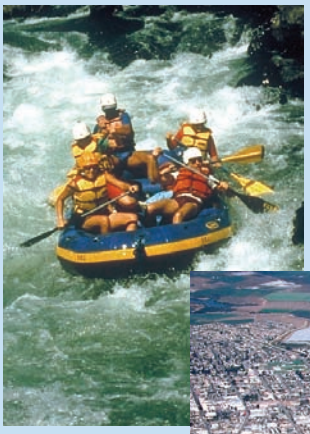
A Strategy for Federal Science and Technology to Support Water Availability and Quality in the United States



September 2007

A Strategy for Federal Science and Technology to Support Water Availability and Quality in the United States

Report of the

NATIONAL SCIENCE AND TECHNOLOGY COUNCIL
COMMITTEE ON ENVIRONMENT AND NATURAL RESOURCES

Subcommittee on Water Availability and Quality

September 2007

EXECUTIVE OFFICE OF THE PRESIDENT
NATIONAL SCIENCE AND TECHNOLOGY COUNCIL
WASHINGTON, D.C. 20502

September 4, 2007

Dear Colleague:

The United States has reaped the benefits of abundant and reliable supplies of fresh water since its founding. However, the impacts of population growth, development, and climate change are placing increasing stress on our Nation's water supplies. For example, a recent Government Accountability Office study determined that 39 U.S. states anticipate some level of water shortage within the next decade.

The Subcommittee on Water Availability and Quality of the National Science and Technology Council's Committee on Environment and Natural Resources was established to consider this issue. The Subcommittee was charged with: (1) identifying science and technology needs to address the growing issues related to fresh water supplies, (2) developing a coordinated, multi-year plan to improve research to understand the processes that control water availability and quality, and (3) enhancing the collection and availability of the data needed to ensure an adequate water supply for the Nation's future.

This report is a result of that interagency collaboration. It provides an overview of the set of challenges that face us in our pursuit of adequate fresh water supplies, lays out the research priorities associated with those challenges, and provides recommendations for a federal science strategy to address this important issue.

Sincerely,

John H. Marburger III
Director, Office of Science and Technology Policy
Science Advisor to the President

CONTENTS

TEXTBOXES

MEMBERS OF THE SUBCOMMITTEE ON WATER AVAILABILITY AND QUALITY

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Robert M. Hirsch, U.S. Geological Survey, Co-Chair
Curt Brown, Bureau of Reclamation
Doug Curtis, National Park Service
Jo Leslie Eimers, U.S. Geological Survey, Co-Executive Secretary
Gary Frazer, Fish and Wildlife Service

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Iris Goodman, Office of Research and Development, Co-Executive Secretary
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Department of Agriculture

Margriet Caswell, Economic Research Service
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Department of State

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National Science Foundation

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Tennessee Valley Authority

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PREFACE

The National Science and Technology Council (NSTC) establishes national guidelines for Federal science and technology investments. Under the NSTC's Committee on Environment and Natural Resources is the Subcommittee on Water Availability and Quality (SWAQ), which is made up of 25 Federal agencies that collectively are responsible for all aspects of Federal water research and/or water resource management.

The Directors of the Office of Science and Technology Policy and the Office of Management and Budget, in their August 12, 2004, joint memorandum, requested Federal agencies, through the NSTC, to "develop a coordinated, multi-year plan to improve research to understand the processes that control water availability and quality, and to collect and make available the data needed to ensure an adequate water supply for the Nation's future." With this report, the SWAQ lays out the research priorities and identifies opportunities to further these goals.

Earlier, the SWAQ prepared a report, "Science and Technology to Support Fresh Water Availability in the United States," which has been widely disseminated and well received by the water management community. In that 2004 report, SWAQ outlined the need for coordinated science and technology efforts to better understand water supply and demand in the United States. Although it serves as a valuable introduction to the issues of water availability, that report did not deal explicitly with water quality. In the present report, SWAQ takes a more comprehensive approach by considering water quality and quantity together, as has been recommended by numerous Federal advisory bodies.

This report describes topical areas for future emphasis in Federal water science and technology programs. The report does not contain an inventory of current programs; rather, the report focuses on topics that would benefit from increased interagency and public/private collaboration and/or increased resources. SWAQ has already begun work on implementation plans for some of the priority topics identified.

NRCS

Salmon River, Idaho

NRCS

Introduction

U.S. Water Resources—Are We Facing a Shortage?

Water is essential to maintain human health, agriculture, industry, ecosystem integrity, and the economic vitality of communities and the Nation. Throughout history, a key measure of a civilization's success has been the degree to which human ingenuity has harnessed fresh water resources for the public good. Indeed, civilizations have failed because of their inability to provide a safe and reliable water supply in the face of changing water resources and needs.

In its early history, U.S. water management focused largely on alleviating or controlling the impacts of floods and droughts. Investments in dams, water infrastructure, navigation infrastructure, canals, and water treatment plants provided safe, abundant, and inexpensive sources of water, aided flood management, and dramatically improved hygiene, health, and economic prosperity. The U.S. water resources, infrastructure, and technologies became the envy of the world.

Water-related science and technology have served our Nation well. The Nation has built infrastructure that provides safe drinking water, agricultural irrigation, hydropower, flood control, and navigable waterways. Through improved waste treatment technology, great strides have been made in improving water quality, and in protecting and enhancing habitat for aquatic organisms and recreational opportunities for the public.

The dawning of the 21ST century brings a new set of water resource challenges. Climate variability and change, mining of finite ground water[1] resources, and degraded water quality dramatically impact the amount of fresh water available at any given time. The increasing competition among water users means that critical decisions will be made about allocating water for agricultural use and consumption by cities, for maintaining water reservoirs and ensuring in-stream flows for aquatic ecosystems, and for industrial and energy production and recreational uses. Even small changes in water quality, quantity, or the time when water resources are available can render water supplies useless for their intended applications or hazardous to life and property. Today, water quantity and water quality are equally critical to the long-term sustainability of the Nation's communities and ecosystems.

