think about the critical role of water in human society. 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 trade-offs that were made to allow these conveniences. How can society extract the water resources it needs while not diminishing the important natural complexity and adaptive capacity of freshwater ecosystems? The requirements of freshwater ecosystems are often at odds with human activity, although this need not always be the case. Our present state of ecological understanding of how freshwater ecosystems function allows us to elaborate the requirements of freshwater ecosystems regarding adequate quantity, quality, and timing of water flow. Communication of these requirements to a

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

Freshwater parameter	Pre-settlement condition	Current conditions	Information source
Free-flowing river kilometers, 48 states	5.1×10^6 km	100 km	Benke (1990)
Number of dams >2 m high	0	75 000	CEQ (1995)
Volume of water diverted from surface waters, 1985	0	10^6 m^3/d	Solley et al. (1998)
Total daily water use, 1995	unknown	1.5×10^6 m^3/d	Solley et al. (1998)
Sediment inputs to reservoirs	not applicable	$1{,}200 \times 10^6$ m^3/yr	Stallard (1998)
River water quality, 1.1×10^6 km surveyed†	unimpaired	402 000 km impaired	EPA (1998)
Lake water quality, 6.8×10^6 ha surveyed‡	unimpaired	2.7×10^6 ha impaired	EPA (1998)
Wetland area, 48 states	87×10^6 ha	35×10^6 ha	van der Leeden et al. (1990)
No. freshwater fish species	822 species	202 species imperiled or extinct	Stein and Flack (1997)
No. freshwater mussel species	305 species	157 species imperiled or extinct	Stein and Flack (1997)
No. crayfish species	330 species	111 species imperiled or extinct	Stein and Flack (1997)
No. amphibian species	242 species	64 species imperiled or extinct	Stein and Flack (1997)

† Only 19% (1 116 500 km) of total river kilometers in the United States 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.

broad community is a critical step for including freshwater ecosystem needs in future discussions of resource allocations. The American public, when given information about management alternatives, supports ecologically based management approaches, particularly toward freshwaters (CEQ 1996).

Several previous studies have addressed the overall condition of freshwater resources, and have recognized that: water movement through the biosphere is highly altered by human activities (NRC 1992, Gleick 1993, Jackson et al. 2001); water is intensively used by humans (Postel et al. 1996, Vitousek et al. 1997); poor water quality is pervasive (Carpenter et al. 1998); and freshwater biota are disproportionately imperiled by societal activities (Dobson et al. 1997, Ricciardi and Rasmussen 1999). 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 of freshwater ecosystems for water of sufficient quality, amount, timing, and temporal variability in order to maintain the natural dynamics that produce ecosystem services, and marketable and non-marketable goods. We suggest steps to be taken toward restoration. The paper concludes with recommendations for how to protect and maintain freshwater ecosystems.

THE REQUIREMENTS OF FUNCTIONALLY INTACT FRESHWATER ECOSYSTEMS

Freshwater ecosystems differ greatly from each other depending on type, location, and climate but share important features. Lakes, wetlands, rivers, and their connected groundwaters have a common need for water within a certain range of quantity and quality. Because freshwater ecosystems are dynamic, they additionally require a range of natural variation or disturbance to maintain viability, or resilience (Holling 1986, Pickett et al. 1992). Both seasonal and interannual variability in flow are needed to support biota and maintain natural habitat dynamics that support production and persistence of species (Naiman 1992, Stanford et al. 1996, Poff et al. 1997). 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 their environments, and many ecosystem processes are strongly influenced by the temporally varying hydrologic regimes that characterize these ecosystems. Water quality, physical habitat conditions, and energy sources are shaped by periodic and episodic water-flow patterns. Natural freshwater ecosystems, therefore, have evolved to the rhythms of hydrologic variability.

The structure and function of freshwater ecosystems are tightly linked to the watershed, or catchment, of which they are a part (Hynes 1970, Likens 1984). As water flows on its way to the sea, it moves through freshwater systems in three spatial dimensions: longitudinal (upstream–downstream), lateral (channel–floodplain, or wetland–lake margin), and vertical (surface water–groundwater). These dimensions represent functional linkages among ecosystem compartments over time (Ward 1989). Bodies of freshwater are ultimately the recipients of materials generated from the landscape, hence they are greatly influenced by terrestrial processes, including human modifications of land (Moyle and Leidy 1992).

