ground water

Issue Paper/

The Science and Practice of Environmental Flows and the Role of Hydrogeologists

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Abstract

Conflicts between ecosystems and human needs for fresh water are increasing. The purpose of this paper is to raise awareness in the hydrogeologic community of environmental flows (EFs) and to address the major challenges involved in their protection. Ground water is a key component of EFs, and therefore hydrogeologists are called upon to get involved in the ongoing debates about maintaining healthy riverine ecosystems. Promising opportunities for achieving EFs in both underallocated and overallocated basins as well as new methods for protecting fresh water ecosystems developed in different countries are outlined. EF protection measures include private water trusts, "upside-down instream flow water rights," the "public trust" doctrine, and water markets, among other measures. A number of knowledge gaps are identified, to which hydrogeologists could contribute, such as our rudimentary knowledge about ground water–dependent ecosystems, aspects of stream-aquifer interactions, and the impacts of land-use changes. The values that society places on the different uses of water ultimately determine where the water is allocated. EF requirements can be legitimately recognized and addressed by basing the environmental needs of hydrologic systems on robust science, focusing on increasing the productivity of water use, engaging society in understanding the benefits and costs of decisions that affect ecosystems, and taking advantage of various opportunities for achieving EF goals.

Introduction: The State of Fresh Water Ecosystems and Resulting Challenges

The state of fresh water ecosystems, such as rivers, lakes, wetlands, and their connected ground water in the United States and much of the world is not promising. Fresh water ecosystems are being severely altered or destroyed at a greater rate than at any other time in human history (National Research Council [NRC] 1992). During the past century, the global human population quadrupled, the area of irrigated agricultural land multiplied more than sixfold, and water withdrawals from fresh water ecosystems increased eightfold (Richter et al. 2006; Gleick 2006; Postel 1999). Revenga et al. (2000) estimate that 60% of the world's rivers are fragmented by dams and other hydrologic alterations. More than one-third of the rivers in the United States are listed as impaired or polluted (U.S. EPA 2000). Fresh water withdrawals in some regions are so extreme that some major rivers, such as the Colorado, Indus, Ganges, Nile, and Yellow, no longer flow to the sea year round (Postel 1995). River ecosystem health deteriorates when natural flows of water and sediments through the river system are substantially disrupted or modified by human activities (Richter et al. 2006, 2003; Poff et al. 1997), indicating that there are limits to the amount of water that can be withdrawn from fresh water ecosystems before their natural functioning and productivity become severely degraded. Water managers and political leaders are becoming increasingly cognizant of these limits as they are being confronted with endangered species or water quality deterioration and changing societal values concerning ecological protection (Richter et al. 2003).

Recognition is growing that fresh water ecosystems provide a variety of essential goods and fundamental life support services (Costanza et al. 1997; Baron et al. 2002; NRC 2004), and that it is in society's best interests to consider rivers and other fresh water ecosystems as legitimate "users" of fresh water (Naiman et al. 2002; Postel

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and Richter 2003; Arthington et al. 2006). Solid evidence for this growing acceptance is the fact that the number of river restoration projects in the United States alone increased exponentially during the past decade (Figure 1), paralleling the increase in scientific reports and in news media articles (Bernhardt et al. 2005). Expenditures on small and mid-size river restoration projects alone have averaged more than $1 billion a year since 1990 (Bernhardt et al. 2005).

However, as human population growth and climate change impose new constraints on the spatial and temporal distribution of water, conflicts between ecosystem and human needs for fresh water are becoming increasingly prevalent (Poff et al. 2003). In addition, the notion that water has value instream continues to be treated with skepticism (MacDonnell 1999). The challenge facing water scientists is to communicate to society the broader view of the dynamic nature of fresh water ecosystems and the benefits they provide, and to define ecosystem needs clearly enough to guide policy formulation and management actions that strive to balance competing demands and visions (Poff et al. 2003).