Lynn Betts, NRCS

Authority to manage water resources is largely delegated to States, Tribes, and local municipalities. SWAQ is committed to productive collaboration with these water resource managers. SWAQ has identified a Federal role that emphasizes the variety of ways that water science and technology can be used to inform policies and decisions for managing water resources for the public good. As we, the citizens of the United States and governmental agencies at all levels, face today's national water resource challenges, the Nation will again rely on opportunities and tools offered by science and technology. Federal water research and development will increase the range of options and will inform the public, water managers, policymakers, and the private sector about the benefits, costs, and risks of the variety of decisions they face.

[1]For the purposes of this report, ground water refers to water under the surface of the earth, such as soil moisture or water found in aquifers; surface water refers to water on the surface of the earth, such as rivers, lakes, wetlands, and estuaries.

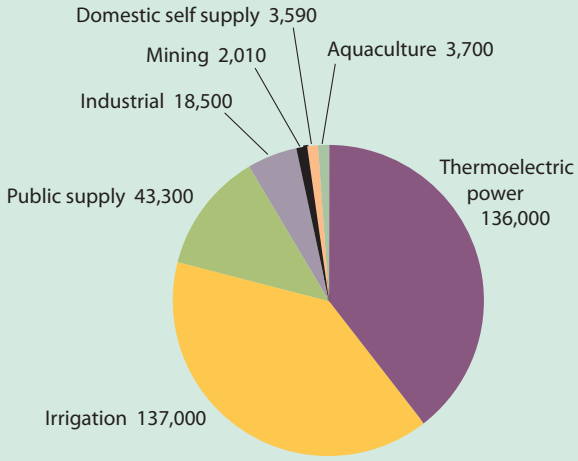
What is our current water use?

Water use is usually defined and measured in terms of withdrawal and consumption—that which is taken and that which is used up. Withdrawal refers to water extracted from surface or ground water sources. Consumption is that part of a withdrawal that is ultimately used and removed from the immediate water environment by evaporation, transpiration, incorporation into crops or a product, or other consumption. Conversely, return flow is the portion of a withdrawal that is not consumed, but is instead returned to a surface or ground water source from a point of use and becomes again available for use. Returned water may be of impaired quality. For example, most of the water withdrawn for once-through cooling of thermoelectric power generation is returned as heated water to the surface water body. A fraction of the returned water evaporates, and the rest is available for other uses—perhaps, after reaching ambient temperature, thermoelectric cooling further downstream.

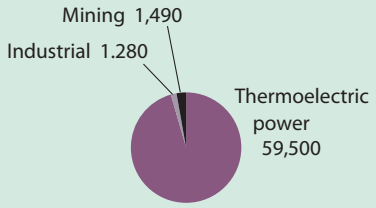
Current figures on water use in the United States are based on a mixture of measurements and estimates. Total water use is a combination of (1) in-stream use for hydropower generation, (2) withdrawals from surface and ground water sources for off-stream use, (3) in-stream use to support ecological needs, and (4) use of rainwater before it reaches a river or aquifer. We have estimates for (1) and (2). In 1995 in-stream use for hydropower was about 3,160,000 million gallons per day. This is about 2.6 times the average runoff of the United States, and reflects the fact that the same water is used to power multiple turbines as it flows through a series of dams. For total offstream water withdrawals (2), our best guess for 2000 is that these averaged 408,000 million gallons per day (Hutson and others, 2004). This is three times the average flow over Niagara Falls, or enough water to fill the Houston Astrodome every two minutes. Eighty-five percent of the water we withdraw is fresh; the rest is brackish or salty. Surface water provides 79 percent and ground water accounts for 21 percent. Since 1980, reductions in thermoelectric-power, irrigation, and industrial water use have helped to stabilize overall water withdrawals despite continued population growth. On the basis of estimates from 1995, the last year for which consumptive use was systematically estimated nationwide, about 30 percent of the fresh water withdrawals were used consumptively, and the remaining 70 percent were returned to surface-water bodies (Solly and others, 1998).

Total U.S. water withdrawals, 2000
(in million gallons per day)

Fresh water withdrawals



Saline water withdrawals



(from Hutson and others, 2004)

Hutson, S.S., Barber, N.L., Kenny, J.F., Linsey, K.S., Lumia, D.S., and Maupin, M.A., 2004, Estimated use of water in the United States in 2000: U.S. Geological Survey Circular 1268, 46 p.

Solly, W.B., Pierce, R.R., and Perlman, H.A., 1998, Estimated use of water in the United States in 1995: USGS Circular 1200, 71p.

Science Informs Water Policy and Management Decisions

Individuals, businesses, and government bodies make decisions daily about water use based on the physical, chemical, and biological properties of the water, as well as on economic, social, legal, and political considerations: Is there enough water? Is it clean enough to drink? Is the supply declining? How will climate variability and change affect future water availability? Can current water use be sustained? (See textbox, "What is our current water use?")

