RFF REPORT

Emerging Climate Change Impacts on Freshwater Resources

A Perspective on Transformed Watersheds

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Introduction

Consequences of Climate Change on Availability of Freshwater Resources

As a result of temperature increases in many regions, experts generally agree that more extremes in the variability of precipitation will characterize most watersheds in the United States (Roy et al. 2005, Intergovernmental Panel on Climate Change [IPCC] 2007). More intense floods and droughts will create numerous challenges for resource managers and for ecologists to understand the newly emerging conditions that affect ecosystem processes (Murdoch et al. 2000; Bates et al. 2008). Some consequences of these extreme events are well understood from previous experience and studies; what may differ from known impacts are the cumulative effects of multiple disturbances occurring in new combinations and at new spatial and temporal scales. The main effects on freshwater resources are likely to consist of greatly increased uncertainty in maintaining sufficient local and regional supplies of high-quality water resources to meet demands for municipal, industrial, and agricultural needs while also sustaining natural ecosystem services. Interannual and regional variability in the distribution of precipitation is already high; if this variability increases in complexity and scale as expected, cascades of interconnected and cumulative impacts will alter regional hydrology and ecosystem capacities to supply reliable sources of high-quality freshwater (Fitzhugh and Richter 2004; Barnett et al. 2008).

Long-term changes are already being documented, even if the causations remain complexly interconnected and not yet completed understood. For example, lake levels are declining in many locations, such as in the Laurentian Great Lakes region (Sellinger et al. 2008; White et al. 2008), western basins (Barnett et al. 2008), and in many other lakes in the midwestern and southeastern states. Drought impacts on lake and riverine transportation routes are increasing. Declines in lake levels and river depths cause increased costs for transportation because shipping loads must be decreased to reduce draft and allow passage through ports and docking locations.

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Evidence suggests that the volumes of water stored in lakes and rivers are declining because of decreases in long-term average precipitation and runoff as well as increased rates of evaporation. Separating these long-term, climate-driven effects from the effects of increased diversions of water for economic and environmental needs is complex, and accurate forecasts are challenging. Given the serious and increasingly worrisome concerns regarding the impacts of climate change on the changing volumes and distributions of freshwater supplies, more evaluation of effective alternative adaptive responses is needed. Generally, it is useful to begin with the assumption that further reductions in lake levels and reservoir storage will have numerous cascading effects, regardless of which of the multiple causations dominates future dynamics (Brinkman 2000; Argyilan and Forman 2003; Lenters 2004; Schwartz et al. 2004; MacDonald 2007; Sellinger et al. 2008; White et al. 2008).

This review focuses first on types of socioeconomic and biotic adaptations. Many individuals, public agencies, and nongovernmental organizations are discovering ways to protect biodiversity and sustain natural ecological processes. Five case studies are highlighted to illustrate some of these alternative adaptive responses to climatic changes at local and regional scales. These approaches could be modified for use in other locations. However, most studies have evaluated uncertainties in the quantities of water supplies over relatively short periods during or immediately after a specific drought event, with limited analyses of water quality. These studies have usually focused at the scale of a single watershed or at a hierarchy of locally nested watersheds. More long-term, spatially integrated research at regional, trans-regional, or continental scales is needed to address the impacts of extreme climate variability on ecosystems and water supplies.

Uncertainties associated with diminished water quality as well as quantity are very likely to increase as a result of major changes in hydrology caused by long-term, unique combinations of extreme drought and flood events. Earlier studies, such as those on the Mississippi or Colorado River drainages, are examples of analyses primarily examining water quantity with little information on quality. More complete analyses of new data on toxins and decades of cumulative effects of fertilizer-derived nitrogen on downstream "dead zones" in coastal regions of the Gulf of Mexico and other near-shore areas demonstrate the ecological importance of excessive nutrients on the loss of biotic production. These transfers of nutrients from continental sources are known to vary in response to droughts and floods. How future combinations of intense seasonal and interannual variability of precipitation will affect these ecologically and economically important coastal zones is not yet well understood.

Other examples of possible increases in degraded water quality include more toxic algal blooms, such as red tides, and increased populations of cyanobacteria (previously considered bluegreen algae). These biotic changes occur following excessive inputs of nutrients—primarily by different combinations of nitrogen and phosphorus—that result in the production of natural chemicals produced by cyanobacteria that cause taste and odor problems as well as threats to human health. Extended growing seasons for cyanobacteria—as well as many invasive species adapted to warmer waters—are likely to occur in lakes, rivers, and estuaries (Wiedner et al. 2007; Paerl and Husiman 2009). Greater distribution and growth of warm-water, harmful cyanobacteria will increase the costs of water treatment and decrease other beneficial uses of waters for irrigation, fisheries, and recreation. The Great Rivers Program and the Great Lakes Program of the U.S. Environmental Protection Agency, along with the analyses of water quantity and quality by U.S. Geological Survey monitoring networks, are addressing many of these issues. However, these studies are often underfunded and will require more comprehensive integration with social and ecological concerns. Future studies will need to include improved land-use practices, enhanced wastewater-treatment facilities, improved water treatment, and sustainable environmental flows and ecosystem services.

Socioeconomic Responses to Increased Uncertainties

Social adaptation and increased learning about alternatives among individual households, communities, and regional and national organizations will probably accelerate as more extreme conditions occur. Currently, infrastructure and storage capacities of surface and groundwater supplies are already very limited in many regions and frequently result in major economic losses associated with droughts and floods. Allocations of waters used in hydroelectric production, cooling for fossil fuel and nuclear power plants, and irrigation are undergoing critical reviews and economic analyses in anticipation of more severe droughts and storm flows (Hanemann 2000, 2005; Kallis 2008).

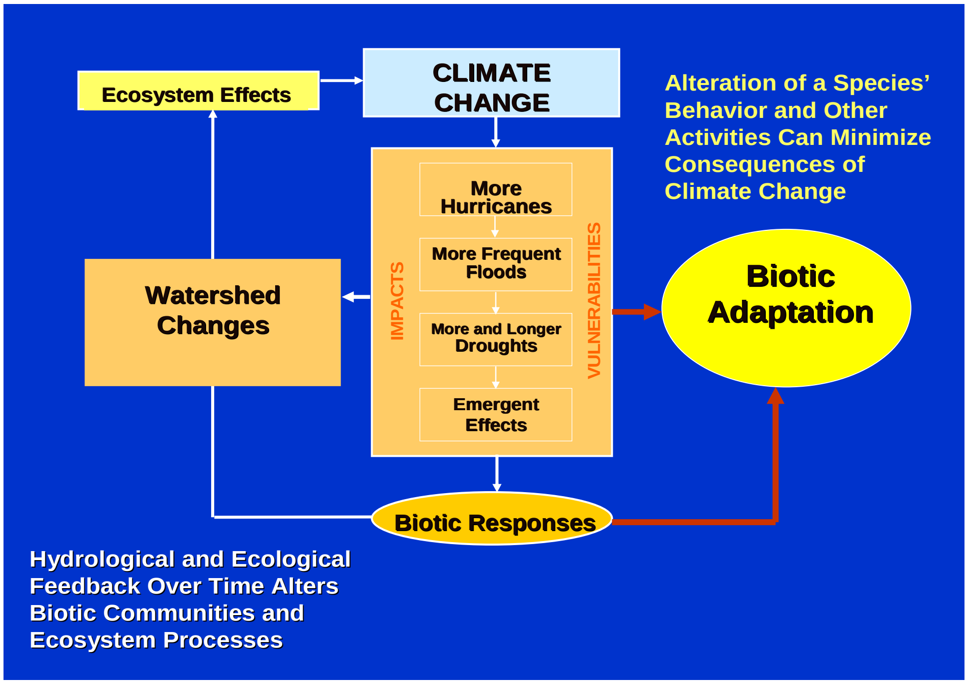
Human population growth and associated landscape changes, along with interannual variability in precipitation, alter hydrology and affect multiple freshwater ecosystem services, such as clean water and fisheries production. In response to these changes, new and existing social networks develop by organizing at local and regional levels to adapt to emerging realities. This review considers examples of how different individuals and groups have learned to sustain multiple freshwater ecosystem services at a hierarchy of scales. Differences among watersheds in terms of their sizes, locations, land uses, and the ecological roles of invasive and native species interact and affect social responses to extremes in precipitation (floods and droughts) that vary in their spatial and temporal distributions. Freshwater ecosystems are complexly connected with socially and climate-driven modifications of landscapes that influence the capacity to sustain supplies of clean water (Bergstrom et al. 2001; Brown et al. 2007).

Biotic Responses to Increased Uncertainties

Biotic adaptations are important in sustaining natural ecological processes, and the protection of native biodiversity is essential to providing vital ecosystem services. Many freshwater species have the behavioral, developmental and genetic capacity for adaptive responses to drought and flood events. Within limits, natural species assemblages will probably be highly resilient to variable hydrology (Figure 1). In some cases, they can disperse to avoid extremes or remain in place and use specific evolutionary adaptations such as dormancy.

