Managing for Variability to Sustain Freshwater Ecosystems

N. LeRoy Poff

Colorado State University, Fort Collins, CO 80523. E-mail: poff@lamar.colostate.edu

Water resources development for human needs has come at a significant cost to the natural functioning of aquatic and riparian ecosystems in the United States and around the world. The construction of hundreds of thousands of dams nationally and globally and the extensive human transformation of land cover have greatly modified the magnitude, timing, and duration of river flows that have historically sustained naturally dynamic riverine ecosystems (Graf 1999; Nilsson et al. 2005; Poff et al. 2006). This pervasive alteration is contributing to the global crisis of biodiversity loss in freshwater ecosystems and to the degradation of many of the natural goods and services that these ecosystems provide to human communities (Postel and Richter 2003; Dudgeon et al. 2006; Poff et al. 2007).

The importance of sustaining healthy ecosystems to support human well-being in a world of shrinking water resource availability is now broadly recognized (World Commission on Dams 2000; Gleick 2003; Millennium Ecosystem Assessment 2003). The many economic benefits provided to human society from maintaining healthy aquatic and riparian ecosystems, coupled with the high cost and difficulty of restoring degraded ecosystems (Bernhardt et al. 2005), have fueled the growing awareness that principles of ecosystem science need to be more fully integrated into water resources planning and management. The term "environmental flows" has emerged to capture the important idea that nature must be allocated a share of water in water resources management if such planning and development is truly to be *integrated* (integrated water resources management or IWRM) (Naiman et al. 2002; Bernhardt et al. 2006). Environmental flows are defined by the Brisbane Declaration (http://www.riversymposium.com/index.php? element=2007 BrisbaneDeclaration 241007) as the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems. In recent years, guidelines for environmental flows have been developed and variously implemented in many places in the United States and around the world. Such developments are certainly encouraging; however, a key issue in actually achieving ecologically sustainable development revolves around just how these environmental flows are defined and implemented.

All too often, there is a precarious balance between provision of even minimal environmental flows and real or perceived human demand, leading to social conflict and associated legal or regulatory challenges (Poff et al. 2003). Maintaining adequate environmental flows in heavily allocated basins is especially difficult and is becoming more commonplace—the Klamath River basin (Oregon and California), the Appalachicola-Chatahoochee-Flint basin (Georgia, Alabama, and Florida), and the recent drought conditions in the city of Atlanta are but a few contemporary examples of conflicts that threaten to undermine the political will necessary to sustain healthy riverine ecosystems. Such conflicts will almost certainly increase in coming years.

Both rapid human population growth and the substantial uncertainty in projecting future water resource availability in the face of climate change (Vörösmarty et al. 2000; Milly et al. 2008) are fueling calls for expanded water resources planning and development. Unfortunately, invigorated expansion of the water infrastructure does not bode well for freshwater ecosystem conservation and preservation. Aquatic and riparian systems are already heavily stressed by current management practices, and unless future planning and management explicitly account for adequate environmental flows, the future health and biodiversity of our riverine ecosystems and species will be even further imperiled.

In the face of prevailing management practices and growing demands for fresh water, will society be able to sustain healthy aquatic and riparian ecosystems capable of benefiting human populations? In contemplating this important (and pressing) question, we must ask ourselves whether our current models and conceptual frameworks are appropriate for achieving sustainable management goals. We must also ask what additional tools are needed and how we might strategically and proactively plan for future threats to aquatic and riparian health imposed by expanded water resources development.

Managing for Variability—A Paradigm Shift

Of course, managing flow regimes for environmental values is not new; it has been practiced for many decades, most broadly in the context of avoiding violation of water *quality* standards set by the Clean Water Act. For most of the 20th century, the dominant paradigm for management of water quantity for environmental purposes was narrowly focused and limited in scope. Reservoir operation rules were typically developed at individual facilities under federal mandates (e.g., the Endangered Species Act) and not at the state level of environmental flow management or water permitting. Where developed, rules mostly emphasized the minimum habitat needs of single species, usually some valued game fish or an endangered fish species. Often these simple minimum flow standards were made more socially acceptable by allowing for recreation opportunities such as fishing and boating. Models simulating hydraulic habitat under different flow levels were developed to characterize the habitat preferences for species of concern (e.g., PHABSIM, see Stalnaker et al. 1995) and, over time, their wide application promoted the simplifying—and untested—assumption that so long as some minimum flow was met, the species would persist and flourish.