The quantity and quality of water needed for river systems to maintain themselves and their functions has been given various names such as instream flows, environmental allocations, ecological flow requirements, or "environmental flows" (EFs). An abundance of literature exists on methodologies for achieving EFs, and the reader is referred to Tharme (2003) for a recent comprehensive review of that literature. Instream or EF science is a relatively new and evolving field that brings together scientists from a variety of disciplines to answer the politically charged question of how much water should be left in the river to meet ecosystem needs and not developed to meet agricultural, industrial, and municipal demands. As mentioned previously, billions of dollars are spent on riverine restoration and rehabilitation projects in the United States alone, yet the science underlying those projects is not currently well understood; thus, the approaches and their effectiveness differ widely (NRC 2007). Therefore, a fundamental challenge identified by an NRC committee (NRC 2007) is to "quantitatively understand how rivers respond physically and biologically to human alterations from dredging to damming, and to specifically address: What are the required EFs (i.e., flow levels, timing, and variability) necessary to maintain a healthy river ecosystem?"

We now know that interdisciplinary collaborations are essential to solving environmental problems. Palmer et al. (2003), among others, argued that successful riverine restoration is best accomplished by collaborative teams that include ecologists, geomorphologists, and engineers. However, hydrogeologists should also participate because ground water is an important component of ecosystem function and services that is connected to and supports river flows, riparian areas, and surrounding river basins, as well as upland terrestrial ecosystems.

In addition to raising awareness of the general hydrogeologic community and calling hydrogeologists to action vis-à-vis EFs, the purpose of this paper is to elucidate some key issues involved in transitioning to instream flow protection. In particular, it outlines some promising tools for instream flow protection, as well as the emerging science and research needs in this new field of EFs. Finally, the paper addresses some fundamental science and society questions and concludes with ways to make progress on the issues involved.

The Importance of Ground Water in EFs

Ground water and surface water are intimately connected systems (Winter et al. 1998; Woessner 2000; Sophocleous 2000, 2002) as manifested in Figure 2, which indicates the fraction of streamflow attributed to ground water, known as the base flow index, for each of the physiographic regions of the United States. Ground water is therefore a major aspect of EFs. However, ground water extraction, river stage modifications in regulated river systems, urbanization of river systems, other land-use/land-cover changes, and additional factors can influence ground water discharge to rivers and streams, with the potential to alter stream base flow conditions. The exchange of water between ground water and rivers is a key component influencing not only river discharge but also water quality, geomorphic evolution, riparian

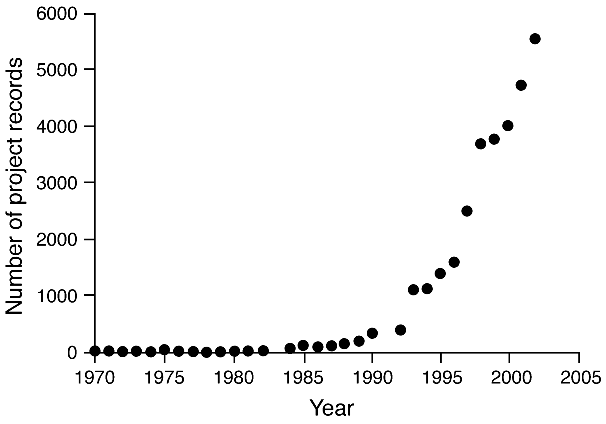

Figure 1. The number of river restoration projects recorded in the National River Restoration Science Synthesis database (modified from Bernhardt et al. 2005).

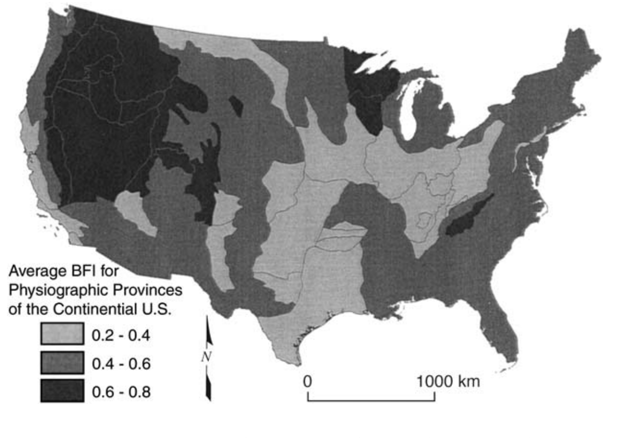

Figure 2. Average base flow index (BFI—fraction of streamflow attributed to ground water; adapted from Becker 2006). Map created from USGS data (Wolock 2003) and physiographic regions of the continental United States.

zone character and composition, and ecosystem structure. However, little is known about how the ground water/river exchange processes influence riverine natural, altered, and restored conditions (NRC 2007).