However, as discussed below, these responses are significantly constrained. Although natural biotic communities generally are capable of altering their species compositions relative to the available pool of species, future decreases in the length of time between extreme events, as well as increases in the intensity and frequency of environmental variability, will probably cause new stresses on their capacities to recover robust functional relationships. Moreover, the rapid spread of nonnative invasive species and disease organisms will create new instabilities and uncertainties. Construction of additional storage reservoirs and increased recreational uses of freshwaters is likely to accelerate the dispersal of invasive species and result in rapid changes in food webs and ecosystem processes. The resiliency of these natural functions is the basis for sustaining ecosystem services; introductions of invasive species already pose a major threat to freshwater ecosystems and cause large economic losses (Rahel and Olden 2008; Rahel et al. 2008).

Figure 1. Effects of Climate Change on Biotic Communities and Ecosystems



Over decades, the cumulative downstream impacts of extreme events can alter natural processes and biodiversity and lead to social responses to variable water supplies. Managing inland waters to sustain endangered species and biodiversity overall is becoming increasingly important and more frequently related to the evaluation of the environmental flows needed to protect native species (Palmer et al. 2008).

Previous Experience and Current Needs for Adaptive Infrastructure and Planning

Several regional and national planning efforts have relied on disciplines ranging from economics and ecology to hydrology, engineering, and law to adapt to the impacts of extreme climatic change on freshwater resources. These plans have typically included several options that reflect different experiences with previous levels of intensity and variability of floods and droughts (Table 1). In many cases, especially when these extreme events were relatively infrequent, the adaptive responses emerged from local government agencies, nongovernmental organizations, and individuals. For example, landowners combined their resources to replace landscaping with more drought-tolerant plants, build temporary levees and numerous small storage ponds for flood control, or drill wells to augment supplies of water for crop irrigation and livestock production. However, over time, these adaptive responses require updating to restore their effectiveness and to minimize the loss of ecosystem services. Currently, many dams, levees, and storage facilities are reaching or exceeding their originally intended design life. Doyle et al. (2008) estimated that restoring this infrastructure will require more than $1.6 trillion to sustain safe levels of operation (Doyle et al. 2008).

Whenever and wherever extreme events become more frequent, the types of adaptive responses increase in scale. More complex, regional organizations often emerge, especially when national economic interests, such as hydropower production, navigation, and industrial water supplies, are involved. Longer time scales and more integrated planning at the regional and national levels typically include increased federal expertise and funding for the construction of larger levees, large and small reservoirs for surface water retention, and the managed recharge of aquifers. Yet in the past, many other sources have funded the built infrastructure associated with water storage and flood control. Of the 80,000 dams in the United States, only about 5 percent of these storage facilities (generally the largest ones) are managed by the federal government. The U.S. Army Corps of Engineers and the U.S. Department of Interior's Bureau of Reclamation have built and managed most of the larger reservoirs, whereas the U.S. Department of Agriculture has supported the development of numerous smaller reservoirs and ponds to control soil erosion and flooding. State agencies and nongovernmental and private landowners have greatly modified watersheds in a variety of ways that relate to water storage and the avoidance of costs associated with severe drought and flooding. Consequently, decisions on where (and if) to build more levees or dams or how to use large and small storage basins and groundwater supplies are often made among county and state agencies as well as by private owners in conjunction with federal agencies. Future record-high and record-low lake levels and flows in rivers will probably exceed the recorded historic ranges of fluctuations that most planners and engineers used in their previous designs. In many regions, costly investments will be required as communities and agencies coordinate responses to climate change and adapt to greater variability and uncertainty.

Extreme variations in high and low rainfall result from a combination of natural variability and human-induced changes that already stress existing infrastructure. The projected increases in the frequency and intensity of extreme precipitation are expected to result in extreme distributions of droughts and floods that will further stress the infrastructure and organizational responses associated with managing freshwater resources (Hurd et al. 1999; Hurd et al. 2004; IPCC 2007).

Table 1. Summary of Adaptive Responses and Related Costs and Consequences

Water availability	Adaptive responses[a]	Cost	Community participation[b]	Public health risk
High flows	Store water in reservoirs for later use and for environmental flows Recharge aquifers	Low	Avoid losses, no building in floodplains No demands for building new dams and reservoirs	High disease potential (Because floods damage water treatment plants)
Medium flows	Store water in reservoirs Recharge aquifers	Low	Prepare for future extreme events	Low disease potential (Because there remains a high potential for biological control of disease vectors)
Low flows	Voluntary conservation Use groundwater sources Plan for water transfers	Moderate	Assist in meeting 10% reduction in water use Install drought-hardy turf and garden landscaping	Medium disease potential (Because high potential remains for biological control of disease vectors)
Extremely low flows	Mandatory conservation Use groundwater sources New sources: desalination Transfer water from nearby sources Monitor water quality No filling of swimming pools; limited boating, fishing Drought-hardy landscaping	High	Store water from roof runoff; recycle Drill new groundwater wells for short-term use Build new reservoirs Migrate to low-cost regions	High disease potential (storage tanks provide habitats for disease vectors). Poor water quality leads to disease outbreaks (Because of a lack of flushing flows to remove disease vectors, poor habitats for biological control species, and increased growth of toxic cyanobacteria)

[a] Adaptive responses primarily by local governmental agencies and organizations.
[b] Additional adaptive responses by individuals and households.

The magnitude of flooding is expected to increase as the distributions and timing of types of precipitation change. Intense rainfall on snow-covered watersheds and on increased areas of impervious, paved surfaces from land development results in flash floods and decreased groundwater recharge. Damage to infrastructure (dams, reservoirs, and water treatment and sewage plants) is likely to increase during larger floods. The frequency and intensity of tropical storms and hurricanes are also expected to increase runoff and erosion, further diminishing the infrastructure to store and treat water. Moreover, increased erosion will fill reservoirs with sediment, reducing water storage, more rapidly than in the past.

Past investments in infrastructure have been extensive but have not kept up with the need to provide efficient storage, treatment, and transfer of water in response to drought. Investment in water-related infrastructural facilities, as a percentage of gross domestic product, has decreased since the late 1990s. Large gaps are prevalent in most regions in the repair, replacement, or upgrading of inefficient, leaky pipelines and other water delivery infrastructure. The next several decades will require more coordinated planning related to different levels of uncertainty and willingness to invest in improved infrastructure as responses to highly variable precipitation.

Because extreme floods and/or droughts have occurred relatively more often in some regions, successful adaptations have emerged that can probably be modified and considered for use in other regions where major climatic changes are expected and additional infrastructure will be needed. For example, as discussed below, some innovative policies were initially developed for dealing with the construction and management of multiple surface-storage reservoirs in the northeastern states (e.g., Massachusetts and New York). Linked surface and groundwater storage (conjunctive uses or aquifer storage and recovery) was initially used in the southwestern states (e.g., Arizona and California). These types of infrastructure and policies for coordinating the use of different sources and aquifer storage can be developed with specific modifications for use in different regions, such as in some southeastern and midwestern watersheds where extreme drought and flood events are increasing in frequency.

Approval by federal, state, and local agencies for new permitting to drill wells, to build reservoirs, and for other construction is often complex and sometimes slow to change when responding to long-term forecasts with high levels of uncertainty. Other examples of adaptation provide more immediate responses, such as providing incentives to conserve water among major users and fixing leakage to avoid water losses in treatment and delivery systems. Increased efficiencies in water management and restricted uses (e.g., bans on watering lawns and home gardens) conserve water quickly and can result in significant long-term changes in planning for improved water treatment and water reuse.

Although large differences exist, each urban center has developed means for conserving water, especially in the arid southwestern United States. For example, the Southern Nevada Water Authority established the Water Smart Landscapes Rebate to provide incentives for property owners to convert high water-demanding lawns to desert landscaping. In this region, every square foot of grass lawns that is replaced with drought-adapted trees, shrubs, and perennial herbs saves an average of 55 gallons of water per year. Land owners receive $1.50 per square foot of grass removed and replaced with desert landscaping up to the first 5,000 square feet converted per property, per year. After the first 5,000 square feet, the rebate is $1 per square foot and the maximum payment for any property in a fiscal year is $300,000. Rebates for well owners are limited to 2,500 square feet per calendar year. However, the 165-gallon-per-day-per-capita water demand for single-family residential use in Las Vegas Valley remains much higher than the 110–120-gallon-per-day level achieved by many other southwestern cities and is much higher than the 38-gallon-per-day use recently achieved in Brisbane, Australia.

Alternatives such as drought-contingent water transfers, water banks, and underground storage are additional responses. Bidding to transfer water from use in irrigation to other uses has also proven effective. As discussed below, farmers in some states (e.g., Georgia) are paid not to use their water rights for irrigation during extensive, prolonged droughts so as to maintain sufficient water for environmental flows or to avoid the need to construct more water storage facilities that are only needed during a rare but extreme drought. The planning for interruptible irrigation has remained an option for decades in several regions (e.g., McCarl and Parandvash 1988; Hamilton et al. 1989; Fisher et al. 1995).

Freshwater Ecosystem Services

This review focuses on responses related to the effects of climate change on freshwater resources with an emphasis on the long-term increase in adaptive capacity to sustain ecosystem services. Numerous inland surface waters, along with groundwater supplies, provide essential ecosystem services for society (Daily 1997; Daily and Ellison 2002; Covich et al. 2004; Heal et al. 2005; Brauman et al. 2007). Inland waters (lakes, ponds, wetlands, reservoirs, and rivers) make up a small fraction of the Earth’s surface and cover only about 0.3 percent of the land area; furthermore, their temporal and geographical distribution is uneven (Smith et al. 2002; Downing et al. 2006). Because of the limited distribution and considerable complexity of inland waters, it is increasingly timely to include an analysis of the total value of ecosystem services in regional planning. Determining the ecological, economic, and social values of adaptive responses to climate change relative to ecosystem services provides policymakers with a comprehensive planning context.