The view that minimum flows for single species are adequate to sustain a desirable ecosystem state promoted the management philosophy of developing simple operational rules for reservoirs that would maximize economic gain while meeting the minimal environmental flow requirement. Such simple rules still dominate much of water resources management, for example, hydropower dam operations (Jager and Smith 2008).

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In the 1980s, a new way of thinking about environmental sustainability arose. Academic ecologists began to formalize their understanding of how temporal fluctuations in environmental conditions act to rejuvenate and maintain habitat quality and overall ecosystem health. Even for single species, the notion of a specific flow "preference" gave way to the realization that dynamic variation in flow is often needed to ensure the species' long-term health. For example, flushing flows below dams can certainly cause some mortality to fish; however, they also cleanse gravel beds, rejuvenate spawning and foraging habitat, and may reconnect the channel to floodplain habitats, all longer-term benefits. This more holistic understanding of ecosystem health established the foundation for a paradigm shift in ecosystem management away from single species with static habitat requirements to whole ecosystems in which the assemblage of species—many having different flow "preferences"—could be sustained by a dynamic flow regime.

This new paradigm in river systems was articulated in the principle of the "natural flow regime" (Poff et al. 1997). Basically, this perspective emphasizes the importance of recent historical (pre-management) hydrologic dynamics in controlling ecological processes, species adaptation, and ecosystem function in streams and rivers. The key elements of this concept are that the variation in flows is essential to sustain the ecosystem (and associated biodiversity) and that the pattern of variation typical for any river is defined by the climatic, geologic, and land cover controls on precipitation and runoff. Because these controlling factors vary geographically, natural flow regimes do so as well. An extensive literature has now accumulated to document how alteration of natural flow regimes has greatly modified ecological function and ecosystem state in streams and rivers throughout the world (Bunn and Arthington 2002; Postel and Richter 2003; Poff and Zimmerman 2009).

The shift to the current paradigm has been dramatic. For example, the Instream Flow Council has made the natural flow regime a cornerstone in developing guidance to help U.S. and Canadian aquatic management agencies implement more effective instream flow programs (Annear et al. 2004). The U.S. Geological Survey has a proposed program in river science that actively incorporates the concept (NRC 2007). The Nature Conservancy's Global Freshwater Program has successfully demonstrated the importance of natural flow variability in a variety of conservation and management contexts, including adaptive flow experiments with dam managers (http://www.nature.org/initiatives/freshwater/). And international interest continues to grow, as evidenced both by a series of scientific and social principles governing environmental flows generated at the River Symposium in Brisbane, Australia, in 2007 (http://www.riversymposium.com/index.php?element=2007BrisbaneDeclaration241007), and by an international scientific consensus on a framework for developing guidelines to guide environmental flow management at regional scales (Poff et al. 2009).

From a water management perspective, the natural flow paradigm clearly dictates that a simple "one size fits all" reservoir operation rule is not adequate to support natural ecological functions across broad geographic regions. Water management for downstream ecosystem health requires meeting the needs of multiple ecosystem components, and this action means mimicking some components of natural hydrologic variability. Accordingly, existing assumptions underlying reservoir operation rules should be reexamined for flexibility in managing for variation rather than a static minimum (Johnson et al. 2004). Such a multi-objective framework clearly presents some challenges to the prevailing management perspective (Jager and Smith, 2008), but new tools are being developed in response to these challenges, such as modeling a range of reservoir operation rules to discover how different environmental flows might be achieved and still meet project goals (e.g., Suen and Eheart 2006; Vogel et al. 2007; Hughes and Mallory 2008). Much more research of this kind is needed. What is especially needed is active engagement of engineers in the creative process of developing flexible operational rules that will promote success in environmental flow management (see Harrison et al. 2007; Richter and Thomas 2007; http://www.nature.org/initiatives/freshwater/partnership/). More generally, managers and planners need to think about how to incorporate natural variability across the spectrum of water management actions, from reservoir operations to basin-wide management of water infrastructure to development of state and provincial water management regulations.