We identify five dynamic environmental drivers that

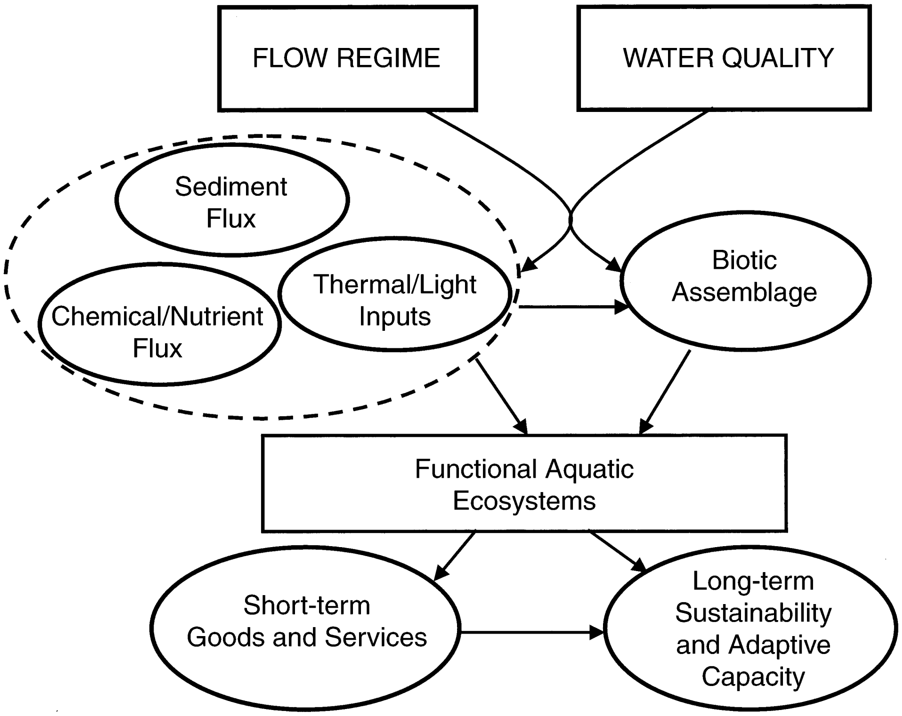

FIG. 1. Conceptual model of major driving forces that influence freshwater ecosystems.

regulate much of the structure and function of any aquatic ecosystem, although their relative importance varies among aquatic ecosystem types (Fig. 1). The interaction of these drivers in space and time defines the dynamic nature of freshwater ecosystems.

1) The flow regime defines the rates and pathways by which precipitation enters and circulates within river channels, lakes, wetlands, and connecting groundwaters, and the residence time of water in the ecosystem.
2) Sediment and organic matter inputs provide raw material to create physical habitat structure, refugia, and nutrient storage and supply.
3) Thermal and light characteristics regulate organismal metabolism, activity level, and ecosystem productivity.
4) Chemical and nutrient characteristics regulate pH, productivity, and water quality.
5) The biotic assemblage influences ecosystem process rates and community structure.

In naturally functioning systems all five of these drivers display natural annual periodicity according to seasonal changes in climate and day length that define a range of variation. Ecosystems and species have evolved to accommodate annual cycles of these drivers, and they have also developed strategies for surviving—indeed requiring—periodic hydrologic extremes caused by floods and droughts that may not occur every year. All five drivers must be considered jointly when evaluating freshwater ecosystem integrity; focusing on one at a time will not yield a true picture of a functional aquatic ecosystem.

Flow regime

The natural or historical flow regime can be described for streams, rivers, wetlands, and lakes (Richter et al. 1996, Stanford et al. 1996, Poff et al. 1997). Certain aspects of the flow regime, particularly for rivers, are critical for regulating biotic production and diversity. These include base flow, annual or frequent floods, rare and extreme flood events, seasonality of flows, and annual variability (Box 1). Flow regime, or hydroperiod, also has relevance for lakes and wetlands by influencing circulation patterns, renewal rates, and types and abundances of aquatic vascular plants (Vollenweider 1976, Van der Valk 1981). The flow regime of a lake or wetland is a critical influence on biotic productivity and is important to determining acceptable nutrient loads from surrounding areas.

> 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. 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

BOX 1. Definition of Flow Conditions for Rivers and Streams

Base flow conditions characterize periods of low flow between storms. They define the quantity of water in the channel and thus directly influence habitat suitability 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 land use.