Examples from case studies in Massachusetts, New York, Georgia, Florida, Colorado, and California are used to illustrate ecosystem services that are sustainable in response to extreme variations in precipitation that vary across watersheds from the mountains to the sea. These previous and ongoing responses to recent droughts and floods provide insights that can be useful in other locations. Considerable research has emphasized the need for comprehensive, integrated ecosystem-level study that forms the basis for adaptive capacity (e.g., Aerts and Droogers 2004; Ficke et al. 2007; Pahl-Wostl 2007; Anderson et al. 2008; Kundzewicz et al. 2008).

Perspectives on Adaptive Responses for Managing Freshwater Ecosystems

Some Terminology and Definitions: Ecosystem-Level Responses to Extreme Changes in Precipitation and Temperature

In the context of this review, extreme environmental changes in temperature and precipitation are those beyond the known range of historic variability. It is important to define specifically bounded ecosystems that include alternative management options. The importance of using an ecosystem approach to define natural and socioeconomic boundaries of watersheds is based on the need for a hierarchical ranking of inputs and outputs associated different scales to help set priorities for establishing and evaluating adaptive responses.

The concept of *ecosystem* is defined as a systems approach to study natural and social dynamics based on measurable inputs and outputs of energy, water, and other materials at appropriate spatial and temporal scales (Covich 1993, 2005). Biotic diversity and human and cultural diversity all interact with physical and chemical components in determining how ecosystems function. Consequently, socially and politically complex issues are associated with community-based water management that sustains ecosystem services (Dellapena 1999; Habron 2003; Warner et al. 2008).

Defining the natural and social boundaries of these open systems requires careful consideration to include unusual events and what might first appear to be “rare” dynamics. Rapid and infrequent—but potentially important—inputs from both local and distant sources can have long-lasting effects. For example, spills or dumping of toxins or excessive nutrients can be transported from (a) flows of surface and groundwaters within a single watershed or aquifer, (b) within a series of hydrologically connected watersheds, or (c) across adjacent regional watersheds linked through the engineering design of sewage treatment plants or water supply sources. These flows can vary greatly in response to variations in extreme events and across different types of watersheds. Moreover, for some issues it can be important to include distant airsheds (such as mineral inputs of airborne dust from the Sahel or China). Inter-regional ecosystem boundaries can also be viewed with regard to trade among agriculturally producing regions. “Virtual water” is represented by crops grown in wet regions and supplied to arid regions as one way to offset the demand for water in arid regions (Hoekstra and Chapagain 2008). This inter-regional concept for optimizing uses of water considers the amount of water available during different periods of production, the amount expended in producing foods and the costs for shipping among regions. In general, these watershed and ecosystem concepts integrate natural and social geography and political and economic issues, as well as ideological perspectives, that lead to adaptive governance of these social–ecological systems (Imperial 2005).

Adaptive responses are defined as adjustments in ecological, social, and economic systems in anticipation of, or following, actual changes in temperature and precipitation that impact freshwater ecosystem services either detrimentally or beneficially (Smit and Pilifosova 2003; Adger et al. 2005; Nelson et al. 2007). The most recent reports by the IPCC (2007) emphasize the importance of developing adaptive capacities for responding to the changes in temperature and precipitation extremes that are likely to affect water resources, wastewater management, public health, and many other issues related to ecosystem services. Previous studies have identified ways to develop this adaptive capacity (e.g., Watson et al. 1996; Smithers and Smit 1997; Wilbanks 2005; Tanaka et al. 2006). The value of developing adaptive responses and capacities increases relative to the length of time available for planning and improving infrastructure and the intensity of damages from catastrophic impacts (Sonnett et al. 2006; Settle et al. 2007).

In general, adaptive capacity will probably increase as the experience and ability of individuals and planners grow over time and lead to improvements in natural, constructed, and social systems. These responses can be developed through an *adaptive management* process (Holling 1978; Walters 2001; Habron 2003). Such a process accommodates changes in environmental conditions with minimal disruption or few added costs (National Research Council 2004; Hedelin 2007; Gerlak 2008).

Adaptive management primarily consists of analyzing alternatives in a systematic way that determines which approaches are pragmatic, cost-effective, and useful as long-term responses to extreme events. Adaptive management avoids “trial-and-error” approaches that lack a design to enhance learning from successes and failures and the analysis of comparative data. Success in resolving conflicts often depends on how completely stakeholders are identified and whether their full, equitable integration is accomplished (Norton 2005). This approach is especially useful in responding to extreme events that previously were rare and that involve a range of interests among diverse water users.

Comprehensive adaptive management optimizes freshwater ecosystem services by protecting and restoring the levels of biodiversity needed for natural processes to continue functioning. As discussed below, many different species are associated with natural processes that provide essential end products of ecosystems valued by society (e.g., clean drinking water, irrigation, aquaculture, hydropower, and recreational and commercial fishing). These processes and products are frequently analyzed in terms of their economic and ecological values (Heal et al. 2005). In most cases, complex trade-offs will have to be considered in terms of natural processes and management decisions regarding alternative allocations and the long-term sustainability of social and natural systems. These trade-offs often vary regionally among communities that differ in their resources and economic potentials for implementing adaptive responses as well as in the variability of precipitation.

Most planners and stakeholders have a good understanding of a flood as an event with a relatively clear beginning and end, although flood durations vary from hours to weeks. Seasons with high flows occur frequently in most watersheds and usually sufficient long-term data are available for using a statistical basis for the definition of record-breaking floods or of those that are considered unusual, such as events that are two standard deviations above the mean in any given month (e.g., Resh et al. 1997). Some regions, such as the lower Mississippi River drainage and parts of the Gulf coast, experience large, frequent floods from high intensities of rainfall. In 2004, floods were estimated to cost the United States nearly $14 billion (National Weather Service 2006), and these costs will probably increase if hurricanes and other major storms result in more extreme rainfall.

In contrast with floods, definitions of drought vary regionally and require careful consideration because they are relatively rare events. Definitions of drought generally require a long record of precipitation to determine what is “normal” or average for a region. Climatologists have documented trends in precipitation that change over several decades, such that the averages for an entire 100-year record of any single watershed can be misleading. Planners need to consider how emerging trends alter what is considered “extreme” drought in any region where long-term data and climate change models are available.

More than 150 definitions characterize different attributes of drought (Dracup et al. 1980; Lake 2003; Steinemann et al. 2006). A poor definition can result in a poor forecast that misses an extreme event’s impact, which might otherwise have been minimized. Moreover, an incorrect forecast of a severe drought that does not occur can cause managers to exceed the available funding for planning drought relief and adaptive responses. Previous failures of drought forecasts in midwestern states by the National Oceanic and Atmospheric Administration have led water managers to impose water restrictions or take other measures that cost water users, especially farmers, major losses (Changnon and Vonnahme 2003). Because irrigation of crops and water used in aquaculture comprise 70 percent or more of water withdrawals in many regions, adaptive planning for allocations of freshwater will often need to consider the total costs and benefits of drought relief for all users (Boyd and Gross 2000; Callaway 2004; Berrittella et al. 2007). Loss of credibility from incorrect or misunderstood forecasts is a major concern for adaptive responses that involve large expenditures and rely on long-term planning (Hartmann et al. 2002; Carbone and Dow 2005). The use of composite indices is effective in many cases, although it is not yet clear how each regional need can be met, given the different types and combinations of environmental impacts across the continent (Ray et al. 2007; Westphal et al. 2007).

To be effective, planners need a strong basis for defining and, if possible, for predicting the onset and severity of drought impacts. A clear, operational definition of a drought that applies to agricultural, industrial, and municipal impacts may remain specific to a given region or economic value. An operational definition of drought related to declining and variable water levels in rivers and lakes is important for planning and developing appropriate adaptations for transportation, water supplies, and recreational uses. This need is likely to increase as seasonal and interannual changes become more climatically complex (e.g. Mendelsohn and Markowshi 1999; Easterling et al. 2004; Burns et al. 2007; Connelly et al. 2007). Long-term monitoring of lake levels is being enhanced by satellite-based altimetry for regional analysis and provides one way to increase the scale of analysis needed to address impacts on ecosystem services (Cretaux and Birkett 2006).

Biotic Diversity Insures Freshwater Ecosystem Services

Forecasting the numerous types of environmental impacts of drought is complex given the many different abiotic and biotic conditions of regional freshwater habitats and specific traits among species to survive a drought or to quickly recolonize their habitats. Because the functional importance of certain species often shifts as environmental conditions change, it is important to retain as many species as possible as “insurance” to provide backup for particular processes.

Species might appear “redundant” during some conditions, but can become critically important during periods of extreme conditions, such as drought.