Providing water for the environment is more than just allocating water for the maintenance of river flows. Provisioning water for the environment requires allocations of water to maintain terrestrial, riparian, wetland, and stygian (i.e., ground water–inhabiting organisms) ecosystems, which also require ground water for their survival (Murray et al. 2003). Ground water–dependent ecosystems (GDEs) are plant and animal communities that depend partly or completely on ground water to maintain their current composition and functioning. These GDEs include (Sinclair Knight Mertz 2001; Eamus et al. 2006) the following: (1) terrestrial vegetation that relies seasonally or episodically on ground water; (2) river base flow systems, including aquatic, hyporheic, and riparian ecosystems that depend on ground water input, especially during dry periods; (3) aquifer and cave ecosystems, often containing diverse and unique fauna; (4) wetlands dependent on ground water influx all or part of the time; and (5) estuarine and nearshore marine ecosystems that rely on ground water discharge. Streams, rivers, springs, and wetlands are all important GDEs that underscore the importance of surface water-ground water interactions.

Few outside of the scientific community understand ground water processes and the generally intimate connection between ground water and surface water. For example, the 1995 "cap" on surface water diversions from rivers in the Murray-Darling Basin in southeastern Australia, designed to guarantee at least some instream flows (which will be briefly discussed in the next section), did not include a limit on extraction from ground water systems connected to the rivers (White 2005). In many parts of the world, ground water is being mined, causing ground water level declines, drying up connected wetlands, decreasing base flows to streams, and causing major problems of salt water intrusion and land subsidence (Sophocleous 2003, among others). As Gippel (2001) pointed out, EF research grew out of surface water hydrology and ecology, so it is not surprising that few studies have been done on ground water processes with respect to EFs. Therefore, hydrogeologists can play a major role in addressing such problems and in contributing to the resolution of the various contentious issues of maintaining healthy aquatic ecosystems.

Environmental Decision Making

The ecological consequences of depriving fresh water aquatic ecosystems of adequate water quantity, quality, and timing of flows often become apparent to people only after those consequences begin to interfere with societal uses of fresh water (Baron et al. 2002). Fishery collapses and nuisance algal blooms are examples of failures in ecosystem processes that are years in the making (Scheffer et al. 1993; Carpenter et al. 1998). Population increases, economic development, land-use changes, and a changing climate will exacerbate water conflicts, leading to even more demands for sound science to inform decision making and incorporate environmental goals into water management (Poff et al. 2003; Sophocleous 2004).

EFs must be seen within the context of applying integrated water resource management in river basins (Dyson et al. 2003). EFs will ensure a healthy river only if they are part of a broader group of measures, such as soil conservation, pollution prevention, and protection of habitats. Taking steps to manage for EFs brings into focus issues of access and ownership of water and water rights (Dyson et al. 2003). All instream flow programs in the United States are largely conditioned by the water rights system in which they operate. Water rights for ecosystem protection now often enjoy the same legal status as rights used for irrigation or other extractive purposes; however, such instream flow water rights in the semiarid regions of the United States (which abide by the "prior appropriation" doctrine) have commonly such a low priority date that they do not offer significant protection to rivers and streams.

River flow manipulation, such as occurs in rivers of the western United States, can lead to multiple damages to riverine and riparian processes and communities (Baron et al. 2002). Changing 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 cottonwood trees that support a diverse riparian community (Scott et al. 1997, 1999). The requirements of fresh water ecosystems and the needs of society for water should be addressed collectively, not piecemeal, for ecological integrity to be maintained or restored (Baron et al. 2002). This requires stakeholders and water managers to work together toward a mutually acceptable future.