Frequent (e.g., 2-yr return interval) floods reset the system by flushing fine materials from the streambed, thus promoting higher production during base flow periods (e.g., Fisher 1983). 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 (Hupp and Osterkamp 1985, Sparks 1995).

Rare or extreme events, such as 100-yr floods, represent important reformative events for riverine 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 riverine environments, such as upland tree species, or nonnative species, whose invasive success is often minimized by natural, high flows (Meffe 1984, Moyle and Light 1996). The restriction of major floods by reservoirs plays an important role in the establishment and proliferation of exotic species in many riverine systems (see Poff et al. 1997, Richter et al. 1997).

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 (Nesler et al. 1988). Along western rivers, cottonwood trees release seeds during peak snowmelt to maximize the opportunity for seedling establishment (Scott et al. 1996). Changing the seasonal timing of flows has severe negative consequences for aquatic and riparian communities (Wootton et al. 1996, Auble et al. 1994).

Annual variation in flow is an important factor influencing riverine systems. For example, interannual variation in runoff volume can maintain high species diversity (Toth 1995). Similarly, ecosystem productivity and trophic structure can vary in response to this interannual variation (e.g., Power et al. 1996).

> ecological function of rivers and aquatic systems. (Postel 1996:45)

Western rivers in the United States are prime examples of how flow manipulation can lead to multiple damages to riverine and riparian processes and communities. Dampening of natural flow variability by managing for only minimum flows has contributed to the widespread loss of native fish species (Moyle and Light 1996), and to the regeneration failure of native cottonwoods that support a diverse riparian community (Scott et al. 1996, 1999). Since the completion of the Glen Canyon Dam (Arizona, USA) in 1963, measurable flows of the Colorado River to its mouth at the Gulf of California have occurred only six times. The wetland area at the mouth of the river has decreased to 5800–63 000 ha (depending on the year), compared with 250 000 ha of original wetlands (Glenn et al. 1996, Postel et al. 1998). The lack of freshwater inflows has contributed to the endangerment of a large number of species in the Sea of Cortez, and the abundance of bivalve mollusk populations has dropped 94% from 1950 values due to loss of benthic productivity (Postel et al. 1998, Kowalewski et al. 2000).

Sediment and organic matter inputs

In riverine systems, sediment flux and organic matter inputs are important components of habitat structure and dynamics. Natural sediment regimes are those that accompany natural flow variation. Natural organic-matter regimes include seasonal inputs from terrestrial environments. Terrestrial organic matter inputs, especially in smaller rivers and streams, are particularly important sources of energy and nutrition, while large, coarse, woody material provides substrate and habitat for organisms (Cummins 1974, Gregory et al. 1991). In lakes and wetlands, all but the finest inflowing sediment is permanently stored, so that over time these systems fill. The invertebrates, algae, bryophytes, vascular plants, and bacteria that populate the bottoms of freshwater systems are responsible for much of the water purification, decomposition, and nutrient cycling that occurs (Palmer et al. 2000). They 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 (Swanson et al. 1988, Allan 1995).

Humans have severely altered the natural rates of sediment and organic matter supply to aquatic systems in ways that both increase and decrease inputs (e.g., Waters 1995). Poor agricultural, logging, or housing-development practices promote high rates of soil erosion. Sediment capture behind dams truncates normal sediment supply to downstream reaches, erodes streambeds, degrades habitat, and prohibits flood events from rejuvenating wetland and riparian areas (Patten et al. 2001). Stallard (1998) estimates that 1.2×10^9 m^3 of sediment accrues yearly into reservoirs of the United States (Table 1). Siltation from agricultural, urban, construction, and unspecified non-point sources is the cause of impairment for fully one quarter of all lakes that do not meet their water quality standards (EPA 1998). Channel straightening, overgrazing of riparian areas, and clearing of streamside vegetation reduce organic matter inputs, but also often increase erosion.

Thermal and light characteristics

Light and heat properties are influenced by climate and topography, and by a waterbody's chemical composition, suspended sediments, and primary productivity. Water temperature directly regulates oxygen concentrations, organism metabolism, and associated life processes. The thermal regime greatly influences organismal fitness and, by extension, the distribution of species in both space (e.g., along latitudinal and altitudinal gradients) and time (e.g., seasonal variation at one location). In lakes particularly, the absorption of solar energy and its dissipation as heat are critical to development of thermal structure and water circulation patterns (Wetzel 1983). These characteristics in turn influence nutrient cycling, distribution of dissolved gases and biota, and the behavioral adaptations of organisms.