The Emerging Frontier of Riverine Sustainability Management

Obviously, managing for "the natural" must not imply that altered systems be completely restored to some premanagement state. Nonetheless, most managed systems can be at least incrementally improved to enhance ecosystem health, and that is certainly a benefit. From a management perspective, the critical question is "how much natural" is enough to attain self-sustaining riverine ecosystems, and can this level be achieved broadly? While scientists have much to offer here in defining the requirements for ecosystem resilience and health, the answers to the question of "how much natural" are ultimately based as much on social preferences as they are on scientific understanding. Society must collectively decide on the desired state of our aquatic and riparian ecosystems and the value of the natural biodiversity and natural goods and services these systems provide—scientists can then provide the knowledge and tools to achieve this state (Poff et al. 2003).

A significant challenge to scientists in helping attain some socially defined goals arises from the fact that many of the tools developed for site-specific evaluation of environmental flows cannot be applied everywhere because they are expensive and time intensive. However, the freshwater biodiversity and ecosystem health crisis demands immediate action. Therefore, tools are being developed for broader regional analysis (Arthington et al. 2006; Poff et al. 2009), but even then we need to prioritize and make tradeoffs because we cannot expect to "save it all." So, the question of "How much?" is further complicated by the emerging challenge for riverine conservation of asking "And where?" How do we strategically prioritize where management actions will maximize conservation goals in the broader regional or geographic context?

One key element is clearly identifying special places on the landscape that afford critical habitats for valued species or provide essential ecosystem functions and understanding how these habitats are connected (Fausch et al. 2002). For example, free-flowing streams and rivers (or tributaries to large rivers) can provide refuges for irreplaceable genetic and species diversity, and they also afford a source pool for colonization of present degraded habitats and for future restoration efforts (Moyle and Mount 2007). In other words, the unmanaged elements of a river network are critical for providing resilience to the larger system. Efforts to identify the places necessary to sustain biodiversity or ecological function at regional scales are now being pursued

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through the development of ecoregional planning tools (Higgins et al. 2005) or proposed freshwater conservation reserves (Abell et al. 2007; Linke et al. 2007).

Visualizing rivers in a "landscape context" is essential for sustainable water development. Conservationists are increasingly recognizing that tradeoffs are inevitable and that the relative costs and benefits to the environment depend sensitively on where individual or multiple projects are placed in a river network. In a likely future of intensified conflict between the needs of humans and nature for fresh water, such strategic environmental assessment will assume a prominent role in water resources planning and management. Major NGOs are already engaged in this process, such as the World Wildlife Fund and The Nature Conservancy (TNC). For example, TNC is working with the Chinese government to identify river segments in the Yangtze River basin that should not be dammed to conserve biodiversity hot spots and key ecosystem service benefits. The proposed hydropower dams in this region are also being designed to operate under the current paradigm of environmental flows to the extent feasible (Harrison et al. 2007).

Prospectus

Achieving the right balance between ecosystem conservation and water resources development represents a tremendous societal challenge. Not only is there substantial uncertainty in the science of environmental flows (Poff et al. 2009), but laws and regulations governing environmental flow allocations are weak and need modification (Eheart 2004; MacDonnell and Grigg 2007). Further, the public policy debate and the political process for setting socially and ecologically acceptable targets are problematic and surely can be improved. In light of these challenges, some opportunities for moving forward may be presented by the convergence of several threads in the public's growing environmental awareness: the ecological costs of water resources exploitation are being recognized; an understanding of the links between ecosystem health and societal well-being is emerging and perhaps solidifying; and the inevitability of climate change and the need for adaptive planning are being rapidly accepted.

But moving the dialog on freshwater sustainability forward in a meaningful way will also require leadership from the technical experts engaged in sustainable water development. Scientists, conservation NGOs, government agencies, water planners, and policy-makers all have a stake in collaboratively discussing how to strategically balance the needs for future water development with ecosystem sustainability at local to global scales. The involvement of water resources planners and managers is essential in this evolving dialog. Planners can take a leadership role by promoting a truly holistic vision of IWRM, one that actively incorporates the need for adequate environmental flows (Bernhardt et al. 2006). And by embracing the paradigm of flow variability as essential to sustainable ecosystem management, planners and managers can set a high bar for future development and thus contribute significantly to helping sustain the health of the Earth's freshwater resources for human benefit.

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