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Adaptations to Sustain High-Quality Freshwater Supplies in Response to Climate Change

Alan P. Covich[1]

As defined by the Intergovernmental Panel on Climate Change, adaptation includes a set of actions to moderate harm or exploit beneficial opportunities in response to climate change. To date, little research has addressed public policy options to frame the nation's approach to adapt to a changing climate. In light of scientific evidence of extreme and unpredictable climate change, prudent policy requires consideration of what to do if markets and people fail to anticipate these changes, or are constrained in their ability to react. This issue brief is one in a series that results from the second phase of a domestic adaptation research project conducted by Resources for the Future. The briefs are primarily intended for use by decisionmakers in confronting the complex and difficult task of effectively adapting the United States to climate change impacts, but may also offer insight and value to scholars and the general public. *This research was supported by a grant from the Smith-Richardson Foundation.*

Policy Recommendations

Scientists expect climate change to affect the availability and quality of freshwater in distinctive ways from those previously experienced. As a result, many current methods to provide sustainable water supplies during extreme droughts, floods, and hurricanes may not be effective. New approaches are needed to respond to these complexly linked, cumulative effects associated with extreme climatic changes. The following actions can help create a policy environment that encourages adaptive responses in times of hydrologic uncertainty.

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- To meet the increased demands for fresh water during periods of greater scarcity, regional adaptations will need to increase redundancy among natural and built systems to provide higher levels of functional resiliency. Planning will require frequent analyses of newly developed cooperative strategies to review both structural and non-structural responses.
- Organizations that now focus mostly on short-term responses to hurricanes, floods, and droughts will need to increase their effectiveness by linking regional and national levels of coordinated data collection and modeling to improve long-term forecasts and proactive, adaptive responses.
- Additional coordination of federal and state agencies will enhance adaptive responses through long-term strategic planning of shared solutions to water scarcity. These adaptations include new, properly located, deep storage reservoirs, optimal management of existing reservoirs, and shared information on the vulnerability of ecosystem services. Optimizing compatible land uses, floodplain protection, and urban design will increase groundwater recharge and storage during wet periods for use during dry periods.
- Newly developed and updated natural and built infrastructure will slow runoff and reduce erosion during floods with protected floodplains, expanded construction of green roofs, water gardens, retention ponds, and widely distributed storage reservoirs.
- Existing water-storage and treatment infrastructure is aging and needs thorough evaluation and upgrading. Agencies will need to monitor reservoir storage capacities because larger and more frequent floods increase sediment transport and infilling.
- Decoupling storm-flow runoff from systems connected to sewage treatment plants in urban and suburban basins will increase downstream water quality during floods and integrate centralized and decentralized natural infrastructure (e.g., wetlands and floodplains).
- Revision of the National Flood Insurance Program will need to consider the full, long-term costs of floods, such as losses of ecosystem services in floodplains and coastal zones. Visualization of possible floods will enhance communication, resulting in more resilience insurance programs that include planning for protected river corridors and greenways.
- Future forecasts based on observations from improved satellites and atmospheric modeling will provide longer lead times for effectively alerting the public to risks of extreme droughts, floods, and hurricanes and will enhance adaptive responses. Improved forecasts will decrease losses and help to avoid rapidly increasing insurance premiums.

- Engaging grassroots programs and diverse stakeholders working on responses to climate change will increase opportunities for teachers, students, and the general public to become more aware of regional and temporal variability in precipitation.
- Learning from regional comparisons of adaptive responses to extreme variations in freshwater availability can provide exchanges of innovative policies. In addition, some adaptive responses will need to develop at the national level as more individuals, agencies, and organizations work together across traditional lines of communication to learn from past limitations. This framework can increase awareness and communication about options for responding to seasonal and inter-annual variability of precipitation among participants across regions.

Introduction

Individuals and communities, as well as governmental and nongovernmental organizations, have developed some effective regional responses—such as increased water-use efficiency, water re-use, water markets, floodplain protection for groundwater recharge, and cooperative sharing during periods of water scarcity—that different regions can adopt more widely (e.g., Western Governors Association 2004; Lemos et al. 2007). These responses include ways to minimize economic and ecological losses to flooding such as providing incentives for protecting ecosystem services and not rebuilding in floodplains and other low-lying areas (e.g., Burby 2001, 2006). Improved sharing of information and policy innovation also increases economic resilience and adaptation through more geographically extensive risk-spreading agreements among insurance and reinsurance industries (e.g., Sturm and Oh 2010).

In general, adaptive capacity will increase as learning experiences are shared and modified to develop resilient socioecological systems. If these local solutions are more widely compared and improved, then what has worked well regionally under the new climatic conditions can be modified for use in other similar situations where incentives and investments in long-term responses are needed. If the anticipated extreme events strongly affect *different locations at different times*, then a regional analysis framework can:

- define natural and sociopolitical boundaries that provide responsive options for appropriate short-term and long-term decisionmaking processes; and
- determine how responses can be implemented over seasonal, annual, and decadal time scales as extremes in precipitation alter availability of water supplies.

Learning from comparisons of successfully coordinated responses will be effective in developing adaptive policies if each local community agrees to long-term cooperative planning for upgrading or expanding both natural and built infrastructure, and policy guidelines for water conservation practices. However, these adaptive responses may be severely constrained if abrupt changes occur frequently and extensively over several adjacent regions. Communities will need to consider additional constraints if some of these waters provide habitats for legally endangered species.

WHAT EFFECTS ON FRESHWATER SUPPLIES ARE EXPECTED?