Water temperature can change dramatically downstream of dams (Ward and Stanford 1979). Mean monthly temperatures ranged between 2°C in winter and 18°C in summer in the Green River, Utah, USA, before completion of the Flaming Gorge Dam in 1962. After dam closure the water temperatures below the dam exhibited a much reduced annual range of mean monthly temperatures between 4°C and 9°C (Vinson 2001). Species richness declined and 18 macroinvertebrate genera were extirpated; other species, notably crustaceans, came to dominate the invertebrate fauna (Vinson 2001). Aquatic insects have not recovered, even after 20 yr of partial thermal restoration. Water temperature also dropped in the Colorado River after closure of the Glen Canyon Dam in 1963 and, along with a dramatic increase in water clarity, this allowed for development of a nonnative trout population and an unusual food web more commonly found in Nearctic regions (Shannon et al. 2001). Water clarity is now routinely >7 m, whereas prior to dam closure the water column was opaque with suspended sediments (Shannon et al. 2001).

Chemical/nutrient characteristics

Natural nutrient and chemical conditions are those that reflect local climate, bedrock, soil, vegetation type, and topography (EPA 2000). Natural waters can range from clear, nutrient-poor rivers and lakes on crystalline bedrock, to much more productive and chemically enriched freshwaters in catchments with productive soils or limestone bedrock.

Cultural eutrophication occurs when additional nutrients from human activities substantially increase productivity beyond the original state (Carpenter et al. 1998). Eastern lakes demonstrate the consequences of excess nutrients and toxic contaminants, as well as nonnative species introductions and overfishing. Lakes Michigan, Huron, Erie, and Ontario suffer from all of the above (Anderson et al. 2001). Onondaga Lake, New York, USA, which was polluted with salt brine effluent from a soda ash industry, responded with marked changes in plankton and fish species composition, including invasive species (Auer et al. 1996, Hairston et al. 1999). Nutrients contributed to 51% of the water quality problems of U.S. lakes identified as impaired in 1996 (EPA 1998). More than one half of agricultural and urban streams sampled in the United States have pesticide concentrations that exceed guidelines for the protection of aquatic life (USGS 1999).

Biotic assemblage

The communities of species that reside in aquatic ecosystems reflect the regional species pools (themselves a product of biogeographic history), and the species' abilities to colonize and survive (see Tonn et al. 1990). The bounds of environmental variation established by flow, sediment, thermal, light, and nutrient regimes, and the presence of and interactions with other species in the system, dictate the suitability of the ecosystem for any particular species. Thus, both biotic and abiotic controls and feedbacks operate to maintain a diverse range of species that are involved in the critical ecosystem processes of primary production, decomposition, and nutrient cycling. The capacity to adapt to future environmental variation is, in part, underlain by the apparent functional redundancy of ecological functions performed by species. High apparent redundancy (i.e., biodiversity) affords a kind of insurance that ecological functions will continue during environmental stress (Walker 1992, Mulder et al. 2001).

Human alteration of environmental conditions can greatly change assemblage structure and ecosystem function. 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