A number of promising new approaches for river rehabilitation have been proposed relatively recently in Europe, South Africa, and Australia and are worth emulating where possible. The Water Framework Directive of the European Union requires member states to achieve "Good Status" in all surface and ground water. Good Status is a combination of "Good Chemical Status" and "Good Ecological Status" (European Commission 2000). Therefore, setting EFs is key in achieving Good Status. Each member country of the European Union has responsibility for translating the Directive into legislation and for adopting implementation measures, which are likely to include controls on water withdrawals and flow alterations. The Directive also establishes criteria for classifying the ecological status of rivers, including river flow and channel characteristics. Although it is too early to judge the effectiveness of this new European policy, it offers great promise for protecting and restoring EF for Europe's rivers.

Scientists in Australia and South Africa have advanced new methods for setting EF requirements, and the concept of allocating flows for ecosystem support in those countries has been translated into actual policy and practice. South Africa's National Water Act, passed in 1998, is a landmark in international water policy (Postel and Richter 2003). The Act integrates public trust principles, recognition of ecosystem service values, and the natural flow paradigm for river conservation (Poff et al. 1997). The law establishes a water allocation known as the "Reserve," which consists of (1) a nonnegotiable allocation to meet the basic needs of all South Africans for drinking, cooking, sanitation, and other essential purposes and (2) an allocation of water to support ecosystem functions in order to conserve biodiversity and secure the valuable ecosystem services they provide to society. This Reserve has priority over all other uses, and only this water is guaranteed as a right.

The Council of Australian Governments (COAG) Water Reform Framework recognized the need to move toward sustainable use of water and greater protection of fresh water ecosystems (http://www.daffa.gov.au/natural-resources/water/national-water-initiative/coag). All Australian states have recently passed new water laws reflecting the agreed-upon COAG goals and are now in the process of setting EF requirements for their rivers. Postel and Richter (2003) summarized Australia's progress to date with the following quote from Arthington (2000): "In one decade in Australia we have seen the concept of instream flows progress from vague notions of 'compensation flows' for riparian users and 'the environment,' and 'minimum flows' to provide habitat for a few species of fish, to the definition of flow regimes to sustain biodiversity and the key ecological processes linking rivers, their floodplains and associated terminal water bodies, including inland lakes, wetlands, estuaries and coastal waters." In addition to these Australian water reforms, the Murray-Darling Basin Commission (MDBC) placed a cap on water extractions (Blackmore 1999; MDBC 2004) to prevent diversions from the basin's rivers from increasing. Located in southeastern Australia, the Murray-Darling Basin covers one-seventh of the country's total area and contains some of the country's best farmland. The attempt to limit diversions and to prescribe a pattern of flow that will sustain ecosystem functions in the Murray-Darling Basin makes it an important test case in river ecosystem management.

According to Baron et al. (2002), U.S. 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. Generally, U.S. policy and regulations comprise a minimum approach toward protecting the environment and a maximum emphasis on making use of that resource, as David Allan and Brian Richter recently pointed out in an interview with *Global Issues* managing editor Charlene Porter (e-Journal USA: *Global Issues*, June 2005). There is little dispute that maintaining some degree of instream flow is desirable to protect and enhance recreation, water quality, and biodiversity. What is disputed is the degree to which maintenance of instream flows inhibits existing consumptive uses of water and what additional actions, if any, are implied by a minimum instream flow regime (Berrens et al. 1996).

Tools for Environmental Flow Protection in the United States

Recent droughts throughout the western United States and increasing demand from a growing and urbanizing population are putting new and different strains on water distribution, affecting water availability for EF protection. EF management will be challenged to balance the continued need for instream and out-of-stream needs. Most water has already been appropriated in the western United States, and it is always difficult to "wind back the clock." Potential sources for water would probably be (1) water already being used in ranching and agriculture, an area to which cities are also turning to purchase or lease water rights; (2) reservoirs in the form of storage rights granted for instream flow releases; and (3) water derived from working with water rights holders to transfer retiring rights to instream uses (Charney 2005).