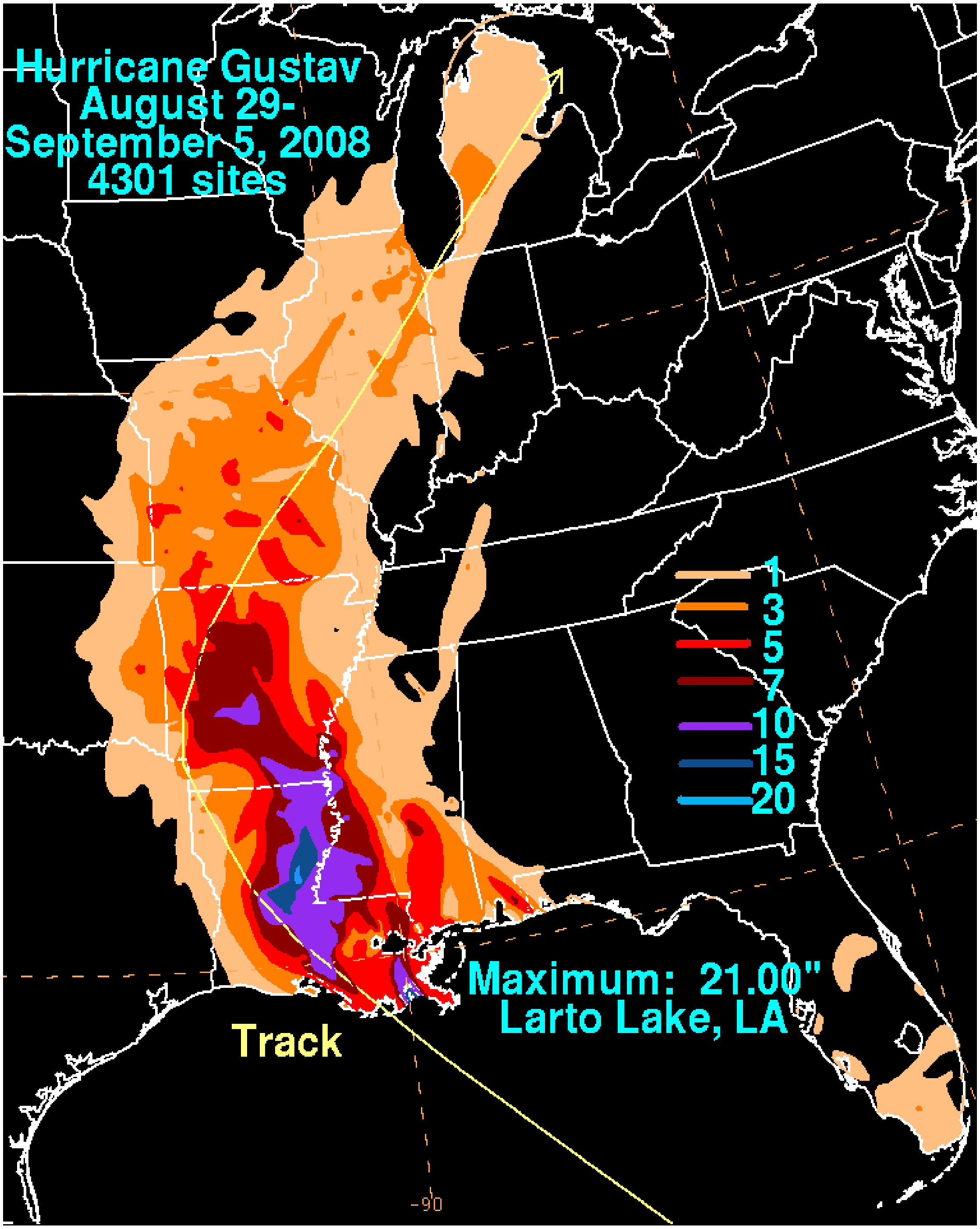
A warmer climate will likely alter current distributions of precipitation and result in decreased water storage in mountain snowpacks as well as increased evaporation from land, lake, and ocean surfaces (IPCC 2007; Bates et al. 2008; Karl et al. 2009). Climate models predict that many regions will have highly variable seasonal and inter-annual distributions of precipitation with more frequent and extreme storm events and droughts (Elsner 2006; Saunders and Lea 2008; Changnon 2009). Some models project nearly a doubling of the frequency of intense hurricanes by the end of the twenty-first century (Bender et al. 2010).

Hurricanes often cause flooding along the Atlantic and Gulf Coasts as well as considerable distance inland (Shepherd et al. 2007; Knight and Davis 2009). A potentially positive effect is that persistent, heavy rainfall can recharge groundwater sources and create “useful floods.” Other positive effects can occur if infrequent floods damage older facilities and accelerate updates to effective water and sewage treatment plants. Infrequent floods can also restore critical habitats for rivers by removing fine sediments and deepening pools in rivers. Deeper pools in rivers and streams remain cooler for longer periods during warm drought periods and are critical habitats for many species of fishes. These positive results can only occur if riparian forests, floodplains, and wetlands are protected to minimize erosion.

Negative impacts occur from the cumulative effects of more frequent flooding, increased bank erosion, and sedimentary infilling that decreases total storage capacity in reservoirs. For example, Hurricane Gustav followed Katrina and Rita within three years and resulted in major inland flooding and erosion (see Box A). Effects of these cumulative impacts from flooding and drought create additional uncertainty in predicting the supplies of high-quality water (Hallstrom and Smith 2005; Kallis 2008; Viscusi et al. 2008; National Science Foundation 2009).

During more frequent multi-year droughts, the demand for water will increase for providing irrigated agriculture, energy production, other industrial and municipal uses, recreational uses, and natural processes (Kundzewicz et al. 2008). Water demand will also grow rapidly as the production of biofuels increases its need for cooling and processing waters. Higher prices and unreliable freshwater supplies could limit energy and industrial production if fragmented planning results in slow or ineffectual adaptation to rapid changes in climate.

BOX A. Hurricane Gustav produced a total rainfall ranging from 6 to 12 inches over several states during its landfall (August 29 to September 5, 2008). Isolated maximum amounts exceeded 20 inches (see below).



Source: Image by David M. Roth, http://www.hpc.ncep.noaa.gov/tropical/rain/gustav2008filleddrainblk.gif/

WHAT EFFECTS ON WATER QUALITY ARE EXPECTED?

High-quality freshwater supplies are subject to increasing uncertainties regarding their turbidity and salinity resulting from climatic extremes, such as floods and droughts. Increased erosion along riverbanks and sewage treatment–plant overflows occur now during floods because many water treatment and sewage treatment facilities are located near rivers and coastal margins. These causes of water pollution and sedimentation likely will be more common during future storm surges and severe floods.

The U.S. Environmental Protection Agency (EPA) estimates that 160,000 systems supply drinking water (about 53,000 supply larger communities) and 1,600 municipal wastewater treatment facilities process 32,000 billion gallons per day (U.S. Environmental Protection Agency 2007). A comprehensive analysis to determine ways to drought- and flood-proof these operations would help to sustain the availability of high-quality water (National Research Council 2007).