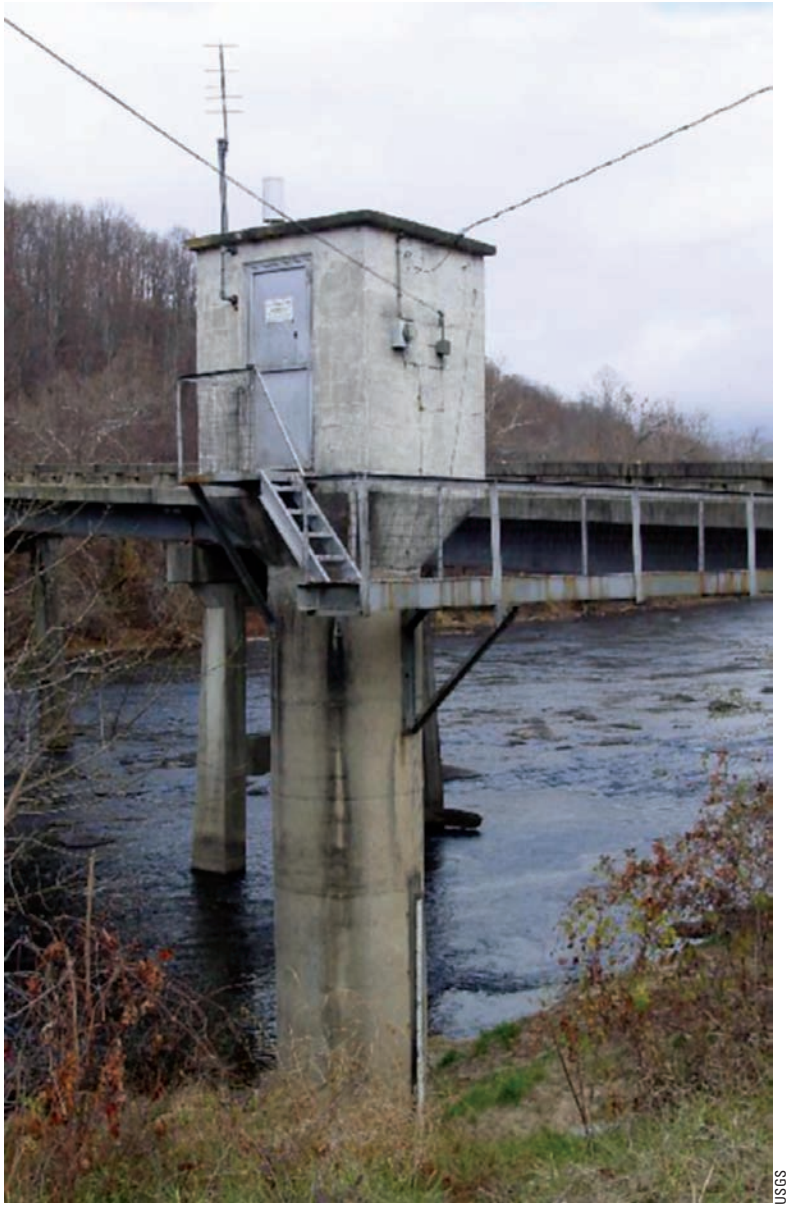
NRCS

New homes replace farmland in Iowa.

Scientists and engineers work to understand and quantify the complex factors that control water supply in order to strengthen water management decisions and provide new options. Scientific concepts and technological tools are used to measure the water supply, expand choices for water use, and reduce the uncertainties in water availability and quality. New measurement techniques, innovative observational network design, improved means for data access, and improved water-supply forecasting systems will help. Predictions of water availability over time are critical for decisionmakers, and are most useful when accompanied by estimates of their reliability. New technologies are being developed for pollution mitigation, water recovery and reuse, efficient water delivery systems, and crop management. Advances in biotechnology and nanotechnology and creative uses of low-quality water increase water management options.

New frameworks for conceptualizing and handling the complexity of water availability, quality, and management issues consider interactions between various physical, chemical, biological, and social components; a systems approach to water management considers the multiple dimensions of competing demands. Effectively dealing with multiple competing demands requires quantitative methods to compare options and assess the tradeoffs among them. With adequate tools to model these complex systems, decision-makers will be able to assess consequences of specific policies and decisions under a broad range of scenarios. This will help the Nation use existing infrastructure more effectively and focus on expansion of the engineered and natural infrastructure where it is most needed.

NRCS



USGS

French Broad River at Asheville, North Carolina. Long-term hydrologic records are used to establish flow status and trends. The USGS has measured streamflow at this site from 1895 to present; current real-time measurements are made in cooperation with the Tennessee Valley Authority.

Principles for Applying Science and Technology to Water Availability and Quality

Several previous reports have considered the research needs related to water resources and the requirements to make the science and technology most useful and effective (National Research Council, 1997, 2001, 2002, and 2004b; National Science and Technology Council, 2004; U.S. General Accounting Office, 2003, 2004). Important principles have emerged from these reports to guide the development of the science and technology needed to support water availability and quality:

- U.S. economic health and prosperity rely on adequate supplies of clean fresh water, and science and technology are fundamental to sustaining U.S. water supply.
- Advances in water science and technology should be applied at Federal, State, and local levels, should inform and be informed by private sector developments, and should be used to provide safe, reliable water supplies.
- "Water availability" has traditionally referred to the quantity of water. By consistently referring to "water availability and quality," we hope to further the idea that "available water" is a function of both water quantity and water quality. That is to say, poor water quality can render water unavailable for many uses.
- A key role for science and technology is to expand options for management and use of the Nation's water resources.
- Water users, managers, and scientists must work together to guide and develop the science and technology needed to support water availability and quality.
- Scientists and managers must employ a systems approach to fresh water withdrawals, use, and disposal that considers physical, chemical, biological, social, behavioral, and cultural aspects.
- Water law, economic incentives, public awareness, public education, and sensitivity to differences in value systems are cornerstones of effective water resource management.

Setting a responsive and effective national water-resources research agenda

[modified from National Research Council, 2004b]

The business of setting priorities for water resources research needs to be more than a matter of summing up the priorities of the numerous Federal agencies, professional associations, and Federal committees. A rigorous process for priority setting should be adopted—one that will allow the water-resources research enterprise to remain flexible and adaptable to changing conditions and emerging problems. Such a mechanism is also essential to ensure that water-resources research needs are considered from a national and long-term perspective. The components of such a priority-setting process are outlined below, in the form of six questions or criteria that can be used to assess individual research areas and thus to assemble a responsive and effective national research agenda.

1. **Is there a Federal role in this research area?** This question is important for evaluating the "public good" nature of the water-resources research area. A Federal role is appropriate in those research areas where the benefits of such research are widely dispersed and do not accrue only to those who fund the research. Furthermore, it is important to consider whether the research area is being or even can be addressed by institutions other than the Federal government.

2. **What is the expected value of the research?** This question addresses the importance attached to successful results of direct problem-solving or advancement of fundamental knowledge of water resources.

3. **To what extent is the research of national significance?** National significance is greatest for research areas that address issues of large-scale concern, are driven by Federal legislation and mandates, and whose benefits accrue to a large swath of the public.

4. **Does the research fill a gap in knowledge?** Because of the complex nature of future water resources research, such research is likely to be interdisciplinary, have a broad systems context, incorporate uncertainty, and address the role of human and ecological adaptation to changing water resources. Gaps in our understanding of these complex interactions are important to fill.

5. **How well is this research area progressing?** Past efforts should be evaluated with respect to funding levels and trends, whether the research area is a part of the agenda of one or more Federal agencies, and whether prior investments have produced results.

6. **How does the research area complement the overall water-resources research portfolio?** The portfolio approach is built on the premise that a diverse mix of holdings is the least risky way to maximize return on investments. The water-resources research agenda should be balanced in terms of the time scale of the effort (short-term vs. long-term), the source of the problem statements (investigator-driven vs. problem-driven), the goal of the research (fundamental vs. applied), and the investigators conducting the work (internally vs. externally conducted).