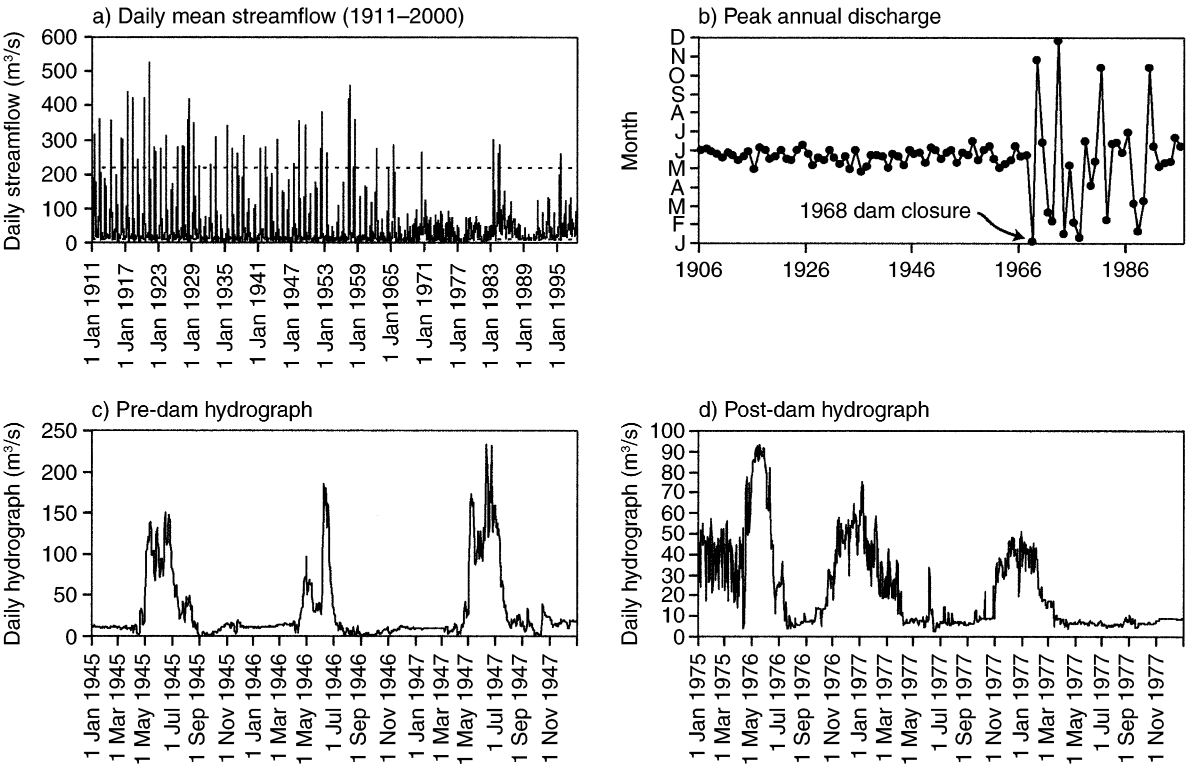

FIG. 2. Hydrologic characteristics for the Gunnison River, Colorado, USA (site no. 09128000; USGS Water Resources Data of the United States [Online, URL: ⟨http://water.usgs.gov/nwis⟩]). (a) Daily mean streamflow for the period 1911–2000. Dashed lines show mean maximum and minimum pre-dam-construction annual flows. (b) Time of year for peak annual discharge in the Gunnison River, showing April–June snowmelt-driven discharge until dam closure in 1968, when discharge maxima switched to the period October–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. Methods of restoring a natural-type flow regime call for establishing a range of natural variation for parameters including maximum and minimum flows, and their timing (Stanford et al. 1996, Richter et al. 1997)

time scales (see Carpenter and Gunderson 2001). Further, introduction of nonnative species that can thrive under the existing or altered range of environmental variation can severely modify food-web structure and processes such as nutrient cycling (e.g., Townsend 1996, van der Zanden and Rasmussen 1996). Exotic species are often successful in modified systems, where they can be difficult to eradicate (Moyle and Light 1996).

POSITIVE STEPS TOWARD RESTORATION

Despite the widespread degradation of freshwater ecosystems, tools are available that can be and are being used to restore aquatic ecosystems to a more natural and sustainable state, or to prevent continued loss of biodiversity, ecosystem functions, and ecological integrity. Based on understanding that riverine systems are naturally dynamic (Poff and Ward 1989, Poff et al. 1997), new statistical approaches toward setting management targets for temporal streamflow variability have been applied or proposed for several rivers, including the Flathead River (Montana, USA), the Roanoke River (North Carolina, USA) and the Colorado River (Wyoming, Colorado, Utah, New Mexico, Arizona, Nevada, and California, USA; Sonora, Mexico) (Richter et al. 1996, 1997, Stanford et al. 1996, Stibrich and Charles 2000). Variable-streamflow techniques seek a balance between water delivery needs for power generation or irrigation, and aquatic ecological needs for hydrological variability and associated characteristics of timing, frequency, duration, and rate of change (Fig. 2). They help to reconnect dynamic riparian and groundwater systems with surface flows, enabling water to move more naturally through the longitudinal, lateral, and vertical spatial dimensions that are essential to fully functional ecosystems.