During droughts, the water quality of sources from the increasingly shallow reservoirs, slow-moving rivers, and over-pumped groundwater will continue to decline. Saltwater intrusions along coastal aquifers will increase and greatly affect water quality. Consequently, insufficient supplies of high-quality water for market and non-market uses in the near future will likely result in major economic losses (Alcamo et al. 2007, 2008). These losses in the economic value of water are already significant. Local and regional planning agencies are just beginning to consider the anticipated additional losses of ecosystem services due to climatic change. Part of any "no regrets" response will require innovative approaches to protect the many species that provide essential ecosystem services needed to naturally recycle nutrients and to sustain water quality.

Policy Responses

Given the urgency in dealing with expected water-supply extremes, the United States needs a cross-agency task force to evaluate possible solutions among private individuals and groups, as well as state, tribal, and federal organizations across regions, by implementing six responses:

- Synthesizing multiple sources of climate-related data and their effects on reliability of the quantity and quality of water supplies to better coordinate communication.

  The federal government has several sources of climate data that are used for planning regional adaptive responses. At least 12 federal agencies and organizations (Table 1) and every state now collect climatic data related to water supplies. Although currently useful, with the expected climatic change, these data will require more comprehensive integration to identify gaps in coverage and provide online information centrally available to a wide array of potential users. These comprehensive assessments of research progress will increase communication and stimulate innovation regarding alternative adaptations to climatic extremes (Beller-Simms et al. 2008; National Research Council 2009a). The resulting new insights and planning processes will build the institutional capacity for monitoring and responding to unprecedented complexities caused by cumulative effects of climatic changes.

Progress in connecting related information is still slow. EPA's many inter-related responsibilities continue to expand but are often not well integrated. In 2002, for example, EPA's Office of Water established the Water Infrastructure Protection Division in the National Homeland Security Research Center to anticipate responses to terrorist attacks on the nation's water supplies. However, EPA has yet to take full advantage of the opportunities to learn from disasters such as Hurricane Katrina in responding to major breakdowns of water-treatment infrastructure (National Research Council 2007). The most secure locations of water treatment plants need to consider upgrading floodplain mapping and responding to likely risks such as sea-level rise. This comprehensive approach is being done in a few cases such in metropolitan Boston (Kirshen et al. 2008). It is increasingly important to evaluate the relative probabilities of threats to public health associated with disease and poor water quality resulting from aging infrastructure and natural disasters as well as from terrorist's attacks.

Table 1. U.S. Climate Centers Involved in Planning Long-Term Climate Impacts on Water Supplies

1. National Climate Data Center, National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce (each state has a center, plus six regional centers and a new National Integrated Drought Information System)
2. Climate Diagnostic Center
3. Climate Prediction Center
4. National Water and Climate Center, U.S. Department of Agriculture Natural Resources Conservation Service
5. National Climate Change and Wildlife Science Center, U.S. Geological Survey
6. Institute for Water Resources, Department of Defense, United States Army Corps of Engineers
7. Hydrologic Information Center, NOAA and the National Weather Service
8. National Integrated Drought Information System, NOAA and Western Governors' Association
9. U.S. Global Hydrology and Climate Center, supported by the National Aeronautics and Space Administration.
10. National Drought Mitigation Center, University of Nebraska
11. Center for Climate Strategies
12. Pew Center on Global Climate Change

- Providing stakeholders rapid access to integrated syntheses and online visualizations of changes in climate and water supplies (Brewer et al. 2006; Shepherd et al. 2007).

These information-providing services can stimulate innovative, proactive adaptive responses at multiple scales of local, regional, and national organization. Governmental agencies and private firms are producing increasingly effective, long-term forecasts. Specific quantitative triggers are providing earlier warnings of drought than before (Steinemann et al. 2006) that can be expanded and made more widely available. Data from sources such as satellite and airborne sensors provide imagery and weather reports that are coordinated to forecast floods, hurricanes, or droughts. For example, there are six- and twelve-week and online national drought-forecast maps. Much of the coordination is organized within the National Oceanic and Atmospheric Administration (NOAA) and the U.S. Geological Survey. These and other sources of integrated information will be enhanced when the National Science Foundation establishes the National Ecological Observatory Network in 2015 (Pennisi 2010). This network of more than 100 sites distributed across 20 climatic domains will track climate-driven changes in continental-scale ecosystem boundaries and biotic responses (Keller et al. 2008).

A major challenge remains to create interdisciplinary uses of these many sources of information in a timely manner that is understood by the public and practitioners (Vajjhala et al. 2007). The Western Governors' Association (2004) proposed centralizing drought information within NOAA through a new National Integrated Drought Information System (NIDIS). The resulting NIDIS Act of 2006 (Public Law 109-430) led to coordination of more than 40 agencies, states, and tribes as a means to enhance long-term, comprehensive planning (Brewer et al. 2006). The NIDIS is being developed to provide all water users access to online data. The website will help the public determine drought risks in near-real time so they can plan proactive adaptive responses before the onset of drought. [2]

A similar need exists for early-warning technologies and organizations that will integrate flood and hurricane forecasts. Although these forecasts are widely distributed, much of the public does not understand them. For example, storm surges that flood coastal zones and rapid inland flooding during hurricanes are generally more lethal than high winds, yet most people are alerted by information only on wind speed. The added value of improved hurricane forecasts on the paths and intensities of storms has been widely demonstrated in lowering losses to homeowners and industry (Sturm and Oh 2010). More integrated visualizations of combined impacts of extreme climatic events will

[2] For more information, visit http://www.drought.gov (accessed 2/8/2010).

increase communication of these future risks and provide for more innovative adaptive responses.

- Developing additional adaptive responses through new partnerships among universities, private, and governmental organizations.

  Several nationally integrated programs have stimulated academic and private development of new technology, sensors, and visualization software. These public–private collaborations likely will continue to increase effective forecasts and rapid communication as well as develop new insights.

- More frequently evaluating reviews of private and public successes and failures in meeting water demand in cross-agency analyses to determine the generality of adaptive processes.