Many freshwater organisms have specific traits that increase their capacity to adapt and persist following extreme events associated with rapidly changing environmental conditions (Lake 2003). Despite some levels of disturbance from extreme floods and droughts, some key species can persist and continue to function (Resh et al. 1997; Lake 2003). For example, species that are relatively short-lived and can reproduce rapidly are often highly adapted for wide dispersal. They quickly recolonize habitats following a disturbance and contribute high rates of biotic production needed for food webs to persist. Some other freshwater species become dormant during stressful periods. In these dormant, or resting, stages they can survive for varied lengths of time in sediments or in variable water temperatures until conditions become favorable to complete their reproduction and life cycles. However, there are limits to their adaptations. New and stressful combinations of natural and human-generated disturbances have detrimental effects on many species, especially at warmer temperatures. Warmer water increases the metabolic rates of plants and animals. Simultaneously, warmer water contains lower concentrations of dissolved oxygen, thereby stressing species already at or near their upper lethal limits of thermal tolerance. Furthermore, the synthetic toxins found in many waters are lethal to many of the freshwater organisms needed to sustain ecosystem services.

Protection of Source Areas in Regionally Connected Watersheds is Essential

Forested and other naturally vegetated headwaters sustain sources of high-quality, clean water. New York City is one of the best-studied examples, having initiated early efforts to secure drainage basins in the Catskill Mountains and in Westchester County to provide a reliable source of water. Other cities (e.g., Boston and Seattle) protect their headwaters or their riparian areas along major rivers (e.g., Denver, St. Louis, St. Paul–Minneapolis, and Washington, DC) and large lakes (e.g., Chicago, Cleveland, and Seattle). Sustaining natural vegetative cover also helps to recharge the groundwater needed by some cities (e.g., San Antonio and East Lansing) and rural communities dependent on aquifer storage. Losses of natural vegetation, such as wetlands along shorelines and riparian buffers or in the headwaters of drainage basins, represent major economic losses as well as losses of critical habitats for a wide range of wildlife and other aquatic and terrestrial species needed to sustain ecosystem services.

Extreme droughts and floods clearly affect the demand for high-quality freshwater for agricultural, municipal, and industrial uses while also causing direct and indirect effects on other social and natural processes tightly coupled to climate change (Adger et al. 2003; Alcamo et al. 2007; Medellin-Azuara et al. 2008). For example, extreme climatic conditions dramatically diminish water quality and increase or decrease base flows of rivers and streams; this, in turn, alters the distributions and abundance of freshwater organisms, the basis for sustaining critical ecosystem services (e.g., Churchel and Batzer 2006; Brauman et al. 2007; Hur et al. 2007).

Recent changes in extreme precipitation have stimulated some new policies and approaches to sustain economic and ecological production processes (Jackson et al. 2001; Gleick 2002, 2003a, 2003b). Socioeconomic policies to increase efficiency and conservation of scarce water resources are responding to these climatic extremes. However, the spatial and temporal scales of current studies regarding adaptations are often limited, even though long-term adaptive responses have regional and national consequences. Given that extreme climatic changes are likely to continue for many decades, adaptive responses will also continue to have complex and cascading impacts throughout local and regional economies. Some organizations have effectively recognized the need to coordinate state, regional, and federal agencies to respond to climatic extremes (e.g., the Tennessee Valley Authority, Bonneville Power Authority, Colorado River Compact, and Delaware River Authority). However, even among well-established regional organizations, allocations of water for multiple uses have often resulted in conflicts regarding environmental flows and fisheries management.

Identifying generalizations used for conflict resolution can help guide discussions regarding regional competition for scarce water supplies (Brosius et al. 1998; Barham 2001; Michaels 2001). For example, many studies on the Klamath River and Snake River Basins in the Northwest, the San Joaquin and Sacramento River Basins in California, and the Missouri River and Rio Grande Basins provide some examples of how agencies have attempted to avoid prolonged debates over water shortages among different users and agencies (U.S. General Accounting Office 2003). These issues usually involve disputes among nongovernmental organizations, several states, and federal regulators (e.g., Michaels 200; Prato 2003; Koontz et al. 2004; Loucks 2006). Consequently, regional responses can potentially increase or diminish the long-term values of essential natural ecosystem services.

Barriers to Adaptive Capacity

Conflicts over water allocations often prevent exchanges of information and ideas on how to resolve differences. Finding solutions among local stakeholders can be more rapid than when regional or interregional groups are involved. Defining the scale, boundaries, and structure of the decisionmaking process is part of the planning process for adapting to change, especially when related to alternative allocations of freshwater (Warner et al. 2008). Some communities quickly find alternative ways to deal with the effects of climatic extremes on their water resources. These rapid responses are usually based on lessons learned from coping with previous extreme climatic impacts. This experience can contribute to plans for backing up water supplies and conserving water by implementing voluntary or enforced restrictions on water uses. Other communities, lacking previous experiences in dealing with extreme events, will be more limited in their planning, resources, and regulatory flexibility. In addition, features of the physical watershed, such as hydrological components (e.g., the number of reservoirs, lakes, and groundwaters that provide potential water storage), and geographical attributes (e.g., sizes, connectivity, and directional orientations of river drainage networks along with the steepness and altitudinal variability of mountains) will greatly influence how effectively consensus develops. The magnitude and frequency of extreme variations, as well as the legacy of previous disturbances (e.g., past and current pollution, unstable biotic communities dominated by nonnative invasive species, stressed infrastructure, and weak economic conditions), will further influence adaptive capacities.

In seeking agreements among competing users, well-defined social attributes should be considered; these include the number of competing needs for water; the types of regulatory constraints; previous legal settlements; and the number and attitudes of participating stakeholders, water managers, regulators, and policymakers. The length of time over which these groups and individuals have worked together and their levels of mutual respect and trust can greatly influence how well decision making progresses. Additional components include the extent and quality of information that can be communicated and evaluated within a decision-making process and the number of organizations involved in regulating water allocations. A need for numerous (and perhaps newly formed) organizational entities to agree on a complex combination of demands for sustaining the extensive irrigation of crops, hydroelectric production, flood control, transportation, numerous endangered species, and aquatic recreation within a single watershed will require considerable discussion and will probably challenge local and regional adaptive capacity development. In contrast, where regulations are highly flexible and the demand for water is relatively focused on a small number of competing uses, a well-defined group whose members respect each other's values will find many opportunities for rapidly building adaptive capacity.

Regional Similarities and Contrasts in Coping with Uncertainty

Although many regional differences distinguish watersheds across North America, several common characteristics that alter hydrological dynamics are associated with a warming climate. The effects of warmer temperatures increase water losses from evaporation in wetlands, rivers, lakes, and storage reservoirs. These greater evaporative losses from storage reservoirs can greatly diminish surface water storage capacities. Plants increase their rates of evapotranspiration to keep cool during warmer periods. Crops and many other types of vegetation increase their demand for water, reducing the amount available for infiltration and recharge of groundwater or runoff to rivers and lakes. As noted previously, warmer temperatures also increase metabolic stress for many plant and animal species. These changes in rates of evaporation and evapotranspiration can alter the seasonal distribution of runoff and water availability.

Even if the total annual amounts of precipitation do not significantly change in many watersheds, spatial and temporal distributions of precipitation can become more intense and shift in seasonal timing. This shift would probably reduce groundwater recharge and disrupt agricultural uses and river transportation. Besides these effects of natural climate changes, there are large regional impacts on the sources of freshwaters that are subject to various regional and national regulations and policies. For example, regulations determining water releases from storage reservoirs are typically set by historic agreements that reflect regional economic and political trade-offs. These earlier agreements may not be effective in dealing with future realities because longer-term planning will be required by different agencies and levels of administration.

Differences in Infrastructural Responses and Land-Use Changes

The combination of both extreme low and high flows in different regional contexts has already led to differences in responses. The extensive rebuilding of water management infrastructure is ongoing in arid regions where coping with uncertain water supplies has a long history. Integration of these plans has required large-scale regional analyses of entire watersheds within large drainage basins such as the Colorado, Columbia, and Sacramento Rivers (e.g., Smith et al. 1996; Gleick 2003b; Easterling et al. 2004; Hurd 2006; Markoff and Cullen 2008; Medellín-Azuara et al. 2008). Typically, these plans and agreements have been based on state and federal funding with long periods of discussion leading to coordination.

In regions where precipitation has usually been sufficient in the past, it is becoming increasingly important to provide additional source-area protection (enhanced riparian and forest cover to minimize erosion and flooding) and policies for sharing scarce resources or building more storage reservoirs for use during extended dry periods. The relatively wet regions of the southeastern United States have experienced the need for this broad-scale, regional planning after experiencing a series of prolonged droughts during the past decade (Glennon 2002). The wet regions of the northwestern United States are anticipating water shortages whenever and wherever the mountain snowpack becomes less reliable as a source of water.

In many of the montane rivers of the eastern and western states, severely dry periods in late summer are currently restricting river flows and causing cold-water fisheries to be stressed by warmer waters and a lack of sufficient flows (Mohseni et al. 2003). These effects are especially pronounced in higher-elevation rivers, where warmer temperatures are changing snowmelt hydrographs and seasonal water temperatures that influence salmonid fishes (Cooney et al. 2005; Battin et al. 2007; Rieman et al. 2007; Crozier et al. 2008; Rahel et al. 2008). These climatic impacts on fishes are leading to concerns about an expansion of dam building and the dispersal of nonnative invasive species that can further threaten the native fisheries and lead to a decline in economically important ecosystem services.

