Water Resources and Sustainable Aquatic Ecosystems: A Vision for 2050

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Chapter 19

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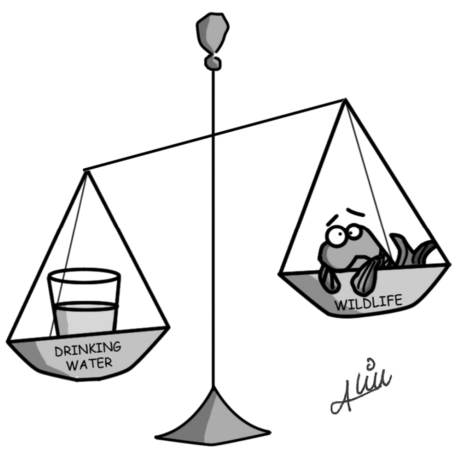
ABSTRACT

Failure to include the goods and services provided by freshwater ecosystems in the design, development and operation of water infrastructure results in the degradation of these ecosystems. Human societies and governments must act with urgency to more comprehensively incorporate robust principles of ecosystem science into planning and management of freshwater resources if long-term sustainability of freshwater ecosystems is to be secured for the 21st century. Absent this, we can expect the state of freshwater ecosystems in 2050 to be massively diminished, perhaps irretrievably so, with unforeseen economic consequences to human populations that depend on the self-sustaining nature of functional freshwater systems. The foundations for integrating ecosystem sustainability principles into water resources planning, development and management already exist. We identify four major pathways forward for achieving a new water management paradigm that will be able to ensure the viability and robustness of freshwater ecosystems for posterity. However, implementing them will require substantial political will, in addition to sustained efforts from the technical community needed to devise water management strategies that meet both human and ecosystem needs.



INTRODUCTION

Sustaining healthy, functioning aquatic ecosystems in the face of increasing human population growth and accelerating climate change is one of the greatest societal challenges facing water resources management now and in the coming decades. Early in the 21st century, water has already become a limiting resource for population growth and poverty alleviation in many areas of the world (WWAP 2009). Further, water scarcity is of growing concern in industrialized countries, particularly when drought cycles coincide with expanding populations. While humans clearly derive benefits from out-of-stream diversions, removing too much water from freshwater ecosystems impairs ecosystem function and diminishes many ecosystem services and goods upon which humans depend (Postel and Richter 2003; Richter 2009). Water resources decision-making typically fails to account for this loss of natural goods and services, making it a hidden cost (Emerton and Bos 2004). Indeed, one unintended consequence of this failure to balance the costs and benefits of water infrastructure is global scale degradation of freshwater ecosystems (Dudgeon et al. 2006; Strayer and Dudgeon 2010).

Human societies and governments must act with urgency to more comprehensively incorporate robust principles of ecosystem science into planning and management of freshwater resources if long-term sustainability of freshwater ecosystems is to be secured for the 21st century. Absent this, we can expect the state of freshwater ecosystems in 2050 to be massively diminished, perhaps irretrievably so, with unforeseen economic consequences to human populations that depend on the self-sustaining nature of functional freshwater systems. The foundations for integrating ecosystem sustainability principles into water resources planning, development and management already exist (Petts 2009; Poff 2009; Richter 2009). However, implementation of meaningful "solutions" presents a major social challenge that will require substantial political will, in addition to sustained efforts from the technical community needed to devise water management strategies that meet both human and ecosystem needs (O'Keeffe 2009).

OUR VISION

Our vision for 2050 is a new paradigm for water management planning, development and management, one that aims to explicitly "balance" the economic and ecological costs, benefits and tradeoffs associated with water extracted from freshwater ecosystems vs. water that remains within the ecosystem. By recognizing that freshwater systems must be managed *both* for the needs of people and ecosystems, a policy of sustainability can be rationally and consistently pursued. Historically, and even today, the balance scale has been grossly tipped to out-of-stream or out-of-lake benefits, which are typically directed to agricultural enterprises and urban populations, while ecosystem-dependent rural populations such as those living downstream of dams bear the brunt of negative impacts of water development (Richter et al. 2010). Joint human-ecosystem sustainability requires that certain management, engineering, scientific and social challenges be addressed. Meeting these challenges requires both immediate and long-term actions to build a foundation that provides the flexibility that will be required to sustainably manage water resources in the future, as human populations grow and climate change introduces new uncertainties in water allocation.