  Online and published reviews by the Government Accountability Office (2002) and the National Research Council (2007, 2009a, 2009b) provide some analyses now, but not many planners or grassroots organizations know about them.

- Updating existing regulations and policies, such as the Clean Water Act, the Safe Drinking Water Act, and the National Environmental Protection Act, to determine how extreme climatic variability will affect needs and funding for increased monitoring and evaluation (Farber 2009).

  Each year new legislation is proposed that affects improved monitoring of water quality. Despite repeated reports calling for restructuring the federal responses to climate change legislation, the large number of congressional committees results in a lack of policy integration that affect the numerous threats to water quality and quantity.

- Lowering the risk of catastrophic losses.

  Federal initiatives such as the National Flood Insurance Program (NFIP) provide support for some such losses (Burby 2001, 2006; Travis 2010). However, the NFIP has not included adequate non-structural floodplain management. Federally subsidized, low-cost insurance stimulated rather than regulated development for a wide range of non-sustainable uses of critically important floodplains and coastal wetlands. As floods and coastal surges continue to increase the costs of this insurance, these losses cannot be externalized over the long term. Improved policies that restrict building and update floodplain mapping will identify ecologically important zones.

  Improved visualization of maps of risks associated with a 100-year flood could help individuals or communities better understand the impacts of increased flooding.

Moreover, individual landowners need better information about their ecologically based flood-proofing options and the rapidly changing locations of floodplains as shifts in land uses and climate affect erosion and flooding. Individuals, communities, and administrative agencies in these areas generally do not consider loss of critical ecosystem services as meeting the criteria for federal support. Yet, managing the floodplain for its natural capacity to slow flood waters and recharge groundwater has significant ecological and economic value in a world of changing climatic extremes. Moving beyond the historic approaches to protecting development in floodplains to managing and sustaining ecosystem services will need to be an important policy shift. The NFIP currently has a $19 billion debt, and losses will likely increase as more extreme floods occur in highly developed areas (Holladay and Schwartz 2010).

Large private insurance companies are at the forefront of climate change research to estimate risks. In cooperation with federal agencies, they can play major roles in informing individuals and communities on risks of floods and hurricanes. They can work with lending sources to encourage development outside vulnerable floodplains and coastal zones. Online data demonstrate that over 1989–2008, hurricanes and tropical storms made up 46.9 percent of total catastrophe losses, with $62.3 billion in losses for 2005, the year of Hurricanes Katrina and Rita. The Katrina losses are by far the highest, with its total reaching $45.3 billion (Insurance Information Institute 2010). Future storms are expected to be even costlier, reaching perhaps $100 billion (Insurance Information Institute 2008).

Many insurance companies are facing greater risks of significant losses from more frequent and widespread destructive weather events because populations and economic developments are often concentrated in high-risk coastal zones, floodplains, and urban centers (Mills 2007; Kunreuther and Michel-Kerjan 2009a, 2009b; Sturm and Oh 2010). Most policies focus on hurricanes and floods, not droughts. Federal- and state-funded programs that attempt to provide assistance will be increasingly in need of major revisions to innovate ways of spreading their risks and sustain supplies of essential water resources.

WHAT POLICY ADAPTATIONS LIKELY WILL WORK?

Providing reliable supplies of freshwater in a world of increased drought and flooding will require improved communication, low-interest loans, and pricing mechanisms for different water uses. Incentives are needed to accelerate learning about what works well under different climatic conditions. These innovations can lead to “pre-positioned policies” as defined by Smith (2010). In the first phase of policy development, identifying benefits that can lead to cooperative, long-term planning across watershed boundaries will help individuals and agencies adapt to droughts by increasing their investments in water reuse, storage, and conservation. In the next phase, newly developed and updated infrastructure will need to slow runoff during floods with expanded construction of green roofs, water gardens, storage ponds, and reservoirs. More planning of alternative land uses and urban design will focus on increasing groundwater storage during wet periods for use during dry periods. Decoupling storm-flow runoff from systems connected to sewage treatment plants in urban and suburban basins will require increased investments in centralized and decentralized infrastructure. Strategically updating and replacing storm-damaged major infrastructure will be an important component in adapting to climatic extremes (Neumann 2009; Neumann and Price 2009). Once these responses are implemented, the water-intensive economic sectors of agriculture and industry likely will remain in water-rich locations (or relocate to seek other regions) with effective long-term planning and policies that provide the highest chances of assured “safe yields.” Sorting out which crops are grown and which industries can be competitive in specific areas will increasingly depend on water availability and regional efforts to create long-term solutions to climate-driven variability in precipitation.

Improved agreements for sharing water whenever possible will increase efficiency of allocations during periods when some locations have floods while others have droughts. Increases in lake levels and surplus storage in some nearby locations can provide opportunities for transferring water to other locations when needed. Developing long-term agreements for reciprocal sharing of water has been successful in a number of regions (Ambec and Sprumont 2002; Alam et al. 2009). For example, the recent Great Lakes–St. Lawrence River Basin Water Resources Compact provides comprehensive coordination of water uses among the United States and Canada, including a large number of metropolitan, local, and county governments from 8 states, 2 provinces, and 49 tribal nations. This agreement developed after 10 years of discussions regarding earlier plans for water transfers outside the basin (Froelich Sponberg 2009). More such agreements are likely to be used in other regions that will begin to experience extreme variability in precipitation, such as in the Southeast, where these effects have been examined for decades (Hawk 1997; Moore 1999; National Research Council 2009b).

Without sufficient groundwater storage and in-channel or off-channel reservoirs, extreme fluctuations in runoff and discharge will make the sharing of any surplus water much more difficult. This variability in runoff and discharge alters rates of nutrient inputs to rivers (and reservoirs) from many types of point (outflow pipe–level) and non-point (landscape-level) sources of nitrogen and phosphorus. These effluents create complex trade-offs in sustaining water quality. The expected climate change impacts will make these analyses even more complex and will require enhanced technology, a nationally coordinated planning strategy, and updated state and federal regulation.