The Challenges of Meeting Future U.S. Demands for Water

In 1800, the 5.3 million citizens of the United States enjoyed virtually unlimited supplies of clean fresh water. When the geographic growth of the Nation ended in 1959, the United States had a population of 179 million. In 2006, the Nation supported 300 million citizens and the population was growing at a rate of almost 1 percent per year. Several regions and major metropolitan areas are growing at double-digit rates. Attempts to address the science and technology needs of the water community will require special consideration of areas with extreme growth in population or water consumption. In addition, trends in water use in the agricultural and energy sectors are major drivers of water resource needs. Other primary factors that influence the future availability of water include climate change and variability, pollution, and increased conflicts over water allocation among different users. Abundant supplies of clean, fresh water can no longer be taken for granted.

Scientific and technical challenges to ensure adequate water supply for the Nation

CHALLENGE 1
Measure and account for its water

CHALLENGE 2
Develop methods that will allow expansion of fresh water supplies while using existing supplies more efficiently

CHALLENGE 3
Develop and improve predictive water management tools

Authority for water resource management is generally delegated to States, Tribes, and localities. But water is crucial to the Nation's economic, social, and environmental conditions, and decisions in any given locality can have impacts far beyond their political boundaries. Given the importance of sound water management to the Nation's well-being, it is appropriate for the Federal government to play a significant role in providing information to all on the status of water resources and to provide the needed research and technology that can be used by all to make informed water management decisions. Decision-makers need three things to support sound management decisions: knowledge of current conditions; socially and technically feasible options that expand our water resources through efficiencies in use or treatments; and the means to evaluate the likely short- and long-term outcomes of their decisions. Water-resource choices belong to cities, States, Tribes, farmers, businesses, and individual citizens. The Federal role described in this report is to create the knowledge, the range of options, and the ability to predict outcomes so that those decisions can be as sound as possible.

The NSTC Subcommittee on Water Availability and Quality (SWAQ) sees three broad categories of scientific and technical challenges that the Nation must meet in order to ensure an adequate water supply:

CHALLENGE 1

The United States should measure and account for its water

The United States should accurately assess the quantity and quality of its water resources, should accurately measure how water is used, and should know how water supply and use change over time

• Know water resources and how they are changing

Many effective programs are underway to measure aspects of our water resources. However, simply stated, quantitative knowledge of U.S. water supply is currently inadequate (U.S. Government Accountability Office, 2005; National Research Council, 2004a). The United States should measure water resources more strategically and efficiently. A robust process for measuring the quantity and quality of the Nation's water resources requires a systems approach. Surface water, ground water, rainfall, and snowpack all represent quantities of water to be assessed and managed—from the perspectives of quantity, quality, timing, and location. A comprehensive assessment of U.S. water resources should build upon significant monitoring programs by water management authorities, States, and Federal gov-

New techniques for measuring sediment

Suspended solids and sediments transport nutrients and other organic matter that are critical to the health of a water body. In natural quantities, suspended sediment replenishes streambed materials and creates valuable habitats such as pools and sand bars. But sediments and sediment-associated contaminants can also degrade the quality of receiving waters and damage the downstream ecosystem. In fact, excessive sediment is the leading cause of impairment of the Nation's surface waters (U.S. Environmental Protection Agency, 2000).

In most streams, the majority of suspended sediments are transported during high-flow periods, the very time when traditionally the fewest data were collected. New sediment-surrogate technologies—devices that infer properties of river sediments using partially or wholly automated methods—show considerable promise toward providing the types and density of river-sediment data needed for safer, quantifiably accurate, and cost-effective monitoring. In several projects across the Nation, the U.S. Geological Survey is cooperating with U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, U.S. Environmental Protection Agency, U.S. Fish and Wildlife Service, State agencies in Virginia, Kansas, California, and Georgia, and university researchers to test instruments operating on bulk and digital optic, laser, pressure-difference, and acoustic technologies in riverine and laboratory settings for measuring fluxes and size characteristics of suspended sediment and bedload, and for selected characteristics of bed material.

Although it is doubtful that any one technology will suffice for all of the Nation's sediment-monitoring needs, multifrequency hydroacoustics holds the most promise as a robust technique for wide-scale suspended-sediment monitoring. The potential exists to provide an unprecedented temporal data density—compared to historical measurements, for which daily data were once the norm—with minimal physical intrusion into the water column. To make the transition from research to operational applications, these new technologies must be rigorously tested with respect to accuracy and reliability in different physiographic settings, and their performances must be compared to those of traditional techniques. These new, more cost-effective technologies are crucial to diagnosing impairments of water bodies from sedimentation and to developing and confirming effective strategies for improvements in these conditions.

Controlled flow studies in the Colorado River

The Glen Canyon Dam cut off 94 percent of the sand formerly supplied to the Colorado River at the upstream boundary of Grand Canyon National Park, and the amount of sand stored along the river has decreased by 25 percent over the past 20 years. The decreased size and abundance of sand bars in the Grand Canyon are indicators of the degree to which the post-dam ecosystem has been altered from the pre-dam condition. Results of controlled-flow studies indicate that an effective means of increasing sand bars is to immediately follow large tributary floods with artificial floods released from the dam. Laser-diffraction and acoustic technologies are now being used to monitor suspended-sediment transport in the Colorado River in Grand Canyon.

Thermoelectric cooling towers

ernment agencies to ensure that regional and national water resources are measured accurately. Data and information about the Nation's water supply should be widely available, should integrate physical and social sciences, and should be relevant to decisionmakers, from the individual homeowner to regional water managers. Without an adequate assessment of water supplies on a watershed or aquifer basis, optimal water management cannot be achieved. Improved knowledge of the size and distribution of the water supply and how it changes over time will allow more efficient and equitable allocation of this precious resource and will minimize overallocation of limited supplies.

• Know water use

To manage water effectively, we should know our present and future demands for water in individual homes, businesses, farms, industries, and power plants, as well as water needed for sustainable ecosystems. Furthermore, data and information about the Nation's demand for water should integrate physical and social

USGS

USGS

Compared to the usual flow and sediment content of the Colorado River (top), the river more than 2 hours and 30 km downstream from a tributary flood (bottom) has its streamflow increased by less than 3 percent, but the silt and clay content is increased 300–400 times and sand content increased 10–20 times (Rubin and others, 2002; Topping and others, 2005; Wright and others, 2005). Discovery of this type of discharge-independent change in sediment transport was made possible through the use of new sediment monitoring technologies.