Point sources of water pollution are readily identified, and many have been controlled, due in large part to the federal Clean Water Act and Safe Drinking Water Acts. Non-point sources of nutrients and toxins now supply the majority of pollutants to freshwater ecosystems (CEQ 1995, Carpenter et al. 1998). In some situations, agricultural runoff has been reduced by using best management practices (BMP), including con-

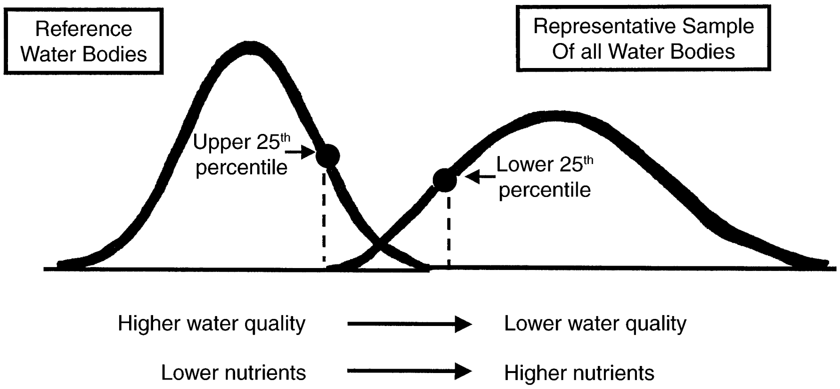

FIG. 3. Two different approaches for establishing a regional reference-condition value for freshwaters. Reference-condition values can be selected from waters that are representative of the most pristine (or least disturbed) condition. If this goal is unrealistic, or if undisturbed water bodies no longer exist in the region, the reference-condition value can be selected from among the least disturbed and lowest-nutrient-concentration 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 modified from EPA 2000: Fig. 6.1.)

trol of erosion and moderate applications of fertilizers, pesticides, and herbicides. BMPs, however, require willing farmers whose willingness is often directly proportional to economic incentives, or to the potency of the regulatory alternative (Young and Karkoski 2000). Total maximum daily load, or TMDL, is a calculation of the maximum amount of a pollutant that a waterbody can receive and still meet water quality standards (EPA 1999). The U.S. Environmental Protection Agency has recently published guidelines for establishing acceptable nutrient criteria for different ecoregions of the United States, recognizing the inherent variability in local and regional availability of nutrients (EPA 2000). To allow for this natural variation, phosphorus and nitrogen water quality standards are established within each region based on comparison with reference, or minimally impacted, waters, or on a percentile of the lowest-nutrient waters (Fig. 3). Once a standard is set, management practices can be enacted that reduce inputs of unwanted nutrients. Atmospheric deposition is an additional large source of non-point pollution that could be reduced through more stringent controls on emissions of sulfur, nitrogen, metals, and organic toxins, and application of more efficient technologies for transportation and energy production (Driscoll et al. 2001).

CHALLENGES AHEAD

The problems confronting freshwater ecosystems are intractable if they are approached piecemeal. At least several government programs have attempted to intervene to prevent drastic ecosystem alteration. But these programs, such as the EPA Clean Lakes Program (Clean Water Act: Section 319(H)), the Wetlands Restoration Act of 1998, and even the Endangered Species Act of 1973, are narrow in their focus, effectively addressing symptoms, rather than the root cause of aquatic-ecosystem decline. Control of pollution is necessary, for instance, but insufficient for maintaining a native species assemblage if the water is not available at the right time, or if invasive species have been allowed to take hold. The needs of aquatic ecosystems, and the needs of society for water must be addressed collectively in order for ecological integrity to be maintained or restored. Politically, this requires broad coalitions of water users working together toward a mutually acceptable future (Kates et al. 2001).

The best time to develop these coalitions is before there are water allocation and ecological crises, but for many parts of the world these opportunities were missed long ago. There is potential for restoration or naturalization, however, and examples from Iowa, California, Colorado, the Great Lakes region, and the Pacific Northwest show promise (Rickert et al. 1975, Rickert 1984, NRC 1992, Rhoads et al. 1999, Bloczynski et al. 2000, Rieman et al. 2000, Young and Karkoski 2000). An ambitious example is the South Florida ecosystem, where water control structures are being physically removed and nutrient inputs curtailed in an attempt to encourage a more natural system (Box 2).