Challenges Confronting Future Adaptive Responses

Policies to lower the numerous risks from climatic impacts have developed over many decades in response to infrequent economic losses from droughts, hurricanes, and floods. These past losses were much smaller than those expected to occur in the future (Farber 2009; Kousky and Cooke 2009; Neumann 2009; Schmidt et al. 2010). In general, previous policies at the state and local levels—for example, some regional water-sharing compacts—are not likely to be sufficient if the predicted trends in climate changes occur. Some regional compacts currently in place for sharing water may only be able to develop new modifications if the climatic changes are relatively slow and local. As with other types of adaptive responses, if changes are simultaneous, widespread, abrupt and extreme, the past organizational structures and policies will need rapid revision. In some regions where water quality and quantity are already limited, the inherent capacity for modifying existing solutions may not be sufficiently robust and resilient.

Many current policies rely on forecasts of droughts, floods, and hurricanes that are based on long records of major climatic oscillations. These meteorological principles for forecasting may not continue to function effectively because the past climatic database is likely a poor predictor of the future. Researchers' considerations of "black swans" and "fat tails" (Taleb 2007; Kousky and Cooke 2009, 2010) examine in detail the inadequacy of data for making predictions about rare events. These "rare" climatic events often cannot be predicted because sufficiently long historic records of climatic variable are lacking in many locations.

Cumulative Effects and Surprises

As the global climate changes, "surprises" can occur if the major impacts are more frequent, extreme, and widespread than in the past, to the point that the cumulative impacts are fundamentally different. Solutions that worked well in the past when droughts were rare and local likely will be ineffective if the impacts are more widely distributed geographically and have a cumulative effect on economic and ecological responses.

Future El Niño-Southern Oscillation forecasts that have longer lead times for alerting the public to risks of droughts, floods, and hurricanes will enhance rapid adaptive responses. Some of these forecasts are based on the importance of the Central Pacific Warming and El Niño-Southern Oscillation patterns, as well as other possible sources of sea-surface warming determined by satellites. These episodic periods of warming affect lead time (ranging from a few days to months) and seasonal forecasts of hurricanes. These forecasts are already sufficiently specific to estimate the general locations of landfalls that can trigger massive inland flooding. Warnings regarding flash floods are usually short-lead-time predictions with variable warning times for the public to respond (hours to days).

Responses to future extreme events can be improved by learning from the results of Hurricane Katrina, an important case study (Landy 2010). This event was predicted well in advance and demonstrates the long-run importance of sustaining natural infrastructure, such as wetlands and floodplains, as well as engineering infrastructure to prepare for unexpected consequences. These natural and built infrastructures are partially redundant, and when well integrated, they can provide combined sources of protection. However, the cascade of interdependent disturbances and the amplification of loss were much greater than expected in the case of Katrina; this catastrophic event resulted in hazards increasing the risks of other hazards (Kousky and Cooke 2009). If a greater extent of wetlands had been protected along the Gulf coastal zone rather than developed, the wetland buffer could have minimized the effects of storm surges and the compounding damages along the coast during Katrina (Day et al. 2008). The value of these natural buffers will continue to be studied in preparation for the next storm surge. However, these wetlands likely will be even more vulnerable following the cumulative effects of other hurricanes, shipping channels, pipelines, oil spills, and clean-up activities.

Legislation to protect water quality and quantity has developed over decades during periods that climatologists have recently determined were "unusually wet." They predict that the future will be drier in many regions, such as the southwestern United States, and more highly variable in all regions. As droughts increase the residence times of stored water in reservoirs, sediments have a longer lead time to release excess nutrients into the overlying water. These warm, nutrient-rich waters are prime habitats for cyanobacteria that cause serious taste and odor problems in drinking water, and, in some cases, these microbes can release toxic substances (Paerl and Huisman 2009).

It is not clear if the current operational definitions of water-quality parameters in the Clean Water Act and the Safe Drinking Water Act will be effective in a world of changed climate with extremely variable flows. Updating these regulations and funding more intensive, frequent monitoring will be needed to provide reliable sources of municipal drinking water. Improvements in water treatment and distribution systems will need to detect and repair leaks that lose water and increase risks of contamination.

Perceptions of Costs of Climate Impacts on Drinking-Water Quality

Consumers have consistently expressed concern over the quality of drinking water and are willing to pay more for what they perceive as higher levels of purity. These avoidance costs will likely increase whenever public water supplies have an outbreak of waterborne diseases or episodes of taste and odor problems as a result of either too little dilution of nutrients during droughts or inadequate treatment-plant operations during floods. The reliable production of clean "raw" water through natural ecosystem processes saves costs of downstream treatment by reducing the amounts of suspended sediments and dissolved nutrients. These savings are especially important during major floods when reliability of water-supply treatments may be compromised and less effective. Increased turbidity, contamination of rivers by overflowing wastewater treatment plants, and overall potential for less effective functioning of ecological and engineering systems can increase water treatment costs (Curriero et al. 2001).

Outbreaks of gastrointestinal illnesses associated with *Giardia, Clostridium, Cryptosporidium*, and other pathogens are associated with flood events and inadequate water treatment processes (Hrudey and Hrudey 2007). The frequency and intensity of these water-borne diseases increase when floodplains and source areas are used for intensive livestock production within riparian zones, resulting in increased erosion and nutrient runoff. Pathogens also increase in abundance and diversity from poorly designed and maintained sewage treatment plants and municipal drinking-water plants. By protecting riparian buffer zones and reducing erosion, fewer nutrients and pathogens enter rivers and reservoirs, lowering the likelihood of disease outbreaks and improving the quality of water *before* it enters treatment plants.

Infrastructural Constraints on Increased Storage Options

The past incentives to build storage reservoirs to control floods and provide clean water during droughts have resulted in the construction of a large number of dams that reached its peak in the 1980s. The number of smaller reservoirs has increased over several decades, but sedimentation and infilling have often reduced storage capacity in older reservoirs (Downing et al. 2006). In general, water-related infrastructure (e.g., drinking-water treatment plants, wastewater treatment plants) is not likely to meet the future needs for water storage and flood control given that more frequent and intense droughts and flood events are anticipated. For example, although the Federal Energy Regulatory Commission analyzes the effectiveness of dams that supply hydropower, the current 50-year interval for reservoir evaluations will need to be shorter if climate impacts become more important.