USGS

Three-frequency array of sideways-looking acoustic-Doppler current profilers deployed at the Grand Canyon streamgage

U.S. Environmental Protection Agency, Office of Water, 2002, National water quality inventory; 2000 Report (EPA-841-R-02-001) accessed online 09/18/2006 at http://www.epa.gov/305b/2000report/

U.S. Environmental Protection Agency, Office of Water and Office of Science and Technology, August 2003, Developing water quality criteria for suspended and bedded sediments; potential approaches: 58 p.

Rubin, D.M., Topping, D.J., Schmidt, J.C., Hazel, J., Kaplinski, K., and Melis, T.S., 2002, Recent sediment studies refute Glen Canyon Dam hypothesis: EOS, American Geophysical Union Transactions, v. 83, n. 25, p. 273, 277-278.

Topping, D.J., Rubin, D.M., and Schmidt, J.C., 2005, Regulation of sand transport in the Colorado River by changes in the surface grain size of eddy sandbars over multi-year timescales: Sedimentology, v. 52, no. 5, p. 1133-1153.

Wright, S.A., Melis, T.S., Topping, D.J., and Rubin, D.M., 2005, Influence of Glen Canyon Dam operations on downstream sand resources of the Colorado River in Grand Canyon, *in* Gloss, S.P., Lovich, J.E., and Melis, T.S., eds., The state of the Colorado River ecosystem in Grand Canyon: U.S. Geological Survey Circular 1282, p. 17-31.

sciences, should be widely available, and should be presented in a manner relevant to decisionmakers ranging from individual homeowners to regional water managers.

Water-use studies should encompass combined surface-water and ground-water management. Water-use data should have seasonal resolution, and should be collected using a combination of measurement and statistical estimation.

• Know the role of ecosystems in maintaining water availability and quality

Society depends on important services provided by healthy aquatic and riparian ecosystems, such as water purification, provision of plant and animal foods, nonstructural flood control, recreation, nutrient cycling, and maintenance of biodiversity. In addition, aquifers, streams, wetlands, and riparian systems make up the natural water infrastructure, and the timing, quality, and volume of water

Edwin Remsberg, CSREES

A researcher sets up a drip irrigation system for lettuce at an experimental station in Alaska.

available for human uses depends, in part, on ecosystems filtering, cleaning, and storing water. In the past, water resource management focused on meeting society's needs for water, with scant attention to water required to maintain healthy ecosystems. The unintended result is that ecosystem services have been compromised in many areas, often leading to costly restoration and exacerbating conflicts over water use. Increasingly, water managers are required to provide ecosystems with water needed to function and stay healthy. We should improve our ability to manage water resources in ways that reduce conflicts while maintaining the integrity of these ecosystems and the services they provide. We should evaluate the services provided by ecosystems, and assess how ecosystems complement and support the services provided by engineered infrastructure. A better understanding of the impact of engineered infrastructure on ecosystem resiliency and productivity will improve watershed management decisions.

• Know the water infrastructure

The United States has invested enormous resources in the development and maintenance of water infrastructure—built infrastructure that is necessary for the Nation's continued health and economic well-being. Water infrastructure, much of it aging and constructed in a time of less competition for water, should be assessed regarding its condition and suitability to meet the Nation's water needs now and in the future. Treatment and delivery infrastructure is vital to communities, and the condition of levees, dams, navigation channels, and ports is also critical to U.S. water supplies. Decisionmakers need to know the vulnerabilities of water infrastructure to natural or manmade disasters.

Recognizing this need, various inventories of infrastructure are maintained by various organizations. The need and opportunities to improve these infrastructure inventories should be explored to ensure that the water managers know when structures exceed their design lifespan, if structures are being properly maintained, if we can improve the operation of structures to better meet current water needs, and if we have adequately assessed flood risk. Water managers need information not only about the water itself, but about the built infrastructure that enables its beneficial use.

CHALLENGE 2

The United States should develop methods that will allow expansion of fresh water supplies while using existing supplies more efficiently

The United States possesses significant volumes of water that cannot currently be used because they are of marginal quality. The National water supply will be bolstered by the treatment and use of these marginal or impaired waters. Just as water managers now rely on information provided by scientists to make informed decisions about the use of existing water resources, so science and technology will help expand management choices and help expand the water supply. Expanding the water supply should be accomplished through technological means by making poor-quality water usable. Efficiency also plays an essential role; increased water efficiencies will be achieved through both technological and institutional mechanisms.

• Develop tools to make more efficient use of existing water supplies and infrastructure

Energy efficiency is widely recognized as an economical means of reducing the need for new supplies of energy. The same is true for water. Thus, we should develop technologies for more efficient use of water in energy production, buildings, agriculture, industry, and for other demands. This will reduce the need for expanding sources of fresh water. Energy production and agriculture are the two sectors with highest demand for fresh water in the United States. New materi-

als and designs will make electricity generation more efficient, producing more energy for every drop of water. New cooling technologies will sharply reduce water requirements for existing and state-of-the-art power plants. New agricultural technologies will yield more water-efficient and drought-resistant crops, generating more food for each volume of water. New technologies will reduce wastewater volumes in municipal and industrial processes. Science and technology will improve water delivery in canals, reduce leaks from pipes, and help control water-consuming weeds, thereby extending the lifespan of existing infrastructure. Finally, economists and social scientists may identify ways to improve acceptance or implementation of innovations in water use and water markets that will facilitate more efficient use of the existing supply.

• Develop tools to expand water resources

The potential for science and technology to expand the fresh-water supply cuts across disciplines, scales, and topics. We should expand U.S. water resources by developing new treatment technologies, by preventing water pollution through better land-use practices, by adopting new approaches to storage, and by creating behavioral, social and economic tools that optimize spending and encourage acceptance of new water management techniques. Water that is currently unusable should be rendered usable with treatment technologies. Advanced water treatment technologies have become more economical, and removing the salt from saline or brackish waters provides a new source of fresh water for industry, agriculture, or communities. Scientific advances will allow us to improve advanced water treatment technologies to treat impaired waters for various uses and allow us to substitute low-quality or reused water for various purposes while at the same time protecting human and ecological health. Improved technologies should also enable better cleanup of waters from industry, energy production (coal, oil, and gas) and mining, or other technologies before the water is released back into the environment. Advanced technologies will also allow use of impaired water in lieu of fresh water for cooling and other thermoelectric generation needs.