A fundamental principle of freshwater sustainability is that human alteration of natural variability of water chemistry and hydrologic processes must be constrained within specified limits that support natural riverine processes (Poff et al. 1997; Richter 2009). Social decisions will not necessarily converge on the "natural" as the most desirable management goal, because competing uses or alternative visions of desirability for ecosystem states (e.g., caused by use of dams) will be desired for different places (Jowett and Biggs 2009; Poff 2009; Poff et al. 2010). But to achieve a vision of "balancing" economic and ecological costs in order to attain desired and sustainable freshwater ecosystems, planning and management must occur at two different scales, both of which are of social and ecological relevance. At the *local* scale, stakeholders and scientists focus on the upstream watershed and the management strategies required to maintain the desired ecosystem condition for a particular site or river. At the *regional* scale, some evaluation of cumulative instream-outstream tradeoffs associated with placement and management of all existing and proposed infrastructure and water extractions is needed to accommodate regional "optimization" of watershed-scale ecosystem performance and freshwater sustainability (Krchnak et al. 2009). This process will need to be replicated for all regions within a governance domain (e.g., individual states, entire US) to account for geographic variation in ecosystem structure and function and for human cultural contexts that differ in socially-desired levels of sustainability for individual projects and for distributed projects in river networks (Poff 2009). This process can succeed only when decision-making and priority-setting take place through transparent, inclusive, and well-informed stakeholder engagement (Richter 2009).

In order to achieve this vision, a new "integration" is required, one that brings scientists, engineers, managers, policy makers and stakeholders together to develop and work cooperatively toward a common set of goals. But there are numerous challenges that must be addressed and overcome for this to happen.

CHALLENGES TO ACHIEVING FRESHWATER SUSTAINABILITY

Management/Policy Challenges

Our existing policy and management system is often dominated by adversarial positions and camps that generally lack a common vision or have asymmetrical political power and who often hold different perspectives on the "value" placed on environmental amenities and natural processes. The challenges of achieving freshwater sustainability are perhaps epitomized in the arid western US, where existing water law greatly favors historical uses of water and fails to provide adequate water for ecosystem sustainability (MacDonnell 2009a,b). In the western US, future demands for water resulting from population growth coupled with a drying climate are projected to be severe (Lettenmaier et al. 2008). However, constraints are rapidly arising in wetter regions of the country as well, such as in the Apalachicola-Chattahoochee-Flint River basin, where urban growth in Atlanta and increasing irrigation demands intersect with drought cycles to create shortages for both humans and ecosystems. Indeed, projections of future conflict and likely impairment of freshwater ecosystems has led to collaborative, stakeholder-driven visioning for state-wide water development and management in Georgia (Georgia Environmental Protection Division 2008).

Scientists, engineers, managers, policy makers and stakeholders must work cooperatively together to identify and develop strategies to sustain largely ignored ecosystem values.

Water resource policy in the US has largely ignored ecosystem values and has fostered a management culture that is too often reactive in nature. Typically, ecosystem needs are not incorporated in the planning phases of water resources design, in no small part because the goods and services provided by ecosystems are not easily placed into an economic valuation context (Emerton and Bos 2004). Post-hoc resource degradation often leads to reactive legal intervention in a narrow regulatory context to stem gross degradation in water quality (e.g., Clean Water Act) or prevent extinction of rare species (e.g., Endangered Species Act) of societal concern.

Climate change and other environmental changes are inevitable in the coming decades at unprecedented geographic scope, and these changes will likely overwhelm the capacity of regulatory systems to manage them. We know natural systems will respond in complex ways and severe degradation of these systems is likely if proactive and adaptive planning and management are not embraced (Palmer et al. 2009; Poff et al. 2002, 2010; Strayer and Dudgeon 2010). The most rational avenue open to us is to recognize that freshwater systems are currently in a stressed state, to anticipate the impacts of new stressors on freshwater ecosystems (including the human reactions to climate change), and to fully explore the range of options for managing water resources in a more sustainable fashion. Thus, the active, coordinated management of existing and future water infrastructure can and must be used to help achieve the balance between human and ecosystem needs for fresh water. Adopting this perspective provides a foundation for climate change adaptation (Matthews and Wickel 2009; Poff 2009).

Achieving a balanced human-ecosystem management ethos will require a more democratic process of broad stakeholder involvement in envisioning the future states of managed ecosystems. Efforts are underway to develop such a process, as for example the strategic environmental planning approach championed by The Nature Conservancy (Richter and Thomas 2007) or stakeholder-driven process captured in the "ecological limits of hydrological alteration" approach (Poff et al. 2010). Having ecosystems represented in the planning and management of water infrastructure requires adoption of a framework on the ecological side for evaluating relative risks to ecosystems under proposed water resources development and management and projected climate changes, and it requires definition of some ecological "currency" that can be appropriately valued in the larger socio-economic models that guide investment in water infrastructure and management.