Fewer reservoirs have been constructed in recent decades than in the past because of changes in the federal-funding formula, increased costs, lack of appropriate construction sites, and frequent opposition by conservation groups concerned with loss of riverine species. Dredging existing reservoirs to increase storage capacities is costly, and distributions of dredged materials are legally complex due to toxins that often accumulate in sediments. Consequently, construction of new surface storage reservoirs is a costly process that is not likely to keep up with increased needs for flood control, water supplies, and hydropower.

To avoid evaporative losses from surface reservoirs, below-ground storage of surplus water during wet periods for later use during droughts will likely increase in some regions. Linked surface and groundwater storage is used in the southwestern states (e.g., Arizona, California). The public is apparently willing to accept use of reclaimed water that has been stored below ground more than water coming directly from a water reclamation plant (Asano et al. 2007). However, some states, such as Georgia, have banned pumping surface water into natural aquifers because the environmental costs of aquifer storage and recovery include the possible depletion or contamination of aquifers. Consequently, aquifer storage and recovery is controversial because of major risks associated with contamination of high-quality natural groundwater by low-quality water being pumped into the aquifer for storage.

The limits of below-ground storage, increased costs of reservoir construction, and high costs of retrofitting dams will likely help accelerate development of cooperative agreements for shared benefits among a number of linked reservoirs, groundwater sources, increased water-use efficiency, and recycling technologies. New agreements and infrastructure for transporting stored water among surface and sub-surface storage sites will likely become part of more regional strategies to increase reliability of supplies. These agreements to share or purchase water could provide more long-term reliability if appropriately planned and managed.

Conclusions

A comprehensive review of current water policies will update and coordinate fragmented approaches to resolve ways to meet unprecedented future needs for fresh water given anticipated extremes in precipitation and temperature. The planning process will need to move beyond considering only direct effects of warming in order to adapt to much wetter and much drier conditions. These extremes in distributions of precipitation likely will challenge plans to provide reliable municipal, agricultural, industrial, and residential water supplies. New approaches and plans will help regions share more data and benefits while determining additional regional solutions to limited water supplies.

Upgraded water storage and treatment infrastructure will allow communities to meet future needs and improve plans for long-term protection of ecological diversity, which sustains the natural processes that help provide clean water. Analyses need to optimize management of a wide range of post-construction potential benefits, such as water storage that sustains the essential biodiversity and floodplain functions. Natural ecosystem services can improve flood control and groundwater recharge (Strange et al. 1999; Loomis et al. 2000; Bunn et al. 2006; Farber et al. 2006; Loehman and Loomis 2008). These values need to be considered in revised federal flood protection insurance programs. Coordinated management benefits of controlled flows can help to restore natural-flow regimes. Ecosystem-based decisions will provide an effective mix of shared benefits at regional scales (Covich et al. 2004; Heal et al. 2005; Covich 2009a, 2009b).

Wider use of recycled water can result from development of improved methods in several regions (Marks and Zadoroznyj 2005). A cross-agency task force will enhance the integration of emerging regional and national plans from different state and federal agencies as well as nongovernmental organizations. Over the next decade, it will be important to determine which governmental agency or new organization is most likely to develop and coordinate these needed policies at regional and national levels. Several candidate agencies reflect the present efforts to make data on national water uses widely available. The U.S. Geological Survey provides integrated analyses of watershed-level supply sources. The recent formation within NOAA of the National Integrated Drought Information System, which has effectively created a public drought portal, is a good beginning at coordinating a wide range of information sources.

Responses to both short- and long-term extremes in precipitation can provide a cost-effective solution to increasingly complex worst-case scenarios characterized by interactive cumulative effects of floods and droughts. Engaging the public to find new ways to conserve water can provide sufficient environmental flows to sustain natural ecosystem services and ensure both the quality and quantity needed in the decades ahead.

References

Alam, Undala, Ousmane Dione, and Paul Jeffrey. 2009. The Benefit-Sharing Principle: Implementing Sovereignty Bargains on Water. *Political Geography* 28(2): 90–100.

Alcamo, J., M. Flörke, and M. Märker. 2007. Future Long-Term Changes in Global Water Resources Driven by Socio-economic and Climate Changes. *Hydrological Sciences Journal* 52(2): 247–75.

Alcamo, J., L. Acosta-Michlik, A. Carius, F. Eierdanz, R. Klein, D. Krömker, and D. Tänzler. 2008. A New Approach to Quantifying and Comparing Vulnerability to Drought. *Regional Environmental Change* 8(4): 137–49.

Ambec, S., and Y. Sprumont. 2002. Sharing a River. *Journal of Economic Theory* 107(2): 453–62.

Asano, T., F.L. Burton, H.L. Leverenz, R. Tsuchihashi, and G. Tchobanoglous. 2007. *Water Reuse: Issues, Technologies and Applications*. New York: McGraw Hill.

Bates, B., Z.W. Kundzewicz, S. Wu, and J. Palutikof (eds.). 2008. Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change. Geneva, Switzerland: IPCC Secretariat.

Beller-Simms, N., H. Ingram, D. Feldman, N. Mantua, K.L. Jacobs, and A. Waple (eds.). 2008. Decision-Support Experiments and Evaluations Using Seasonal to Inter-annual Forecasts and Observational Data: A Focus on Water Resources. Synthesis and Assessment Product 5.3. Washington, DC: Climate Change Science Program and Subcommittee on Global Change Research.

Bender, Morris A., Thomas R. Knutson, Robert E. Tuleya, Joseph J. Sirutis, Gabriel A. Vecchi, Stephen T. Garner, and Isaac M. Held. 2010. Modeled Impact of Anthropogenic Warming on the Frequency of Intense Atlantic Hurricanes. *Science* 327(5964): 454–58.

Brewer, Michael, Tim Owen, Roger Pulwarty, and Mark Svoboda. 2006. *National Integrated Drought Information System (NIDIS): A Model for Interagency Climate Services Collaboration*. Silver Spring, MD: National Oceanic and Atmospheric Administration.

Bunn, Stuart, N. LeRoy Poff, and Robert J. Naiman. 2006. The Challenge of Providing Environmental Flow Rules to Sustain River Ecosystems. *Ecological Applications* 16(4): 1311–18.

Burby, Raymond J. 2001. Flood Insurance and Floodplain Management: The US Experience. *Environmental Hazards* 3 (3–4): 111–22.