No one simple answer or guide exists to provide for the environmental needs of rivers alongside human needs, as each river system is different and each country's situation is different. However, opportunities for achieving EF goals exist in several situations as briefly outlined here based on U.S. experience: (1) in river basins with unallocated water, water can be set aside to attain or maintain flow goals using, for example, direct appropriations, as the State of Colorado has effectively implemented, or through increased efficiency measures such as in the State of Oregon, which permits water users to salvage water by implementing conservation measures but requires that 25% of the salvaged water be made available to the stream, or through other measures (NRC 2005); (2) in basins with large storage or hydropower dams, where dam operations can be used to release targeted instream flows; (3) in basins where water is already overallocated, the challenge of EFs may include reallocating water from existing uses and returning it to the river, a course of action that often leads to conflicts. However, several western U.S. states have established statutory or administrative strategies for EF protection, which support the notion that EF programs can be implemented even in highly arid regions (NRC 2005). The NRC (2005) committee reviewing the Texas instream flow program identified additional options for overallocated regions. For example, water trusts in several western U.S. states (see further on in this section) could facilitate willing buyer/willing seller transactions in which senior consumptive water rights could be acquired and converted to instream uses for dry years, or for several years, or in perpetuity. Another way of adjusting existing water rights to ensure water for the environment is by addressing new flow protections on existing permits when changes to those permits are requested, as when permits are sold or put to new uses not originally authorized. In all cases, a range of stakeholders must be involved in this process of restoring EFs. Compounding such problems is the uncertainty of available science to support decision making, as has been pointed out by an NRC report evaluating the science underlying the U.S. federal management of water to protect endangered fishes in the Klamath basin of Oregon and California (NRC 2002).

A recent addition to instream flow protection is the development of private water trusts. Water trusts are generally nonprofit organizations whose mission is to work cooperatively with water right holders, governmental agencies, and other interested parties to restore flows to priority streams. Currently, water trusts in the western United States exist in four states—Colorado, Montana, Oregon, and Washington (Charney 2005). A key aspect of the water trust approach is the use of market-based approaches to acquire instream flows through lease, purchase, or donation from willing parties.

Around the world, water professionals are seeking better understanding of the ways in which river flows can be modified for human purposes while maintaining an adequate semblance of the composition, structure, and function of natural ecosystems (Richter et al. 2003; Poff et al. 1997). One interesting idea proposed (Silk et al. 2000) is that of turning conventional instream water rights "upside down." Instead of prescribing flows for ecosystem support, and implicitly allocating all remaining flows for extractive or other economic purposes, so-called "upside-down instream flow water rights" are defined by turning the question around and asking instead: How much can a river's natural flow pattern be modified in order to meet irrigation, hydropower, and other water development demands and yet still meet the flow needs of the river ecosystem itself (Postel and Richter 2003)? This degree of water development is then specified, and all the remaining flows are allocated to protection of ecosystem functions and services (Silk et al. 2000). These "upside-down instream flow water rights" may be most applicable on rivers not overly developed and may work best when implemented with a precautionary approach; that is, reserve only a modest amount of water for development initially, and add more incrementally as scientists develop clearer delineations of where ecological harm will occur (Postel and Richter 2003). The U.S. National Park Service and the State of Montana negotiated agreements concerning a number of national parks, including Glacier National Park and Yellowstone National Park, that ended with "upside-down" instream flow water rights that protected the natural flow regime of many streams in the parks (Silk et al. 2000). The difficulties of determining flow levels that do not occur at a predictable time led to the establishment of a cap on future consumptive uses in the basins and to leaving the remaining flows instream (Amman et al. 1995).

Another tool for flow protection and restoration is the "public trust" doctrine (Dunning 1993; Blumm and Schwartz 1995), which can cause existing water rights to be altered or revoked in order for a state to fulfill its trust obligations. In the western United States, where many rivers and streams are already overallocated, the public trust doctrine is highly controversial because of the threat it poses to existing water right holders (Postel and Richter 2003). California's Supreme Court 1983 ruling on Mono Lake on the eastern side of the Sierra Nevada is a case in point. Postel and Richter (2003) and Narasimhan (2003), among others, summarized that case. The city of Los Angeles had been granted water rights by the state to divert most of the flow from four of Mono Lake's five feeder streams. Mono Lake, a host to unique ecosystems, is a terminal point for surface runoff and ground water seepage in a closed hydrologic basin in eastern California. Several decades of these diversions caused the lake's level to drop 13.7 m and its volume to shrink by half. In 1979, the National Audubon Society, the Mono Lake Committee, and other groups filed suit, claiming that Mono Lake was protected by a public trust. The case eventually went before the California Supreme Court, which ruled in 1983 that the public trust did indeed apply. Specifically, it ruled that the "public trust doctrine and the appropriative water rights system are parts of an integrated system of water law. The public trust doctrine serves the function in that integrated system of preserving the continuing sovereign power of the state to protect public trust uses, a power that precludes anyone from acquiring a vested right to harm the public trust and imposes a continuing duty on the state to take such uses into account in allocating water resources." Ultimately, Los Angeles was required to greatly curtail its withdrawals from Mono Lake's tributaries. In most western U.S. states, the entity vested with the power to grant water rights, usually an administrative agency or a court, is required to take public interest considerations into account. Protecting the public interest is related to the larger doctrine of public trust (Blumm and Schwartz 1995; Narasimhan 2003).