Engineering/Technical Challenges

In the broadest sense, there are three major "technical" challenges to realizing sustainable water management by 2050. The first is significant improvement of irrigation efficiency and agricultural productivity on both irrigated and rain-fed croplands. This will serve to keep more water in streams and rivers and thus provide more management flexibility. The second is overcoming the energy and brine disposal barriers to desalination for urban water supplies. With the projection of more than half the human population in 2050 living within 100 kilometers of a coastline, desalination could greatly alleviate current pressures on inland water sources. Third, for inland waters it is critical that the siting and operation of water infrastructure (i.e., dams, and particularly hydropower dams) be done in the most ecologically compatible manner possible to avoid and mitigate ecological and social impacts at local to regional scales.

On this third front, much progress has been made in recent years. Reservoir management tools have been developed that better "optimize" environmental flow needs given the project design and goals (Dittman et al. 2009; Hughes and Mallory 2008; Suen and Eheart 2006; Vogel et al. 2007). The US Army Corps of Engineers (USACE) has entered into a cooperative program with The Nature Conservancy to provide environmental flows below USACE dams for downstream ecosystem benefits. Results from these actions can be used to adaptively manage larger river systems that have dams on them (Richter et al. 2006; World Commission on Dams 2000). There is much effort to develop scientifically-based flow-ecology relationships that can be regionalized based on flow regime typologies to afford some guidance for environmental flow management required to sustain freshwater ecosystems in some desired state (Arthington et al. 2006; Poff et al. 2010). All these activities suggest a self-organizing nexus of planners, engineers, hydrologists, scientists and managers working to achieve some targeted degree of ecosystem health in the face of human demands for fresh water. Continuing efforts along these lines are essential to reach our vision of 2050 water management.

Scientific Challenges

A fundamental scientific challenge is to be able to specify the spatial and temporal scales needed to understand and manage for ecosystem resilience and sustainability. Focused effort on better articulating the relationships between flow regime, its alteration, and ecosystem dynamics is increasing rapidly (Arthington et al. 2010; Poff et al. 2010), but identifying the "bounds" on ecosystem sustainability (Postel and Richter 2003; Richter 2009) remains a research goal.

Scientists now understand that local ecosystems exist in a regional context, where movement of water, nutrients, individual organisms and genetic information is critical to sustaining the interconnected elements in a landscape setting (Fausch et al. 2002;

Poff et al. 2007; Pringle 2001; Strayer and Dudgeon 2010). This growing scientific perspective is feeding into conservation planning, where the location of dams and other water infrastructure has to be viewed both in terms of local effects and how the structure(s) will influence broader regional connectivity and sustainability. This poses an additional political challenge because environmental impacts of water infrastructure are typically viewed only at the local scale. In the future, local-scale planning will become increasingly ineffective as a viable strategy to sustain freshwater ecosystems if river basins or networks become increasingly fragmented by water infrastructure placement and management.

Another key scientific challenge is to understand ecosystem responses and adaptation to rapid global change, i.e., how human activities (land use modification, climate change, spread of invasive species) variously alter hydrologic and biological processes and thus diminish ecological resilience and sustainability. Developing this understanding is challenging due to massive alteration of earth surface processes (water, sediment and nutrient flux) over the last few hundred years. These changes have created transient (or non-equilibrium) states for the majority of freshwater ecosystems we currently observe, impairing even "reference" sites that are often used to gauge ecosystem health (Humphries and Winemiller 2009; Wohl 2005).

Management decisions to sustain freshwaters must be made in the face of considerable scientific uncertainty.

The inescapable reality is that management decisions to sustain freshwaters must be made in the face of considerable scientific uncertainty. This uncertainty need not cripple the process of securing a more balanced allocation of water for people and nature, in part because we know that "no action" is not an acceptable path if freshwater sustainability is to be taken seriously. Even in the face of uncertainty, scientists are reasonably able to bound management scenarios and thus offer a risk-based assessment that can guide critical management decisions needed to promote freshwater ecosystem resilience and sustainability (Poff et al. 2010).

An additional challenge facing scientists is the human dimension of freshwater sustainability. Freshwater ecosystems are complex social-ecological systems (Berkes and Folke 1998), meaning that human desires must be taken into account and stakeholders will decide the desired ecosystem endpoints based on cultural value systems. Human preferences have to be articulated in order to frame the tradeoffs that are faced in water management decisions (Baron et al. 2003). A more integrated effort between social scientists, ecological scientists and water managers is beginning to develop (Krchnak et al. 2009; Richter 2009), but rapid progress in this area is sorely needed.

FOUR STEPS TOWARDS A NEW WATER MANAGEMENT PARADIGM

The fundamental challenges described above stand in the way of creating a regulatory and management framework that efficiently promotes long-term sustainability of freshwater ecosystems for the benefit of nature and humans. We see four major pathways forward for achieving a new water management paradigm that will be able to ensure the viability and robustness of freshwater ecosystems for posterity.