Edwin Remsberg, CSREES

Begonia bulbs are produced using reclaimed water.

Preventing water pollution by managing land-use practices may prove to be more cost-effective than treating contaminated water. In addition to improving the methods for treating impaired waters to make them suitable for use, we should develop and test land-use practices that help prevent the impairment of water and that enhance supplies within the watershed.

Storage and recovery of water should also be improved so that water not immediately needed for in-stream use may be saved for future use. Reliability of water supplies is enhanced by storing water from wet seasons or wet years for use in dry seasons or dry years. Aquifer storage and recovery is becoming more common. Hydrologic science should be used to answer questions about the feasibility and efficiency of aquifer storage; social sciences are needed to address issues of property rights and incentives.

Using behavioral and management sciences, we should develop a “toolbox” of public awareness and education, technology transfer, incentives, legal, institutional, and economic systems that affect water use to gain acceptance for water-saving technologies, water reuse, and markets for water quantity and quality. With these tools, managers will be able to develop strategies to increase adoption of water-saving technologies in agriculture, individual homes, and industry. We should apply behavioral and management sciences to reduce conflict and better manage competing demands on our water resources, and to develop ways to better incorporate scientific and technical information into water-resource decision-making. Social sciences will help managers make tradeoffs and manage risks to

optimize agricultural yields, power production, municipal supplies, ecosystem viability, navigation reliability, and flood protection.

CHALLENGE 3

The United States should develop and improve predictive water management tools

Today's decisions and policies will shape our water future. The effectiveness of those decisions depends on the quality of information and on incorporating knowledge about the reliability (or conversely, the uncertainty) associated with predictive management tools. In addition to improved water data, the United States should develop and expand a variety of forecasting and predictive models and systems. Scientists should improve our knowledge of how water resources change because of natural events and human actions. We should develop an array of tools, using behavioral, management, and other social sciences, to educate and influence water-use behavior of individual water users, businesses, industries, and resource managers.

• Develop tools to anticipate the outcomes of short-term decisions about water release, withdrawal, storage, and use

Short-term predictive models or forecasting tools on time scales of hours to seasons are crucial to effective management of our water resources and water-resource infrastructure, and to the protection of public health and aquatic life. Predictions and forecasts support decisions such as to store or release water, divert water for off-stream use, treat water, or, in times of flood or water-quality incidents, keep the public and water users out of harm's way.


NRCS

These decisions are made while facing uncertainty about predictions. If that uncertainty is reduced and accurately described, then decisions will be made that tend to make for better use of the resource and increase public benefits and/or reduce risk. There are many examples of situations where predictions incorrectly indicated that the upcoming season would be one of severe supply shortfalls. Based on incorrect predictions, managers instituted shortfalls of deliveries to users, resulting in severe, unnecessary negative consequences for water users. Alternatively, there are many examples where predictions incorrectly indicated supply abundance, yet shortfalls ensued. Improved forecasts will prevent costly mistakes and stretch the utility of existing supplies and infrastructure.

Forecasts should be developed collaboratively among Federal agencies, local and State governments, the private sector, and universities and other educational institutions, as appropriate. Using data collected at appropriate scales and intervals, effective models will allow water managers to visualize hydrodynamics in real time and to anticipate the consequences of their management decisions.

• Develop tools to anticipate the outcomes of long-term planning and policy decisions

Communities of water users and water resource managers should anticipate long-term water availability and quality on time scales of years to decades. They should base resource-management, planning, and policy decisions both on historical data and on predictions about future hydrologic, meteorologic, and ecologic conditions. For example, stakeholders should know that climate change is predicted to result in altered regional precipitation frequency and water resources (dryer conditions in some locations, wetter conditions in others). Both probabilistic and physical models for predicting long-term hydrologic, meteorologic, and ecologic conditions should provide the scientific basis for planning and policymaking. The very practical matter of communicating scientific information

and modeling capabilities to decisionmakers and stakeholders is also important as we expand the use of predictive water management tools.

Long-term planning and policy decisions—such as whether to build a dam, remove a dam, build a treatment plant or aquifer storage and recovery facility, install best management practices, change the laws, permit withdrawals, or change prices—are informed by predictions. Long-term models and other analyses should anticipate the effect of specific management decisions on water supply and quality and should be used to evaluate a range of water-policy options in advance of their implementation. Models and other analyses are useful for solving the types of conflicts over water resources that in the past have assumed a single "right" level of human use or ecological condition. By explicitly simulating ranges of human uses and achievable ecological conditions, effective models will provide a basis for predicting the future capacity of watersheds and aquifers to provide water supplies under a variety of scenarios, and they will thus provide a basis for management and policy decisions.

USACE

A breached levee along the Sacramento River, California, is being repaired.

NRCS

Native grasses and trees in a conservation buffer along Bear Creek, Iowa.

A Federal Science Strategy to Meet U.S. Water Challenges

This report proposes a science and technology strategy to address the water challenges that face the United States. The current strategy builds on the earlier report of this Subcommittee (National Science and Technology Council, 2004). Each of the following seven strategic elements is intended to address one or more of the broad water challenges facing the Nation. The elements of Federal collaboration to implement the strategic plan are:

- Implement a National Water Census
- Develop a new generation of water monitoring techniques
- Develop and expand technologies for enhancing reliable water supply
- Develop innovative water-use technologies and tools to enhance public acceptance of them
- Develop collaborative tools and processes for U.S. water solutions
- Improve understanding of the water-related ecosystem services and ecosystem needs for water
- Improve hydrologic prediction models and their applications