The ecological consequences that come from depriving freshwater aquatic ecosystems of adequate water quantity, timing, and quality often become apparent to people only after those consequences begin to interfere with societal uses of freshwater. 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 have high interannual variation in environmental regimes and ecological states that mask gradual change in physical and chemical factors. Others are resilient to a certain amount of disturbance, allowing the persistence of biological relationships within a range of fluctuations in

BOX 2. South Florida Case Study

The south Florida ecosystem covers ∼47 000 km^2 (18 000 square miles) ranging from Orlando in the north to the Florida Keys at its southern extreme. It includes the Kissimmee River, Lake Okeechobee, Everglades National Park, and Florida Bay. The landscape is essentially flat; the elevation drop from Lake Okeechobee to Florida Bay, a distance of 161 km (100 miles), is <6.1 m (20 feet). South Florida has undergone enormous changes in population, land use, and hydrology over the past 100 yr, resulting in profound changes to ecosystem structure and function. The channelization of the Kissimmee River caused the loss of 11 000 ha (33 000 acres) of floodplain habitat (Koebel 1995). Accelerated eutrophication of Lake Okeechobee from runoff associated with dairy and beef cattle operations shifted algal, invertebrate, and macrophyte composition (Havens et al. 1996, Steinman et al. 1999). Phosphorus enrichment of the northern Everglades from sugar cane farms has changed periphyton structure and biomass, while increasing cattail at the expense of sawgrass (McCormick et al. 1996, Newman et al. 1996). Changes in the discharge of water to estuaries has resulted in massive diebacks of seagrass, because of either too much (Kraemer et al. 1999) or too little (Sklar and Browder 1998) freshwater.

Efforts began in the early 1900s to drain the Everglades wetlands, which were viewed as wastelands and useless swamp. Hurricanes and floods prompted massive water management projects. There are now >2600 km (1600 miles) 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. Management projects were designed in the 1950s when it was anticipated the population in the region would be two million by the year 2000. Today, the region is home to over six million people. More significantly, the water projects were not designed with environmental protection or enhancement in mind. Although it is not possible to restore this region to its pristine condition, efforts are underway to redesign the south Florida environment to make it more compatible with the way the system used to function.

Environmental problems unintentionally created by water management projects include (1) up to 6.4×10^6 m^3 (1.7 billion gallons) per day of excess rainwater channeled directly to the ocean to keep urban and agricultural lands from flooding, causing salinity imbalances in estuaries and influencing biota; (2) Lake Okeechobee treated as a reservoir for water supply or flood control, instead of as a natural lake; (3) altered water supply and periodicity for the Everglades, greatly harming biota; and (4) deteriorated water quality throughout the region. Approximately 50% of the historic Everglades has been converted to agricultural or urban use. Populations of wading birds have been reduced 85–90%. 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 habitat and species.

As a result of these environmental problems, the U.S. Congress directed efforts to develop a Comprehensive Everglades Restoration Plan (Water Resources Development Act of 2000), an ambitious, innovative partnership that includes the goals of enhancing the region’s ecological and economic values, as well as its social well-being. The objectives of restoration activities 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 yr or more to implement.

The ecological goals of the plan are to increase the total spatial extent of natural areas, improve habitat and functional quality, and improve native species richness and biodiversity. Success will be evaluated with quantitative criteria, such as a goal for Lake Okeechobee of reducing the water column concentration of total phosphorus from a current concentration of 110 to 40 μg/L. Rigorous programs of scientific research will continue throughout project implementation, so that major uncertainties can be addressed. This information, combined with results from the monitoring networks, will be evaluated so that the plan can be adaptively managed.

biotic elements and ecological processes. Once a threshold is reached, however, freshwater ecosystems may change rapidly to a new stable condition that is very difficult to restore back to previous natural conditions (Holling 1973, Sparks 1992, Scheffer et al. 1993). Fishery collapse and permanent cultural eutrophication from nutrient inputs are two examples (Walters 1986, Scheffer et al. 1993, Carpenter et al. 1998). Monitoring of biological and physical condition, coupled with understanding of ecological dynamics, can aid detection of problems before they become critical.

Toward a Balance Between Human Use and Needs of Freshwaters

The sustainability of aquatic ecosystems can best be ensured with a variable flow regime, adequate sediment and organic matter inputs, natural fluctuations in heat and light, clean water, and a naturally diverse biotic community. Failure to provide for these natural 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 connected strongly to terrestrial environments, rather than isolated bodies or conduits. Further, aquatic ecosystems are connected to each other.
2) Dynamic patterns of flow that are maintained within the historical range of variation will promote the integrity and sustainability of freshwater aquatic systems.
3) Aquatic ecosystems additionally require sediments, thermal and light properties, chemical and nutrient inputs, and biotic populations to fluctuate within natural ranges, neither experiencing excessive excursions from their historical ranges, nor being held at constant, and therefore unnatural, levels.