Another relatively recent tool for reallocating water to meet increasing demands is establishing water markets. Water markets allow various entities to purchase water or water rights specifically to enhance river flows. Between 1990 and 1997, a total of 2.94 billion cubic meters of water—a volume equal to 16% of the average annual flow of the Colorado River—was leased, purchased, or donated for the purpose of enhancing river flows in the western United States (Landry 1998). Water markets have the greatest role to play where water has been heavily appropriated. However, according to Postel and Richter (2003), despite many promising uses of markets, the buying and selling of water rights has made only a small contribution to the large task of reallocating water to natural systems. Nevertheless, local, state, and federal agencies could make more effective use of this tool.

In addition, many aspects of federal law can intrude into and may override the U.S. state-based system of water management. The Endangered Species Act, the Clean Water Act, and the Wild and Scenic Rivers Act are just a few such examples. U.S. federal legislation imposes requirements above and beyond those of state instream flow programs (Covell 1998). In practice, however, federal authorities have rarely interfered with state systems of water rights and allocation, according to Postel and Richter (2003). The present challenge with these overlapping and at times competing federal and state authorities lies in interpreting, enforcing, and, where necessary, amending these authorities such that they collectively do a better job of balancing human uses of water with the protection of aquatic ecosystems (Postel and Richter 2003).

Emerging Science for Environmental Flows

When the majority of instream flow programs were established in the 1970s and 1980s in the United States, the focus was on the protection of a "minimum" flow, as alluded to earlier. The sciences associated with river management at the time focused on the need for a minimum amount of water to be left in a stream, particularly the effect this flow had on fish. It was believed that low flows were the primary constraint on the health of aquatic species (Postel and Richter 2003).

The water required to meet specific ecosystem needs is a complex issue that is not well understood and is currently the subject of considerable research. Although much of the focus recently has been on minimum flow requirements, there is now increasing recognition of the central role the natural flow regime of a river (comprising the five components of variability: magnitude, frequency, duration, timing, and rate of change or flashiness) plays in sustaining biodiversity and ecosystem integrity rather than just low flows (Poff et al. 1997; Richter et al. 1997; Rosenberg et al. 2000). Thus, meeting the needs of fish, riverine habitat, and other environmental values requires management not only for a given minimum flow but also for a range of flows that mimic the natural flow regime of a stream. Since the inception of instream flow programs, biological and hydrologic sciences have evolved to demonstrate the importance of variable flows to stream health and associated biological communities.

The most serious and continuing threat to ecological sustainability of river ecosystems is the alteration of flow regimes (Naiman et al. 1995; Bunn and Arthington 2002). Four key principles highlight the important mechanisms that link hydrology and aquatic biodiversity and illustrate the consequent impacts of altered flow regimes (Bunn and Arthington 2002): (1) flow is a major determinant of physical habitat in streams, which in turn is a major determinant of biotic composition; (2) aquatic species have evolved life history strategies primarily in direct response to the natural flow regimes; (3) maintenance of natural patterns of longitudinal and lateral connectivity is essential to the viability of populations of many riverine species; and (4) the invasion and success of exotic and introduced species in rivers is facilitated by the alteration of flow regimes.