Implement a National Water Census

Just as it is critical to the Nation to have up-to-date statistics on population, economic activity, agriculture, energy, and public health, it is also critical to know the status of our water resources. The United States has a strong need for an ongoing census of water that describes the status of our Nation's water resource at any point in time and identifies trends over time. The system will include all components of the natural and human water cycle: precipitation, snow pack, soil moisture, ground-water recharge and storage, river flow, reservoir storage, evaporation, water use, and infrastructure. Much data is already collected for these parameters, and agencies have already made a start at unifying this effort, but more complete information is needed so that policymakers and the public can ask simple questions such as: How much water do we have in this state or river basin today and how does that compare to a few months ago or a few decades ago? How is water use changing over time? What is the status of our engineered water infrastructure? What is the status of our ecosystem or natural water infrastructure? Answers to these questions should be easily accessible and in a form useful to water managers and the public. A National Water Census will require a combination of improvements in monitoring networks and sensors, software to assimilate the data collected and interpolate values for the many locations not monitored, and an internet portal to convey the information to users. If a National Water Census is to be implemented, some of the next steps for the water availability and use component may be found in a 2002 Report to Congress, "Concepts for a National Assessment of Water Availability and Use" (U.S. Geological Survey, 2002). The Census will also include water quality monitoring so that managers are aware of times and places where water quality is degraded and unable to sustain its intended uses. The Census will permit estimates of the movement of pollutants from watersheds to their downstream river reaches, lakes, reservoirs, estuaries, and the coastal zone. The benefits of a National Water Census will accrue through a combination of monitoring networks integrated with models to estimate water-quality conditions at those places not monitored.

NRCS

Mt. Rainier, Washington. Snowmelt in the west provides water for crops and cities.

Hydrologic applications of microgravity measurements: measuring changes in ground-water storage

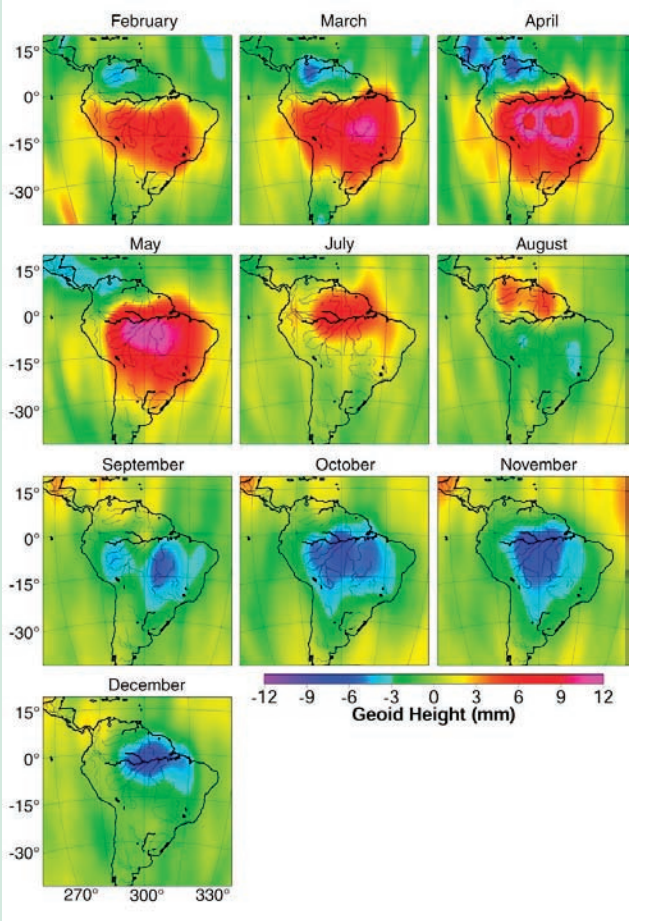
Ground water is stored within the pore spaces of aquifers. Monitoring changes in the amount of water stored in aquifers once required costly measurement and analysis of changing ground-water levels at numerous wells. Now, the National Aeronautical and Space Administration (NASA) and the U.S. Geological Survey (USGS) are using space-based and land-based gravity methods, respectively, to measure changes in ground-water storage. These methods apply Newton's law of gravity—the acceleration of gravity is directly proportional to mass. As an aquifer is drained by pumpage or filled by recharge, its mass changes, which results in changes in the strength of the gravitational field. Repeated measurements of the gravitational field from space or at a network of terrestrial stations are compared to produce gravity change across a study area. The gravity change is integrated to estimate total change in mass and ground-water storage.

The NASA Gravity Recovery and Climate Experiment (GRACE) measures change in ground water on a regional and subcontinental scale. Two co-orbiting satellites completely map the Earth's gravity field on a monthly basis with an accuracy of better than a μGal (one part per billion of the Earth's gravity).

The USGS is using repeat microgravity surveys in several drainage basins to better define ground-water budgets and estimate specific yield of the aquifer. Recent technological advances in geophysical techniques have made measurement of the extremely small gravitational changes caused by fluctuations of water volume practical. An aquifer's specific yield can be estimated if measured water-level data are available for correlation. Results from a microgravity study in southern Arizona showed that storage change ranged from a 66,000 acre-feet accretion in 1989-99, an El Niño year, to a 268,000 acre-feet depletion in 2000-2001. Hence the importance of systematically monitoring storage change, when one year may account for most of the recharge that occurs over many years.

Other agencies cooperating to develop these methods include the National Oceanic and Atmospheric Administration's National Geodetic Survey, who use precise gravity for geodetic control, the National Science Foundation, and the Pima County, Arizona Department of Transportation and Flood Control District.

Time-differenced microgravity measurements have the potential to provide water managers of the future with answers to questions about changes in water storage, which will be crucial to making informed decisions about water use and conservation. Other uses for this technology include evaluating new methods for artificially recharging ground water and evaluating the effect of climate change on ground-water storage.



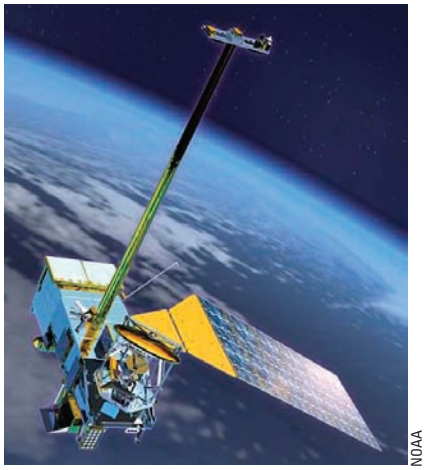
GRACE data measured the weight of as much as 10 centimeters (4 inches) of ground-water accumulations from heavy tropical rains, particularly in the Amazon basin (shown here) and Southeast Asia. Red color shows increased gravity resulting from ground-water storage. Smaller signals caused by changes in ocean circulation were also visible.