The increased uncertainty about the vulnerability of water supplies to provide safe drinking water is stimulating demand for building more storage reservoirs in many locations. Sites for reservoir construction, however, are increasingly limited, especially in proximity to urban locations where demand is growing, and the capacity to construct new reservoirs appears to be decreasing in the United States. The rate of increase in impounded surface area of reservoirs has dropped from an annual average rate of 4 percent prior to 1960 to about 1 percent per year since then (Downing et al. 2006). Yet water scarcity may reverse a series of policy decisions on the protection and restoration of cold-water fisheries. Over the past 15 years, some dams have been removed (e.g., Limmerick 2003; Clark 2004; Gowan et al. 2006; Pacca 2007) to help reestablish fisheries. With more concerns and funding for building new dams and reservoirs as a way to adapt to drought, the potential for reversing dam removals is increased. Construction of more dams and reservoirs could accentuate threats to native species from the dispersal of invasive species and from the downstream thermal effects of hydroelectric releases (Rahel and Olden 2008; Rahel et al. 2008).

Extreme Fluctuations in Supplies Affect Water Quality

Reduced flows decrease recreational uses of rivers and lakes for fishing and boating and diminish the values of waterfront properties (Cordell and Bergstrom 1993; Huszar et al. 1999; Elswerth et al. 2000; Hanson et al. 2002; Lewin et al. 2006; Connelly et al. 2007). Moreover, reduced flows increase the concentrations of pollutants and increase the costs of treating source waters for municipal supplies (Beck 2005). Water system managers are concerned about maintaining water quality as well as quantity following climatic extremes. Some communities have already shifted to obtain more of their municipal water supply from high-quality groundwater sources in response to recent droughts. They will probably continue to adapt their management decisions to cope with uncertain effects that have previously created problems. Studies demonstrate that managers with prior experience addressing extreme events are more likely to plan ahead and to respond adaptively to forecasts of high-risk disturbances from droughts, floods, and lightning strikes (O'Connor et al. 2005; Dow et al. 2007).

In many locations, increased erosion in river drainages alters flood control reservoirs. Extremely high flows transport sediments that fill storage reservoirs and reduce water storage capacity needed during dry periods (Bennett et al. 2002; Wren et al. 2007). Simultaneously, altered land uses and land cover also increase runoff and decrease the infiltration of water needed to recharge groundwater storage (Chormanski et al 2008). These land-use processes cause additional variability in river flows, fluctuations in levels of reservoirs, and reductions in storage capacity following high rates of sedimentation.

Pulsed storm flows lead to increased inputs of pathogens (Auld et al. 2004; Brookes et al. 2004) and breakdowns in drinking water treatment facilities and wastewater treatment plants (Rose et al. 2000; Hrudey and Hrudey 2007). These facilities require costly upgrades, and failure to maintain infrastructural capacities can lead to episodic public health challenges (Craun et al. 2002; Dow et al. 2007; Reynolds et al. 2008; Rogers and Louis 2008). Outbreaks of diseases are increasing as a result of the cumulative effects of climate change on freshwaters, especially large floods (Curriero et al. 2001; Rose et al. 2000; Auld et al. 2004). Furthermore, altered land uses result in the contamination of surface and groundwater sources (Kistemann et al. 2002; Jiménez. 2003; Lloyd et al. 2007).

Declines in water quality are major concerns regarding both drought and flood impacts with upstream and downstream coastal connections. With regard to water quality, taste and odor problems and/or serious illness can result from excessive nutrients that accumulate during droughts because of a lack of flows to dilute effluent from wastewater treatment plants. Overflows from treatment plants during floods and the breakdown of treatment effectiveness are known to create disease problems that continue to stress current water management decisionmaking (Rose et al. 2000; Auld et al. 2004). Salinity can also increase downstream, producing negative impacts on drinking water withdrawals from rivers, and can affect saltwater intrusion of groundwaters. In general, numerous connections exist between decisions on inland freshwater management and impacts related to sea level rise and changes in salinity (IPCC 2007, Huntington 2008).

Even though supplies are becoming more uncertain, demand for freshwater is rapidly increasing within and between states as populations continue to become more urbanized and affluent. The concentrations of populations along urbanizing corridors are often located along rivers and lakeshores, where water supplies have traditionally been developed. However, demand for freshwater resources for landscaping, recreational fishing and swimming, golf courses, and other economically important urban activities is increasing (Loomis and Feldman 2003; Loomis et al. 2005; King et al. 2007). These needs are competing with other municipal, industrial, and agricultural uses as well as with the natural flow regimes required to sustain biodiversity and natural ecosystem processes.

Six Case Studies To Illustrate Regional Adaptations

The case studies below demonstrate that a range of plans and incentives can resolve regional problems in cost-effective ways. In each case, the longer the time available for adaptive responses and the greater the communication among stakeholders, the more effective have been the results. Incentives for stimulating adaptive responses have been used in several states to adjust to severe drought impacts. Plans for adapting to extreme climate changes need to consider multiple locations to resolve supply issues. The use of a total ecosystem services approach provides one means by which to consider trade-offs among competing uses of water in ways that combine economic interests and requirements for environmental flows (Heal et al. 2005; Arthington et al. 2006). As discussed below, regional connections often exist among upstream and downstream uses of water; therefore, any adaptive planning needs to consider the appropriate scale and boundaries in planning to deal with extreme flow variability.

1.) The Colorado River Compact

The Colorado River Compact provides an example of how large regional decisions can be coordinated and legally defined to cope with the long-term variability of water resources if adequate information is available and forecasts are reliable. This current complex set of laws and regulations resulted from a series of discussions beginning in 1922. It was a response to individual states diverting water without any restrictions in place even though the League of Southwestern States had been formed in 1917 to develop the region. The original agreement led to rapid economic development, irrigated agriculture, and dam building to generate hydropower. Since then, the Colorado River has become the most regulated and litigated river in the world as the various states continue to deal with water shortages (Christensen et al. 2004; Jacobs and Pulwarty 2004; Pulwarty et al. 2005; Wilhite and Pulwarty 2005).

When the seven states that comprise the Colorado River Basin first agreed to allocate water to the upper and lower sections of the river basin, they initially focused on only a few issues and left out some important considerations. States in the Upper Basin were generally able to resolve agreements, but the Lower Basin states developed several conflicts that required additional legal actions. Consequently, the compact responded over decades to newly recognized changes in precipitation, population growth, and other socioeconomic variables that developed as demand increased for water and more information became available on the impacts of droughts and floods. Originally, information on interannual variability of precipitation was inadequate; therefore, the early decisions were based on inaccurate estimations of the water budget. The compact was negotiated during a period of unusually high precipitation, and the return to more typical rainfall created an overallocation of water committed to downstream states and to Mexico that could not be sustained. Moreover, Native American water rights had not been considered as part of the original compact. Nor did the early agreements consider the impacts of lower water flows on the river channel or on off-channel habitats for native fishes.

A series of legal decisions and additional discussions has resulted in successful plans by the states and federal government to address these complexities. For example, Nevada and California have agreements to allow for the storage of surplus water in water banks that can be transferred during long droughts. Nevada, California, and Arizona have all developed groundwater resources to provide a more predictable mix of sources than had resulted when only Colorado River water was considered. The states can build water projects for other states as ways to resolve long-term needs for the more than 30 million people who rely on Colorado River water (Committee on the Scientific Bases of Colorado River Basin Water Management, Water Science and Technology Board, and Division on Earth and Life Studies 2007).

2.) The Boston Metropolitan Region

The Boston metropolitan region contains approximately 3.2 million people, more than 40 percent of Massachusetts's population. The region has benefited from long-term planning in building much of the infrastructure needed to minimize risks associated with climate change, such as drought and sea level rise (Kirshen et al. 2006, 2008a). Construction of reservoirs and aqueducts has allowed for the transfer of water from drainage basins in relatively rural western regions to eastern urban and suburban users. Efforts have also been made to ensure the protection and use of local water supplies. This coordinated planning provides an example of how different sources of water can be used during drought conditions by creating organizational structures to anticipate necessary allocations and to determine the best locations for infrastructural needs (Ruth and Kirshen 2001; Westphal et al. 2003, 2007).

Metro Boston uses three different arrangements in the total water supply system. The main storage basin, Quabbin Reservoir, was completed in 1939 and has a large volume of high-quality water. The watershed contains 40,000 hectares of managed forest located in the central part of that state. The forested drainage basin provides habitat for wildlife and protects the tributaries from excessive bank erosion and rapid infilling of the reservoir with sediment. Sustaining the storage capacity of the reservoir by protecting the source areas is a major adaptation that requires wide stakeholder participation.

The Massachusetts Water Resources Authority (MWRA) operates both the Quabbin and Wachusett Reservoirs and serves about 50 towns within the region. Although Quabbin Reservoir is the primary water source for metropolitan Boston, other portions of the region are supplied by local groundwater and surface water systems. In addition, some locations are partially supplied both by local sources and the MWRA. This coordinated management responded effectively to drought conditions in the entire state during 2001 and 2002 by using water in ways that minimized the impacts in those areas with a low intensity of drought while responding to greater needs in other areas with more intense drought. The objective of this planning was to reach a level of "tolerable risk" across the region by tapping into different local sources and also by relying on the Quabbin–Wachusett reservoir system to supply water for many communities during drought.