Being able to predict the ecological benefits that are likely to result from EFs is a major research need and an important part of managing flow in rivers. Strong evidence shows that both river ecology and river geomorphology are altered when river flows are changed from natural conditions. This evidence is summarized by Lloyd et al. (2005) in a review of 70 studies that examined responses in fish, birds, plants, trees, and macroinvertebrates, as well as geomorphology in river flows altered by drought, prolonged inundation, flood mitigation, augmentation, abstraction, or irrigation. Sixty-one of the 70 studies (i.e., 87%) determined that modifications to river flow were followed by responses in the ecology and/or geomorphology. Despite the unequivocal evidence for ecological responses to flow change, the relationship between these two measures was not simple. Small flow changes could produce large ecological responses and no simple thresholds were detected. However, as only a few studies in Lloyd's et al. (2005) examination provided quantitative information on flow change and ecological response, a larger database is required before the nature of the flow change-ecological response relationship can be properly described and used for prediction.

An Australian national workshop held in Canberra in November 2003 by the National Ground Water Committee (NGC) identified knowledge gaps for ground water management reforms toward achieving efficient and sustainable use of water resources and providing water for the environment. The resulting report from that workshop (NGC 2004) forms the major basis for the synthesis presented subsequently related to EF research needs to which hydrogeologists could significantly contribute.

Most of the emphasis on EF in recent years has been placed on surface water, and relatively little has been placed on ground water. Consequently, knowledge about GDEs (previously discussed in the section on the importance of ground water in EFs) is generally rudimentary. The main factors causing impacts on GDEs are water level changes, salinity increases, changes to the discharge flux (both quantity and quality), and biodiversity threats such as weed infestation (NGC 2004). Two time lags that are associated with GDE protection need to be better understood. The first is the hydraulic time lag between commencement of ground water pumping and reduction in water availability to an ecosystem as ground water development always results in declines in natural discharge with consequent environmental impacts. The second is the time that it takes for an ecosystem to respond by deteriorating or perishing. There is a need to characterize and value GDEs at a catchment scale so that priority GDEs are identified and an appropriate level of protection is initiated. A major challenge is providing quantitative criteria on which to base protection of priority ecosystems because some ecosystems depend totally on ground water (obligate), while others are only partially dependent at certain times of the year (facultative). Currently, little is known about indicators of ecosystem stress that allow adaptive management. There is also no guidance on what impacts are acceptable. Indeed, there are no generally accepted ways of valuing ecosystems, and no obvious way of determining costs of loss of ecosystem function (NGC 2004).

Changed land-use patterns can increase or decrease water availability (Scanlon et al. 2007) by changing the balance between surface runoff and ground water recharge, and it is not currently possible to accurately predict the effects of land-use change on a catchment's water balance or water quality. The hydrological impacts of different land-use types on aquifer behavior, including the change in the volume of recharge, the change in discharge patterns, flooding, and waterlogging, are not well understood (NGC 2004). Bunn and Arthington (2002) point out that a major challenge is separating the impacts of the direct effects of modified flow regimes from those associated with land-use changes that often accompany water resources development, such as conversion of forest to irrigated agriculture.

Water managers need to predict how far certain attributes of the flow regime can be altered from their natural state before an impact occurs. They also need to be convinced that providing additional EFs, such as reducing irrigation allocations at considerable cost, can produce demonstrable environmental benefit (Bunn and Arthington 2002). As Bunn and Arthington (2002) also pointed out, our limited ability to predict and quantify the biotic response to flow regulation is a major constraint to achieving ecological sustainability. Because of the inherent complexity of ecosystem responses to variable flow regimes, water managers or stakeholders should not expect scientists to be "perfectly right" about EF needs on their first attempts, as Richter et al. (2006) warned. Therefore, the process of determining EF needs should be viewed as an iterative process, in which each management action such as flow restoration is viewed as an experiment that must be monitored and evaluated carefully, enabling scientific refinement of EF recommendations through time. This process of deliberate learning through testing, evaluation, and modifying management actions is the essence of adaptive management (Richter et al. 2006; Holling 1978).