Burby, Raymond J. 2006. Hurricane Katrina and the Paradoxes of Government Disaster Policy: Bringing About Wise Decisions for Hazardous Areas. *Annals of the American Academy of Political and Social Science* 604: 171–91.

Changnon, Stanley A. 2009. Characteristics of Severe Atlantic Hurricanes in the United States: 1949–2006. *Natural Hazards* 48(3): 329–37.

Covich, Alan P. 2009a. *Emerging Climate Change Impacts on Freshwater Resources: A Perspective on Transformed Watersheds*. Washington, DC: Resources for the Future.

Covich, Alan P. 2009b. Biodiversity of Aquatic Ecosystems. In *Encyclopedia of Inland Waters Vol. 1*, edited by G.E. Likens. Amsterdam, The Netherlands: Elsevier, 379–86.

Covich, A.P., K.C. Ewel, R.O. Hall, P.G. Giller, D.M. Merritt and W. Goedkoop. 2004. Ecosystem Services Provided by Freshwater Benthos. In *Sustaining Biodiversity and Ecosystem Services in Soils and Sediments*, edited by D.H. Wall. Washington, DC: Island Press, 45–72.

Curriero, Frank C., Jonathan A. Patz, Joan B. Rose, and Subhash Lele. 2001. The Association between Extreme Precipitation and Waterborne Disease Outbreaks in the United States, 1948–1994. *American Journal of the Public Health Association* 91(8): 1194–99.

Day, John W., Robert R. Christian, Donald M. Boesch, Alejandro Yáñez-Arancibia, James Morris, Robert R. Twilley, Larissa Naylor, Linda Schaffner and Court Stevenson. 2008. Consequences of Climate Change on the Ecogeomorphology of Coastal Wetlands. *Estuaries and Coasts* 31(3): 477–91.

Downing, J.A., Y.T. Prairie, J.J. Cole, C.M. Duarte, L.J. Tranvik, R.G. Striegl, W.H. McDowell, P. Kortelainnen, N.F. Caraco, J.M. Melack, and J.J. Middelburg. 2006. The Global Abundance and Size Distribution of Lakes, Ponds, and Impoundments. *Limnology and Oceanography* 51(5): 2388–97.

Elsner, James B. 2006. Evidence in Support of the Climate Change—Atlantic Hurricane Hypothesis. *Geophysical Research Letters* 33: L16705.

Farber, Dan. 2009. A Legal Framework for Climate Adaptation Assessment. Issue Brief 09-14. Washington, DC: Resources for the Future.

Farber, S., R. Costanza, D.L. Childers, J. Erikson, K. Gross, M. Grove, C.S. Hopkinson, J. Kahn, S. Pincetl, A Troy, P. Warren, and M. Wilson. 2006. Linking Ecology and Economics for Ecosystem Management. 2006. *BioScience* 56(2): 117–29.

Froelich Sponberg, Adriene. 2009. Great Lakes: Sailing through to the Forefront of National Water Policy? *BioScience* 59(5): 372.

Government Accountability Office. 2002. Water Infrastructure: Information on Financing, Capital Planning and Privatization. Washington, DC: GAO 02-764.

Hallstrom, D.G., and V.K. Smith. 2005. Market Responses to Hurricanes. *Journal of Environmental Economics and Management* 50(3): 541–61.

Hawk, Mary. 1997. Interstate Compacts: Allocate Surface Water Resources from the Alabama-Coosa-Tallapoosa River Basin between Georgia and Alabama; Allocate Water Resources from the Apalachicola-Chattahoochee-Flint River Basin among Alabama, Florida and Georgia. *Georgia State University Law Review* 14: 47–56.

Heal, G.M., E.B. Barbier, K.J. Boyle, A.P. Covich, S.P. Gloss, C.H. Hershler, J.P. Hoehn, C.M. Pringle, S. Polasky, K. Segerson, and K. Shrader-Frechette. 2005. *Valuing Ecosystem Services: Toward Better Environmental Decision-Making*. Washington, DC: National Research Council.

Holladay, J. Scott, and Jason A. Schwartz. 2010. Flooding the Market. New York University School of Law Policy Brief No. 7. New York: Institute of Policy Analysis.

Hrudey, S.E., and E.J. Hrudey. 2007. Published Case Studies of Waterborne Disease Outbreaks—Evidence of a Recurrent Threat. *Water Environment Research* 79(3): 233–45.

IPCC (Intergovernmental Panel on Climate Change). 2007. Summary for Policymakers. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson. Cambridge, UK, and New York: Cambridge University Press, 7–22.

Insurance Information Institute. 2008. Hurricane Gustav Heads Toward U.S. Gulf Coast on Third Anniversary of Hurricane Katrina's Arrival. Press release, August 29. http://www.iii.org/media/updates/press.796552/index.html/ (accessed 2/10/2010).

Insurance Information Institute. 2010. Catastrophes: Insurance Issues. http://www.iii.org/media/hottopics/insurance/catastrophes/ (accessed 2/10/2010).

Kallis, Giorgos. 2008. Droughts. *Annual Review of Environment and Resources* 33: 85–118.

Karl, Tom R., Jerry M. Melillo, and T.C. Peterson. 2009. *Global Climate Change Impacts in the United States*. Cambridge, UK, and New York: Cambridge University Press.

Keller, Michael, David S. Schimel, William W. Hargrove and Forrest M. Hoffman. 2008. A Continental Strategy for the National Ecological Observatory Network. *Frontiers in Ecology and the Environment* 6(5): 282–84.

Knight, David B., and Robert E. Davis. 2009. Contribution of Tropical Cyclones to Extreme Rainfall Events in the Southeastern United States. Journal of Geophysical Research 114: D23102. doi:10.1029/2009JD012511

Kirshen, P., M. Ruth, and W. Anderson. 2008. Interdependencies of Urban Climate Change Impacts and Adaptation Strategies: A Case Study of Metropolitan Boston USA. *Climatic Change* 86(1–2): 105–22.

Kousky, Carolyn, and Roger M. Cooke. 2009. *Climate Change and Risk Management: Challenges for Insurance, Adaptation and Loss Estimation*. Washington, DC: Resources for the Future.

Kousky, Carolyn, and Roger M. Cooke. 2010. Adapting to Extreme Events: Managing Fat Tails. Issue brief 10-12. Washington, DC: Resources for the Future.