Actively Incorporate Ecosystem Principles into Management

A major step toward sustainability is to regularly and more fully include ecosystem needs in the process of integrated watershed planning and management (Bernhardt et al. 2006). Management of water infrastructure must rapidly move away from simple rules such as minimum allowable flows to more actively incorporate ecosystem principles of dynamic flow variability. The science of environmental flows is rapidly advancing and should form the basis for managing toward sustainability (Poff et al. 2010; Richter 2009). Simultaneously, a broader watershed-scale perspective must be adopted that actively seeks to promote connectivity of sites within a river network to promote freshwater ecosystem sustainability. This recognition requires that the planning and design of new water infrastructure examine both the local and regional impacts on freshwater sustainability (Opperman et al. in review; Poff 2009; World Bank 2009).

Integrate Social and Ecological Sciences into Sustainability Management

A science-based management of freshwater systems requires a more sophisticated integration of the social and ecological sciences to provide a common framework for finding sustainable solutions to the threats of water scarcity and ecosystem degradation. This is essential given the projected future demand for water by an expanding human population under the potential high uncertainties of climate change. Protecting ecosystems against unnecessary degradation will be greatly aided by development of techniques of ecosystem valuation that account for the economic benefits and costs of water resources planning and development. More effort is needed to develop an ecosystem services framework that articulates both ecological and social benefits from leaving water in freshwater ecosystems.

> ***More effort is needed to develop a framework that defines the ecological, economic and social benefits of freshwater ecosystems.***

Coordinate Regulatory and Management Authorities Over Water

Attaining suitable water quality for biological integrity is federally regulated; however, little federal authority exists to require water flow regimes in freshwater ecosystems to be managed toward long-term integrity (sustainability). Therefore, federal agencies with water science and/or management missions (US Bureau of Reclamation, USACE, US Geological Survey, US Forest Service, US Fish and Wildlife Service, etc.) should engage in a collaborative program to assess the sustainability of freshwater ecosystems under their jurisdiction. Some efforts to examine water supply have already been collaboratively undertaken by agencies in the federal government with respect to climate change (e.g., Brekke et al. 2009). All federal and state dam managers should be required to reassess the operations of their facilities to identify opportunities for restoring ecosystem benefits. Federal and state agencies should cooperate to undertake vulnerability assessments for freshwater ecosystem sustainability at local to regional to national scales. Existing data on physical and biological characteristics of the nation's surface waters should be assembled and viewed through the lens of ecosystem vulnerability. This baseline information is a critical foundation for sustainable management planning at regional to national scales.

Interdisciplinary Education and Research

A key need is the education for individuals who will be the technical experts in the various aspects of water resources management. Certainly, training workshops for the current generation of technical experts can be valuable. More fundamentally, a serious commitment to interdisciplinary graduate training is needed to break down the narrow disciplinary barriers between ecology, environmental science, resource economics, political science and engineering that fragment the multiple elements required for sustainable freshwater resources planning and management.

From a research perspective, the attainment of viable solutions for water management that meet both the needs of people and ecosystems is surely a grand challenge (National Academy of Science 2001). Focused efforts are needed to bring together life scientists, physical scientists, social scientists and economists, resource managers, and engineers to pursue solutions. Initiatives modeled after the National Science Foundation's cross-cutting Dynamics of Coupled Natural and Human Systems would provide one option. This should be pursued on regional scales that reflect natural differences in climate, water infrastructure and freshwater ecosystems.

THE WATER RESOURCES WORLD OF 2050?

What will the water resources planning and management world of 2050 look like? If the above key challenges confronting freshwater sustainability can be addressed, we would hope to see a full integration of ecological, physical and social sciences to provide a unified framework for sustainable management of limited freshwater resources. In 2050 we would expect research to be explicitly and comfortably interdisciplinary. Engineering, physical scientists, ecologists and social scientists will all be well versed in each other's fundamental principles and understanding. Mid-career professionals will have facility in more than one disciplinary field due to their graduate training and their professional collaborative experiences. The link between these disciplines will be tight and highly functional.

From a regulatory standpoint, water quality and water quantity, and the management of surface water withdrawals, groundwater pumping and dam operations will be fully integrated at the whole watershed scale. The water needs of freshwater ecosystems (and the social and environmental tradeoffs) will be included in the planning and development phases of water infrastructure, contributing to a truly integrated water resources planning and management.

At local to regional to national scales, water resources planning and management will explicitly account for environmental needs. The provisioning of water for freshwater ecosystems will be part of an open discourse wherein the "value" of limited water will be publicly debated and the optimal allocation of water for people and the environment will be based on social values and the best available scientific information. The unifying goal of water management will be to balance human and ecosystem needs so that freshwater ecosystems can be sustainably managed for the benefit of future generations.

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