Science and Society

Although no one wants to give up reliable water supplies, a balance needs to be struck between allocating water directly for people—for public supply, agriculture, and industry—and for "the environment," which should be seen as water indirectly for people—through the goods and services provided by functioning ecosystems (Wallace et al. 2003). Human security and well-being are closely related to maintaining ecosystems such as forests, wetlands, and river ecosystems and avoiding environmental degradation. The values that society places on the different uses of water ultimately determine where the water is allocated. As long as healthy riverine ecosystems are not a societal priority, the present deteriorating situation of ecosystem services (Vitousek et al. 1997; Revenga et al. 2000; Sophocleous 2003) will not be improved even if scientists better quantify the ecological impacts of streamflow and further enhance the accuracy of their models. Therefore, what is needed is a change in people's perceptions of how we relate to our natural environment, so that environmental needs move up the hierarchy of competing priorities. Thus, any attempts by water professionals to influence perceptions on ecosystem goods and services will be efforts well spent. A worthwhile effort along these lines is undertaken in the Ecosystem Services Project in Australia (Cork 2003), where the key feature of the approach was to engage a broad segment of society in understanding and debating the benefits and costs of decisions that affect natural ecosystems. The philosophy adhered to is the following: just as services provided by businesses need to be described and marketed in language that consumers understand and identify with, so ecosystem services need to be expressed in relation to the perceptions of the general public if that public is to value the services (Cork 2003). However, practical realities of increasing human needs for water may preclude protection of all ecosystems from degradation. Therefore, a prioritization scheme for ecosystem protection is called for. Murray et al. (2006) have recently proposed a promising methodology for valuing and prioritizing GDEs for such protection.

Finally, in an international survey study, Moore (2004) identified and analyzed perceptions of EFs and implications for future water management. Here, I distill and synthesize some important pertinent conclusions and inferences mainly from that study. Environmental change is an inherent part of human development, and modification of the landscape for production of critical resources is unavoidable. As populations grow and water scarcity increases in many parts of the world, the ability to manage water resources effectively and equitably and without jeopardizing the resource base on which society depends becomes more complex and difficult. By basing the environmental needs of rivers, wetlands, estuaries, and other hydrological systems on rigorous science, these needs can then be legitimately recognized and addressed by water management authorities. Providing robust science is an area where hydrogeologists can contribute significantly. The objective in implementing EFs is not to return rivers or any other water system to their pristine, natural state but to rehabilitate them as practically possible and to allow the ecological requirements of rivers to be included in the debates over sustainable water resource allocation. The debate for reaching a balance in water allocation and usage by different water sectors and the environment does not have to focus on how much water is to be reallocated or "lost" to different sectors, which may lead to disputes and conflict, but to determine the ways the different sectors can increase their water-use efficiency and productivity. By increasing the productivity of water in different sectors, the saved water can be used in other ways deemed appropriate by society, such as meeting the basic environmental needs of ecosystems. Recognizing the trade-offs and associated costs and benefits of the environmental, social, and economic concerns will enable decision makers and policy makers to make informed choices regarding water use.

Concluding Statement

As seen from the introductory statements, the state of fresh water ecosystems continues to deteriorate throughout most of the world. This is because the main drivers—population, food, and energy requirements—continue to expand, and it is exceedingly difficult to "wind back the clock" in developed basins where regulations and laws, often developed without the benefit of current scientific advances, are now firmly rooted. Science and policy applied to EFs in the United States and elsewhere do not adequately protect aquatic ecosystems. More work is needed. In addition, the current movement in the United States toward development of biofuels will push for even more farming and irrigation expansion, thus exacerbating the unfavorable state of fresh water ecosystems.

Despite this discouraging picture, hopeful opportunities do exist, especially if hydrogeologists follow this call to action to strive for progress in both the science issues as well as the societal/political debates involved. By following a combination of necessary steps, such as (1) basing the environmental needs of hydrologic systems on robust science; (2) focusing on increasing the productivity of water use; (3) engaging society in understanding the benefits and costs of decisions that affect natural ecosystems; and (4) taking advantage of various opportunities for achieving EF goals (some of which are outlined previously in the sections on Environmental Decision Making and Tools for EF Protection), such needs can be legitimately recognized and addressed. Employing innovation to protect EFs, and adopting holistic policies like the ones currently being pursued in South Africa, Australia, and the European Union, the hope is that basic EF requirements also will be met. Engaging hydrogeologists in interdisciplinary and integrative teams addressing such contentious environmental problems will definitely help the cause.

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