A similar approach for allocating water from different sources is used in Springfield, Massachusetts. The Springfield Water and Sewer Commission coordinates five reservoirs and a hydroelectric power station in a linked systems approach to planning that has proven to be cost-effective during periods of regional drought (Westphal et al. 2007). These reservoirs were built by a combination of local, state, and federal funding. One was originally designed as a flood control reservoir by the U.S. Army Corps of Engineers but now can be used in conjunction with other reservoirs as emergency supply sources during drought. This expanded use of a floodplain reservoir illustrates how infrastructure can have multiple long-term benefits that only become well defined over time. When these different storage reservoirs and groundwater supplies are used as a coordinated system, along with drought advisories on limiting water uses, statewide planning can be effective during critical periods by lowering demand and providing adequate supplies.

Metro Boston has responded effectively in adapting to drought conditions, but other areas in eastern Massachusetts face increasing demands, and their groundwater supplies and river flows are being depleted. Portions of the Ipswich and Eel Rivers have dried up during long, dry summers. A recent study by the Boston Metro Area Planning Council indicated that some towns are approaching the limits set by the state on the volume of groundwater they can withdraw, and others will probably approach their limits within 10 to 15 years. In southeastern Massachusetts, the city of Brockton is considering building a desalination plant as part of its planning for future water supplies. However, because of the difficulty of safely locating desalination plants, they are often expensive alternatives as uncertainty increases relative to the costs of coastal construction. The high energy needs and concentrated effluents can make desalination projects unattractive water supply options. The effects of sea level rise, increased storm surge, and coastal subsidence all increase risks that will probably limit the construction of desalination plants in many coastal areas.

The U.S. Environmental Protection Agency funded a recent study, the Climate's Long-term Impacts on Metro Boston (CLIMB), that examined regional forecasts and models (Kirshen et al. 2008b, 2008c). CLIMB estimated that damages could accumulate to $94 billion for the Boston metropolitan area as a result of large storms and other anticipated impacts of global warming in the next 100 years. Population growth along the coasts also contributes to the damages. The new MWRA Deer Island wastewater treatment plant was built at a relatively high elevation to accommodate anticipated rising sea levels. Coastal flooding and flooding of the Charles River Basin will require additional water management solutions over the coming decades if forecasts prove correct.

3.) New York City

The New York City water supply program includes large-scale, multireservoir planning that is similar to the first example from Massachusetts in that both cities began in the late 1800s and early 1900s to purchase lands, relocate small towns, and build large reservoirs with well-managed, forested watersheds. New York City provides one of the largest and best-studied examples of how to adapt to increasing demands for water by having designed its system to include multiple storage reservoirs and to manage different source areas. The water supply system has developed since 1900 and consists of three complexly connected large watersheds containing 19 reservoirs and 3 lakes that flow into 3 aqueducts (Pires 2004). This system provides about 5 billion liters of drinking water every day for more than 9 million people (Blake et al. 2000; Foran et al. 2000; Arscott et al. 2006). The need to sustain clean, pathogen-free drinking water in New York City has led to a multi-billion-dollar investment in riparian protection, infrastructural enhancements, and watershed improvements to meet U.S. Environmental Protection Agency standards regarding microbial contaminants. To avoid or delay the construction of a costly filtration plant, the city is restoring ecosystem services throughout its integrated watersheds (Heal et al. 2005).

Although this example of long-term planning has resolved many issues related to water quantity and quality, future supplies of freshwater are still uncertain. The Catskill Mountains, a large part of this system, are undergoing climatic changes; a warming trend is causing the snow to melt earlier and to increase the runoff into rivers and reservoirs. How this seasonal shift will change over the coming decades and what effects warmer temperatures and longer periods of drought might have on water supplies remains uncertain (e.g., Blake et al. 2000; Burns et al. 2007). Some are concerned that even without a continued warming trend, the natural variability in climate will reduce flows into the Delaware River; this could result from drought effects as well as from increased demand for water. The reduced flow could increase salinities of the Delaware River estuary. Moreover, salinities might also increase as a result of sea level rise in the coastal zone. These downstream changes in river salinity affect groundwater recharge zones and freshwater intakes that supply the Philadelphia metropolitan area (Wolock et al. 1993).

Despite the success so far, considerable effort is still needed to coordinate state agencies in New York and Pennsylvania as well as federal agencies and local conservation organizations. This level of collaboration and cooperation typifies most large regional challenges. Having resolved previous challenges, regional water managers have important experience and means of communication that will probably form the basis for the next phase of adaptive management.

4.) The Flint River Drought Protection Act

The Flint River Drought Protection Act in Georgia is an example of providing incentives to change water uses during periods of limited supply. The state legislature sought to adapt to a prolonged drought by reducing diversions of water from groundwater and perennial streams for crop irrigation. One goal was to protect the diversity of fishes and invertebrates living in the tributary streams and main channel of the lower Flint River and in the coastal estuary in this complex ecosystem (Glennon 2002; Baker and Jennings 2005). A major consideration was to improve environmental flows and downstream protection of Apalachicola Bay, an economically important source of oyster production in Florida that is affected by changes in river inflows and salinity (Wilber 1992). Moreover, several rare and endangered species of freshwater mussels and fishes are listed by federal and state agencies in the lower portion of the drainage that flows into the Apalachicola River in Florida, the outflow from Lake Seminole. The lake level is associated with inflows from the Flint River as well as the Chattahoochee River and Spring Creek to form Lake Seminole, the fifth most productive bass fishery in the nation.

Because a major driving force of this act was to respond to issues regarding regional downstream flows that affect interstate economies (in Georgia, Alabama, and Florida), this example of providing incentives has the potential for wide application. A long-standing controversy over the timing of water withdrawals by the city of Atlanta from Lake Lanier, a large, deep reservoir, has resulted in legal actions (Glennon 2002; Terrill et al. 2002; Postel and Richter 2003). Lake Lanier, like Quabbin Reservoir, was built initially to control flooding, but over time has proven most important in providing municipal water supplies. Both Lake Lanier and Lake Seminole were constructed by the U.S. Army Corps of Engineers and both are managed by the Corps. The Flint and Apalachicola Rivers and Lake Seminole have large inflows of groundwater, and any reduction in irrigation use would allow for recharge of the groundwater and would influence downstream flows and lake levels. Fluctuating lake levels are known to influence the recreational uses and value of all of the rivers and connected reservoirs (Cordell and Bergstrom 1993; Jakus et al. 2000; Hanson et al. 2002; Loomis and Feldman 2003; Richardson and Loomis 2004; Connelly et al. 2007).

The Flint River Drought Protection Act created an electronic auction among farmers who held permits for pumping water to irrigate their crops (peanuts, corn, and cotton) and who were willing to accept a payment not to irrigate in a year that was expected to undergo severe drought. The effectiveness of this incentive to reduce irrigation withdrawals voluntarily requires effective forecasting to determine the potential for a severe drought (Steinemann 2003). The Georgia Environmental Protection Division directed the program and relied on the state climatologist to determine on March 1st whether a drought would impact the summer stream flows. It was known that pumping irrigation water from surface streams would divert significant water from the streams that are connected with and recharge the Floridan aquifer, one of the largest aquifers in the southeastern states. Although this aquifer is large, it is shared with Florida and requires careful management because it is vulnerable to pollution from deep injections of municipal wastewater, brines from reverse-osmosis desalination, and landfill leachates (Maliva et al. 2007).

This legislation was created in 2000 and then implemented in 2001 and 2002 following a multiyear drought. In response to several rounds of voluntary bids from nearly 200 farmers, the state accepted bids that ranged from $30 per acre to $200 per acre (average of $135.70) from 194 farmers. During the first year, 33,000 acres were removed from irrigation at a cost to the state of $4.5 million; in the second year, 74,000 acres were removed with costs ranging from $128 to $136 per acre and a total cost of $5.2 million. It is estimated that the net benefits to the state's economy ranged from $100 to $350 million in the avoidance of agricultural losses during a severe drought year. If not implemented during a drought year, losses in agricultural production could reach nearly $1 billion; and if the auction were used when not needed, the state could lose $5–$30 million (Steinemann 2006). The program was implemented in 2001, 2002, 2005, 2006, and 2007 but not in 2003 and 2004. Its costs and effectiveness for protecting stream flows relative to shellfish and fish populations are still being analyzed.

Various modeling techniques and the use of expert opinions have been developed recently to establish accurate triggers for implementing a response in anticipation of a severe drought in the southeast (Steinemann and Cavalcanti 2006). If drought frequency and duration continues to increase, the cost of the program may not be sustainable. A related effect occurs farther downstream, where changes in the flow of the Apalachicola River alter the salinity of Apalachicola Bay, an estuary that supports a $5 billion shellfish industry (Livingston 1991; Livingston et al. 2000). The trade-offs between sustaining the salinity downstream and sustaining the upstream water flows are complex and widespread. For example, the economic and ecological values of shellfish are also influenced by hurricane impacts along coastal zones, where other climatic effects have major ecological and economic interconnections. Nonetheless, this bidding process by the

Flint River farmers is one that could be replicated elsewhere during periods of extreme low flows as one part of a plan to sustain flows and protect biodiversity as well as alternative economic impacts.