It is one thing to state the requirements for maintaining aquatic-ecosystem integrity. It is another to enact these concepts in the context of today's complicated society. U.S. water policy currently supports increased exploitation of water supplies in order to meet demand, and maintenance of water quality and flow primarily as they relate to human health (Gleick 1998). But the age of ever-increasing exploitation is over. We must redefine water use based on a finite supply and inclusion of freshwater ecosystem needs (Postel 2000). For these reasons we offer the following recommendations for how water is viewed and managed:

1. *Incorporate freshwater ecosystem needs, particularly variable flow regimes, into national and regional water management policies, along with water quality and quantity*.—The dialog that will bring about a change in water policies can succeed if conducted in a nonconfrontational manner. It must be based on mutual respect of the many users of freshwater. The best solutions to problems are nearly always proposed by those directly involved and affected, and since 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 are already moving in this direction, with support and guidelines from state and federal agencies (Western Water Policy Review Advisory Commission 1998). 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 freshwaters are viewed within a landscape, or systems context*.—Many of the problems facing freshwater aquatic ecosystems come from outside the water body. While this is already recognized by some, agencies and laws lag behind. One place to initiate a change is through existing governmental permitting processes. Renewal requests to the Federal Energy Regulatory Commission (FERC), 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 are ideal occasions to integrate ecosystem needs alongside the traditional water uses. The Environmental Protection Agency's TMDL (total maximum daily load) Program is an effort to address both point and non-point source pollutants to a water body but has not yet been fully implemented.

3. *Increase communication and education across disciplines*.—Interdisciplinary training and experience—particularly for engineers, hydrologists, economists, and ecologists—will foster a new generation of water managers and users that think about freshwaters as systems with ecological purposes as well as water-supply functions.

4. *Increase restoration efforts for wetland, lake, and river ecosystems, using ecological principles as guidelines (NRC 1992)*.—Some restoration has occurred, but a greater effort is required to restore the ecological integrity of the nation's water resources (EPA 1998). Restoration is the reinstatement of driving ecological forces, but many wetland restoration projects, for example, have not gone beyond the mere replanting of vegetation, ignoring underlying hydrologic and geomorphic, biotic, and biogeochemical processes (Society of Wetland Scientists 2000, Malakoff 1998). Successful restoration projects may even foster complacency among the public. A recent Gallup Poll (22 April 1999) found that Americans are increasingly satisfied with the nation's environmental-protection efforts, making them less likely to support the monetary and political effort to enact further change (Saad 2000). The extent of restoration and protection applied to each

water body will be a hotly debated topic, since active management is inherently a social process (Rhoads et al. 1999). Restoration efforts encompass a spectrum from close to full recovery of native species and environmental conditions, to naturalization, whereby aquatic systems are managed to maintain dynamic, biologically diverse aquatic ecosystems that do not necessarily resemble native ecosystems (Rhoads et al. 1999).

5. *Maintain and protect the remaining minimally-impaired freshwater ecosystems we have*.—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'' (Leopold 1949:190). Many restoration projects fail to reestablish ecosystem function once major processes have been disturbed. It is far wiser and cheaper to conserve what we have. Functionally intact freshwater ecosystems can provide a source of propagules/colonists for restoration projects elsewhere.

6. *Bring the ecosystem concept home*.—Society has been taught to think about the environment as something somewhere else. Ecological processes are viewed as occurring in remote and exotic places, not as essential to *our* daily lives, or strongly influenced by *our* actions. Ecosystem sustainability requires that human society recognize, internalize, and act upon the interdependence of people and the environment of which they are a part. For freshwaters, 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 lifespans and management guidelines of decades to at most a century. Freshwater ecosystems have evolved over much longer periods of time, and their sustainability must be considered from a long perspective. Governmental policies, mass media, and a market-driven economy all focus more on perceived short-term benefits. Local watershed groups interested in protecting their natural resources provide a good first step toward long-term stewardship. They need to be matched by state and national acknowledgment that fundamental human needs for water can only be sustained through policies that preserve the life-support systems of aquatic ecosystems.

Abramovitz (1996:10) described freshwater ecosystems as ''biological assets [that are] both disproportionately rich and disproportionately imperiled.'' They need not be so threatened. By inclusion of the need for naturally varying flow regimes, and reduced pollutant and nutrient inputs, natural freshwater aquatic ecosystems can be maintained or restored to a sustainable state that continues to provide the amenities and services society has come to expect, as well as helping native species to flourish.

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