Kundzewicz, Z.W., L.J. Mata, N.W. Arnell, P. Döll, B. Jimenez, K. Miller, T. Oki, Z. Şen, and I. Shiklomanov. 2008. The Implications of Projected Climate Change for Freshwater Resources and Their Management. *Hydrological Sciences Journal* 53(1): 3–10.

Kunreuther, Howard, and Erwann Michel-Kerjan. 2009a. *At War with the Weather: Managing Large-Scale Risks in a New Era of Catastrophes*. Cambridge, MA: MIT Press.

Kunreuther, Howard, and Erwann Michel-Kerjan. 2009b. Encouraging Adaptations to Climate Change: Long-Term Flood Insurance. Issue brief 09-13. Washington, DC: Resources for the Future.

Landy, Marc. 2010. Climate Adaptation and Federal Megadisaster Policy: Lessons from Katrina. Issue brief 10-02. Washington, DC: Resources for the Future.

Lemos, Maria Carmen, Emily Boyd, Emma L. Tompkins, Henny Osbahr, and Diana Liverman. 2007. Developing Adaptation and Adapting Development. *Ecology and Society* 12(2): 26.

Loehman, E., and J. Loomis. 2008. In-Stream Flow as a Public Good: Possibilities for Economic Organization and Voluntary Local Provision. *Review of Agricultural Economics* 30(3): 445–56.

Loomis, J., P. Kent, L. Strange, K. Fausch, and A. Covich. 2000. Measuring the Total Economic Value of Restoring Ecosystem Services in an Impaired River Basin; Results from a Contingent Valuation Survey. *Ecological Economics* 33(1): 103–17.

Marks, June S., and Maria Zadoroznyj. 2005. Managing Sustainable Urban Water Reuse: Structural Context and Cultures of Trust. *Society and Natural Resources* 18(6): 557–72.

Mills, Evan. 2007. Synergisms Between Climate Change Mitigation and Adaptation: An Insurance Perspective. Mitigation and Adaptation Strategies for Global Change 12(5): 809-842.

Moore, C. Grady. 1999. Water Wars: Interstate Water Allocation in the Southeast. *Natural Resources and Environment* 14: 5–10.

National Research Council. 2007. *Improving the Nation's Water Security: Opportunities for Research.* Washington, DC: National Academies Press.

National Research Council. 2009a. *Restructuring Federal Climate Research to Meet the Challenges of Climate Change*. Washington, DC: National Academies Press.

National Research Council. 2009b. *Summary of a Workshop on Water Issues in the Apalachicola-Chattahoochee-Flint and Alabama-Coosa-Tallapoosa (ACF-ACT) River Basins*. Washington, DC: National Academies Press.

National Science Foundation. 2009. *Transitions and Tipping Points in Complex Environmental Systems*. Advisory Committee on Environment and Education Report to the National Science Board. Washington, DC: National Science Foundation.

Neumann, James E. 2009. Adaptation to Climate Change: Revisiting Infrastructure Norms. Issue brief 09-15. Washington, DC: Resources for the Future.

Neumann, James E., and Jason C. Price. 2009. *Adapting to Climate Change: The Policy Response—Public Infrastructure*. Washington, DC: Resources for the Future.

Paerl, Hans W., and Jef Huisman. 2009. Climate Change: A Catalyst for Global Expansion of Harmful Cyanobacterial Blooms. *Environmental Microbiology Reports* 1(1): 27–37.

Pennisi, Elizabeth. 2010. A Groundbreaking Observatory to Monitor the Environment. *Science* 328(5977): 418–420.

Saunders, M.A., and A.S. Lea. 2008. Large Contributions of Sea Surface Warming to Recent Increase in Atlantic Hurricane Activity. Nature 401: 557–560. doi:10.1038/nature06422.

Schmidt, Silvio, Caludia Kemfert, and Peter Höppe. 2010. The Impact of Socio-economics and Climatic Change on Tropical Cyclone Losses in the USA. *Regional Environmental Change* 10(1): 13–26.

Shepherd, J.M., A. Grundstein, and T.L. Mote. 2007. Quantifying the Contribution of Tropical Cyclones to Extreme Rainfall along the Coastal Southeastern United States. *Geophysical Research Letters* 34: L23810.

Smith, V. Kerry. Forthcoming. Pre-positioned Policy as Public Adaptation to Climate Change. Issue brief. Washington, DC: Resources for the Future.

Steinemann, A.C., M. Hayes, and L. Cavalcanti. 2006. Drought Indicators and Triggers. In *Drought and Water Crises: Science, Technology, and Management Issues*, edited by D. Wilhite. New York: Dekker, 71–82.

Strange, Elizabeth M., Kurt D. Fausch, and Alan P. Covich. 1999. Sustaining Ecosystem Services in Human-Dominated Watersheds: Biohydrology and Ecosystem Processes in the South Platte River Basin. *Environmental Management* 24(1): 39–54.

Sturm, Tristan, and Eric Oh. 2010. Natural Disasters as the End of the Insurance Industry? Scalar Competitive Strategies, Alternative Risk Transfers, and the Economic Crisis. *Geoforum* 41: 154–63.

Taleb, Nassim N. 2007. *The Black Swan: The Impact of the Highly Improbable*. New York: Random House.

Travis, William R. 2010. Going to Extremes: Propositions on the Social Response to Severe Climate Change. *Climatic Change* 98(1–2): 1–19.

U.S. Environmental Protection Agency. 2007. *Drinking Water Infrastructure Needs Survey and Assessment. Fourth Report to Congress*. EPA-816-R-09-001. Washington, DC: EPA Office of Water.

Vajjhala, S., A. Krupnick, E. McCormick, M. Grove, P. McDowell, C. Redman, L. Shabman, and M. Small. 2007. *Rising to the Challenge: Integrating Social Science into NSF Environmental Observatories.* Washington, DC: Resources for the Future.

Viscusi, W. Kip, Joel Huber, and Jason Bell. 2008. The Economic Value of Water Quality. *Environmental Resource Economics* 41(2): 169–87.

Western Governors Association. 2004. *Creating a Drought Early Warning System for the 21st Century: The National Integrated Drought Information System*. Western Governors Report. Denver, CO: Western Governors Association.