5.) The Comprehensive Everglades Restoration Project (CERP)

CERP, in Florida, is a major example of how reallocating water associated with the Floridan aquifer is accomplished at large scales (Bush and Johnston 1988; Lee et al. 2002; Sklar et al. 2002). CERP is a partnership of federal (U.S. Army Corps of Engineers and U.S. Geological Survey) and state (South Florida Water Management District) agencies that was first approved in 2000 as part of the Water Resources Development Act. CERP was first estimated to cost $7.8 billion over 30 years of construction. The cost of CERP infrastructural modifications has increased to $20 billion and to require over 40 years of construction (for review, see Doyle et al. 2008). It covers 18,000 square miles (47,000 square kilometers) in 16 counties of central and southern Florida. The entire project includes hundreds of flow-control structures, many pump stations, thousands of kilometers of levees, and some 2,900 kilometers of canals. The project is designed to divert freshwater that previously entered the Atlantic Ocean and Gulf of Mexico and to store it during wet years for use during drought years. One part of this program is designed to pump up to 1.7 billion gallons per day of water into the Floridan aquifer during wet years. Water can be withdrawn and (a) allocated to the Everglades when necessary for ecosystem restoration, (b) used to avoid coastal saltwater intrusion into aquifers, and (c) used to provide water for farmers and others in southern Florida. This program is an example of how aquifer storage and recovery can work where rapid aquifer recharge is managed with relatively low expenditures for pumping and where the water can be pumped out quickly when needed. Such aquifer storage and recovery programs are known to work well in specific geological formations (such as in sandstone aquifers and karst, limestone regions) if the surplus water is of high quality and does not diminish existing natural groundwater quality and its diverse biota.

In this and related storage projects, the quality of alternative sources of water used for managing aquifer storage is the main concern (Blomquist et al. 2001; Gordon and Toze 2003; Ying et al. 2003; Dillon et al. 2006, 2008). Because stormwater and treated sewage waters are often used for aquifer storage, extensive treatment to break down organic matter and chemicals to disinfect pathogens are used to improve water quality before the reclaimed water is pumped below the surface. Chemicals used to kill pathogens and disinfection can be toxic to the diverse natural biota living in groundwaters. These distinct species provide important beneficial ecosystem services reliably and at low or no cost, and sustaining their functional roles has often been ignored. Moreover, some disinfection chemicals and their breakdown compounds can also be carcinogens that increase public health risks (Leenheer et al. 2001; Pavelic et al. 2005). Another limitation in the managed recharge of an aquifer is the concentration of suspended solids and organic materials that can clog up the system and reduce the porosity of the aquifer (Rinck-Pfeiffer et al. 2000; Vanderzalm et al. 2006; Pavelic et al. 2007). Clogging slows down flow rates and reduces the exposure of the water to beneficial microbes and invertebrates that break down a wide range of contaminants.

Although the costs of treatment for reclaiming and reusing water are significant, aquifer storage and recovery programs avoid the costs of constructing large reservoirs above ground. The belowground storage used in these programs also avoids blooms by toxic algae and cyanobacteria while minimizing the loss of water to evaporation and thereby minimizing increases in salinity. In addition, the public is often more willing to accept the use of reclaimed water that has been stored below ground over water coming directly from a water reclamation plant (Asano et al. 2007). The aquifer-stored and recovered water is perceived to have been enhanced by ecosystem processes associated with natural groundwater (Dillon et al. 2008).

6.) The San Joaquin River

The San Joaquin River in southern California is an example of management for irrigation waters that simultaneously provides water for environmental flows. Municipal water suppliers in southern California and local irrigators in the Imperial Irrigation District agreed on ways to increase water supply by increasing the efficiency of the infrastructure. The municipality funded improvements of irrigation canals by providing waterproof liners to minimize leakage. This adaptive approach is needed widely because water saved by avoiding losses from leakage can be made available for various municipal needs during drought and for environmental flows. Appropriate cooperation can also encourage water management agencies to build more retention, recycling, and reclamation systems by reducing water losses from leaky water distribution systems. Water utilities across the country have often deferred maintaining infrastructure because they lacked funding and were reluctant to increase prices. Costs for repairing and enhancing water infrastructures can be minimized in many regions by considering a wide range of options already used by communities in California, where drought management has been well developed.

Adaptation Policies

Extreme drought and flood events have occurred relatively often in some regions where successful adaptations have emerged. Some of these policies can be modified for use in other regions as climatic changes require adjustments. For example, as discussed above, policies dealing with regional water management using multiple, linked storage reservoirs for *water sharing* in the northeastern states (New York and Massachusetts) is likely to work elsewhere when the spatial distribution of drought impacts is uneven. Similarly, management of combined surface reservoirs and groundwater storage (conjunctive uses or aquifer storage recovery) for water banking has been developed over decades in several western states, especially California, by local governments and associations. Aspects of both of these multisourced management approaches can probably be modified for use in some southeastern and midwestern watersheds where prolonged drought and flood events are increasing in frequency. However, such changes will need wide discussion and planning for new infrastructure because these modifications will have added costs and will need to have the approval of local stakeholders and state and local agencies as well as federal agencies. Generally, permitting for water allocations is complex and slow to change when responding to long-term forecasts with high levels of uncertainty. This complexity is especially high when states are already engaged in legal challenges over regional allocations. Case studies discussed above from

California, New York, Georgia, Massachusetts, and Florida provide numerous examples of how large-scale, long-term analysis of nested watersheds and groundwater connectivity can be instructive in adjusting to the complexities of extreme events while sustaining ecosystem services and environmental flows.

Five Examples of Climate Effects and Associated Adaptive Responses.

1. Climate Effect: Drought severity will limit supplies of drinking water and municipal supplies; the physical structure of each watershed will modify the duration of the scarcity and alter the resiliency of adaptive responses.

Adaptive Response: Increase the use of water from groundwater sources and regionally scaled, interconnected surface sources, if available.

- Supplementary supplies can be obtained on a temporary basis during periods of scarcity in some regions by drilling more and deeper wells to increase groundwater supplies (if the number of wells can be limited to avoid adverse effects, e.g., saltwater intrusion or aquifer depletion).
- Water supplies will persist longer in larger, deeper rivers within larger watersheds, whereas supplies from small, shallow streams will be more subject to drying out and the loss of key species and ecosystem processes.
- Water supplies will also persist longer in deep storage reservoirs draining large, well-managed watersheds. Some of these reservoirs may have been designed originally for flood control rather than for water supplies during drought. This unexpected use of capacity designed for one use but later found to resolve new problems with a different use is an example of a shift in adaptive values and capacities.
- The reliability of water supplies can be increased by the use of interconnected multiple reservoirs ("multiple-lake chains"); it is possible to manage combined sources with different storage capacities in a coordinated regional approach to permit water sharing when one area has surplus storage.
- The reliability of water supplies can be increased by developing models to optimize the locations of new water storage reservoirs and to improve the management of existing reservoirs. This coordination enhances allocations of limited water for alternative uses and makes it possible to sustain environmental flows to protect biodiversity.
- Reliability can increase wherever groundwater supplies exist in belowground storage. Conjunctive storage among linked surface and subsurface storage capacities can be increased during wet periods with minimal loss of surplus water to evaporation.
- Additional supplies of water can be obtained in coastal areas by considering the costs of desalination relative to other alternatives that can rapidly supplement surface and subsurface water supplies.

- Other additional supplies can rapidly be obtained with low- or no-cost “soft” solutions, such as conservation among residential uses of water during the driest seasons and years.
- Additional water for nonagricultural uses, such as municipal or environmental needs, can be obtained by substituting crops that require minimal amounts of water during the stressful periods in place of crops that are less water efficient.
- Supplementing supplies of treated water with reclaimed water that can be used for irrigating lawns, landscaping, and crops saves high-quality water supplies for other uses.
- The distribution of water locally and regionally can be compared using the costs and effectiveness of building fewer large and deep above-surface reservoirs relative to more widely distributed small and shallow reservoirs. The trade-offs between local management and low costs or losses during transport can be evaluated relative to the reliability of large, deep storage reservoirs and losses to evaporation.
- The trade-offs of costs and benefits of small and large dams and storage reservoirs on biotic distributions can be compared to determine (a) how to minimize losses of essential biodiversity, (b) the susceptibility of invasive species, and (c) how to sustain ecosystem services.

2. Climate Effect: Drought severity will limit the seasonal availability of some sources of energy because supplies of freshwater for hydroelectric production and cooling waters will be scarce; the physical structure and location of each watershed will modify severity and resiliency as temperature increases and precipitation decreases.

Adaptive Response: Conserve the use of water and electrical power and increase efficiency through the improved design of cooling systems; increase seasonal supplies of energy from other regions with high river flows, if available.

- The demand for water for hydroelectric production and for cooling water for fossil fuel and nuclear power-generating plants can be reduced by using water or power from other, larger river sources.
- Where groundwater is available, spring-fed, cooler-water sources can be used to avoid the use of warmer water from river or lake sources.
- The seasonal use of air conditioning and refrigeration can be reduced to decrease demand for electric power when power generation is low.
- Increasing the efficiency of water reuse can minimize the quantity of water needed from rivers and lakes for cooling power-generating plants by recycling water from well-designed cooling ponds.
- Avoiding return flows of warm water from cooling systems can prevent the diminished water quality and habitat for cold-water fisheries that can result when flows return to the river or lake at warmer temperatures.

3. Climate Effect: Flood damage to infrastructure (e.g., dams, reservoirs, and water treatment plants) will increase the costs of maintaining water treatment, waste treatment and power-generating plants, especially in regions with older facilities or those with long periods of deferred maintenance.

Adaptive Response: Increase the vegetative cover in watersheds to improve water quality and minimize runoff.

- The integration of water management within watersheds to provide source-area protection can be improved by enhancing riparian and forest cover to minimize erosion and flooding. Appropriate vegetative cover can slow the rate of runoff and reduce the transport of sediments and nutrients that degrade downstream water quality.

Adaptive Response: Minimize the erosion of sediments within watersheds associated with floods.

- Monitoring sedimentation in rivers and reservoirs allows for a determination of how infilling of large and small reservoirs can reduce storage capacities, turbidity, and nutrient conditions over time.
- Land uses that result in high rates of sedimentation of reservoirs (e.g., urban development and agricultural practices) can be altered.
- Riparian corridors can be managed for the extreme high flows associated with tropical storms, hurricanes, and other major sources of flash floods. Establishing appropriate riverside vegetation can sustain biotic communities that minimize erosion and landslides.

Adaptive Response: Minimize water runoff by increasing the construction of retention structures (e.g., green roofs, small storage ponds, and sand-dam storage) and the restoration of headwater streams.

- The design of green buildings and landscapes can improve the infiltration of water to recharge groundwater and can minimize runoff that results in flooding.
- Headwater streams have often been enclosed in pipes to increase the rates of water transport and to establish dry land for development. These small streams can be reestablished by opening up the channels to increase the infiltration and recharge of groundwater while slowing the downstream transport of water and dissolved nutrients from nonpoint sources.

Adaptive Response: Broaden the capacity for rainwater harvesting as a supplement for local uses in watersheds.

- The installation of tanks to store grey water from residential uses or road runoff can increase limited water supplies and the potential for groundwater recharge (if storage facilities are properly maintained and water is kept clear of microbial risks and disease-transmitting vectors, such as mosquitoes).

Adaptive Response: Increase the construction of flood control reservoirs to provide alternative storage of water needed during dry periods.

- Breakdowns and malfunctioning of reservoir storage, storm flow, and wastewater treatment plants will require upgrades and improved long-term planning to locate new sites for the construction of additional deep storage reservoirs.

Adaptive Response: Reduce the demand for clean water during severe droughts and floods with public policies designed to provide essential supplies at low or no cost.

- Limited subsidies can encourage equitable allocations of scarce water by lowering costs for residential water fees for those with low incomes and can minimize social justice issues during extreme droughts. Costs for drilling new wells ("mining" groundwater) will increase dramatically as wealthy individuals and neighborhoods drive up the costs of coping with extreme conditions.
- If watersheds experience continued stressful effects of climate change, it may be cost-effective to move people to other locations. Short-term "migrations" such as those associated with severe hurricanes can temporarily reduce local demands for freshwater. Severe floods and droughts persisting in specific watersheds will provide opportunities to develop and test creative coping strategies among stakeholders and local, state, and federal organizations.
- Other mechanisms to subsidize supplies of residential waters can buy time to determine the best ways to cope with the severity of deleterious impacts.
- Water can be reallocated from those uses considered nonessential (e.g., car washes, swimming pools, and golf course irrigation) to essential uses if stakeholders and policymakers can reach consensus.

4. Climate Effect: Droughts and floods can cause landslides, change habitat quality, alter distributions of freshwater species, and result in a diminished capacity for ecosystem services.

Adaptive Response: Monitor habitat quality in critical regional habitats (e.g., deep lakes, persistent flows from deep springs, and large rivers) that serve as spatial and temporal refugia.

- Critical habitats can be managed to minimize the mortality of fish and shellfish (e.g., through restricted fishing during some seasons or years, limits on harvest, or increased catch-and-release regulations) to provide source populations for reestablishing wide distributions of species needed to sustain ecosystem services.
- Fish spawning areas can be monitored to determine if changes in sedimentation, substrata suitability, and habitat quality are in need of restoration.
- Comprehensive decision-support systems can include the total value (including economic, ecological, and social values) associated with biodiversity and ecosystem services. This analysis can be used to enhance allocations of limited supplies of high-quality water during periods of extreme stress (e.g., by restricting boating to avoid disrupting fish spawning grounds during certain seasons).

- Communicating the importance of the total value of ecosystem services will provide stakeholders with information on optional trade-offs to determine how allocations of water during dry periods can minimize long-term losses.

5. Climate Effect: Intense rainfall decreases water clarity and changes habitat quality for recreational fishing, boating, and swimming; severe drought reduces lake levels and restricts spawning habitats for fish and visitor access for recreational activities.

Adaptive Response: Increase the width of riparian buffer zones, evaluate the effectiveness of different types of current vegetation, and use best management practices to minimize bank and shoreline erosion. Stabilize and redesign boat ramps and provide access under different water levels and restrict access when appropriate.

- Sustaining water quantity and quality can maintain recreational activities and associated economic impacts in rural and urban areas.
- Restricting the harvest of commercial and recreational fisheries during extremely low- and high-water periods can provide some degree of protection by eliminating this source of mortality.
- Monitoring locations where vulnerable species occur and determining if rare species can be protected from extreme, stressful conditions can minimize local extinctions and the resulting impacts on ecosystem services by the loss of key species.
- Identifying the most vulnerable watersheds with assistance from NGOs and state and federal agencies can reduce risk of species losses in specific drainage basins.

Summary

Various types of climatic impacts will have distinct differences in the associated public health risks that can increase the costs of dealing with either very high or very low flows (Table 1). These extreme flows also affect biodiversity and sustainability of essential ecosystem services. Although the importance of biodiversity is widely recognized, the capacity to retain environmental flows and the key species that supply natural ecosystem services is not yet widely integrated into the long-term planning of water allocations and reservoir operations. New policies continue to emerge that require solutions to minimize environmental impacts. The economic costs for finding water to meet these environmental flows will increase whenever there is a need to supplement supplies during periods of water scarcity (Callaway 2004). Those higher costs can reduce options for sustaining environmental flows unless some transfers can be obtained from nearby sources that have periods of surplus water. Yet the long-term value of sustaining biodiversity by providing these environmental flows will increasingly be recognized by planners and stakeholders.

Many communities have a high capacity to adapt to climate changes by minimizing their economic losses resulting from extreme events and long-term trends. The ways in which they decide to supplement their water supplies during droughts and to store water during floods can be informed by a step-wise, integrative adaptive process similar to other types of adaptive management. Each option can be analyzed and evaluated for effectiveness to determine future best management practices (Holling 1978; Walters 1986, 2001; Habron 2003). The effects of high, medium, low, or extremely low flows have different likely options for responding by either storing water for later uses or finding water from newly defined groundwater sources (Table 1).

Periods of high flows provide opportunities to store water in large, deep reservoirs for use to maintain environmental flows in those periods where water is scarce. The fundamental challenge for many regions is to transfer some water from wet periods and regions for use in dry periods by a network of spatially distributed users with different sources and where there are different variations in precipitation. Although storing water at the surface in reservoirs is a common solution, much of this supply is lost to evaporation. As discussed above, the use of underground storage minimizes evaporation loss, but other issues become important. Large subsurface reservoirs are not available in many regions and, when they are available, they need to be recharged readily from surface supplies while retaining their high quality for use aboveground during dry periods. Such water banks are currently operating in Arizona, California, and elsewhere.

Meeting the demand for irrigation water in arid and semiarid areas while also sustaining future food production can be resolved in part by where crops are grown with different water demands and traded among locations to optimize water-use efficiency. If high water-demanding crops are exported to a dry region from a relatively wetter region, then the relatively drier area will not have to use local water supplies during extreme droughts. A transfer of water used to grow crops is a transfer of "virtual water"; this practice is increasing throughout many regions.

It has been clear for decades that the social complexities of the responses by individuals and communities increase with scarcity, but long-term planning and governmental agreements are required for interbasin transfers and these negotiations often take detailed discussions of options (Hanson et al. 2002; Burch and Robinson 2007). The needs for regional sharing of water will probably increase as different locations experience high variability in precipitation. The adaptive capacity to transfer surplus water from one watershed to another (i.e., to one that lacks water in any given year) will probably increase if the political and economic complexities can be resolved (Franck and Pompe 2005). Conjunctive uses of groundwater storage and surface water management are already moving water from one type of storage reservoir to another (Pulido-Velazquez et al. 2004; Park et al. 2007; Medellín-Azuara et al. 2008). Improved forecasting and infrastructure for effective transfers will provide for a sufficiently reliable basis for negotiating water exchanges during different years (Hartmann et al. 2002). These techniques will continue to require research and community-wide involvement. The importance of managing storage reservoirs to optimize multiple allocations that protect the biota, provide ecosystem services, and meet fluctuating needs for water supplies becomes clear as highly variable interannual extremes increase (Vogel et al. 1999; Labadie 2004; Jager and Smith 2008).

The adaptive process begins and ends with many decisions by diverse individuals and households on how they use water and how they value freshwater ecosystem services (Magnuson 2002; Gilg and Barr 2006; Lund et al. 2006; Brauman et al. 2007). Challenges will remain formidable even with the prospects for adaptive learning and technological changes to improve the efficiency of water storage, treatment, and conservation.

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