The Subcommittee on Water Availability and Quality has identified the following critical actions to implement a National Water Census:

- A national water quality monitoring network has been designed by the National Water Quality Monitoring Council. This is an important component of a National Water Census; the census of water resources will complement and coordinate with the Council's monitoring principles and design.
- In partnership with State, regional, and local water agencies, devise an interagency national strategy for conducting a National Water Census; that is, a periodic inventory of the quantity and quality of the nation's (1) water resources (surface-water, ground-water, and snow resources), (2) water use, and (3) water infrastructure.
- Develop and adopt data collection, data communication, and data availability standards and protocols for nationwide (1) water resources, (2) water use, and (3) water infrastructure.
- Integrate existing monitoring networks to provide nationally uniform (1) surface and ground-water and snow data, (2) water-use data, and (3) infrastructure data.
- Develop a strategy to establish regional and national priorities for the highest level needs for (1) surface- and ground-water and snow monitoring, (2) water use, and (3) water infrastructure monitoring in the United States.

Develop a new generation of water monitoring techniques

The monitoring of water quantity and quality is ripe for technological innovations that hold the promise of more comprehensive, accurate, and timely data at a cost savings compared to current labor-intensive methods. A new generation of water monitoring techniques will transform the way we monitor the quantity and quality of water in a river, lake, aquifer, wetland, estuary, snowpack, soil, and the atmosphere and improve measurement of the amounts of water withdrawn, consumed, and returned by various human activities. Cost effective, precise, and timely monitoring is especially important when health and property are at risk during floods, droughts, and accidental or deliberate contamination of source waters. Rapid detection of pathogens in recreational waters should reduce the occurrence of unnecessary, inconvenient, and expensive beach closures, and rapid detection of contaminant plumes in rivers should save lives and dollars by protecting drinking-water intakes. Many different monitoring technologies are promising for these purposes, including new in-situ sensors for chemical, biological, and radiological contaminants, time-differential gravity measurements to determine aquifer storage (see textbox, "Hydrologic applications of microgravity measurements"); microbial source tracking to determine the source of pathogens in recreational and drinking water (see textbox, "Microbial source tracking to identify the source of fecal contamination"); hydroacoustics to measure water velocity and sediment transport; remote sensing of quantity and quality (currently effective at regional or continental scales); and nanotechnology for use in a variety of rapid analytical methods.



NOAA

The next generation U.S. weather monitoring satellites are scheduled to begin orbiting in 2012.

New water-monitoring methods have significant potential for development of world markets. Biotechnology is particularly promising in the face of an ever- increasing level of concern about worldwide movements of pathogens that are spread by domestic and wild populations of animals. Development of new water-monitoring technologies helps maintain American preeminence in water science and technology, and strengthens our economy. The businesses involved in this field have a strong export market—the world looks to the United States for advancement in water monitoring and other nations want to use the technologies used by U.S. gov-

Microbial source tracking to identify the source of fecal contamination

Many of the Nation's resource waters fail to achieve sanitary water-quality standards as required by the Clean Water Act, and public health is at risk from exposure to water contaminated by human or animal fecal matter. Water-resource managers need a scientific basis by which to provide good stewardship over water resources. Microbial Source Tracking (MST) refers to a group of tools now under development by the scientific community to distinguish among different sources of fecal contamination. The U.S. Environmental Protection Agency, U.S. Geological Survey, National Oceanic and Atmospheric Administration, and U.S. Department of Agriculture are working together to develop and test a set of tools that range from detection of antibiotic resistance profiles and genetic "fingerprints" of individual isolates to probing whole-water nucleic acid extracts for the presence of source-specific pathogens (such as *Cryptosporidium* and various viruses) or other genetic markers.

Significant progress has been made, but none of the currently available tools is completely accurate, nor is any one tool universally applicable to all objectives. To attain the potential of MST, several key components are being addressed, including:

- Further development of methods to rapidly and quantitatively recover DNA and RNA from water samples
- Further development of methods to rapidly and quantitatively detect markers in extracts by quantitative polymerase chain reaction, microarrays, and other new methods
- Consistent and comprehensive characterization of marker occurrence and distribution among host populations
- Identification and characterization of novel host-specific markers

Federal agencies are working toward the day when MST will indicate specific sources of fecal contamination to drinking water sources. This will give managers the tools needed to target regulations and investments to most effectively reduce *E. coli* and enterococci counts to meet recreational-water quality standards, and support requirements for development of Total Maximum Daily Load plans to comply with water-quality health standards. In addition, identification of fecal sources is relevant to source-water protection programs and to the development of accurate microbial risk assessment models.

Stoeckel, D.M., 2005, Selection and application of microbial source tracking tools for water-quality investigations: U.S. Geological Survey Techniques and Methods 2-A3, 43 p.

Santo Domingo, J.W., 2005, Microbial source tracking guide document: Environmental Protection Agency report 600-R-05-064, 135 p.

ernment agencies. Also, significant savings will be achieved if we revolutionize the way that water data are collected. Even with the advent of sophisticated sensors, solid-state data storage devices, and satellite telemetry, there is still a large human labor component in monitoring systems, with high costs associated with bringing technicians to a field site to calibrate and service equipment and collect samples.

A consortium of Federal agencies engaged in water monitoring will prioritize and plan implementation of specific improvements to water monitoring science and technology. For example, agencies that currently track the source of pathogens will work together to take recent advancements in genomic research and use them to help ensure safety in recreational waters.

The Subcommittee on Water Availability and Quality has identified the following critical actions to develop a new generation of water monitoring technology:

- Develop sensors and measurement systems to remotely measure water volumes and movement—inexpensively, precisely, and in real time—in rivers, lakes, aquifers, wetlands, estuaries, snowpack, and soil.
- Develop sensors and systems to measure water quality inexpensively in real time.

- Develop and adopt data collection, data communication, and data availability standards and protocols for new monitoring technologies.

Develop and expand technologies for enhancing reliable water supply

As traditional water supplies in streams and fresh-water aquifers become allocated to users, new supplies of water from marginal or impaired sources, such as industrial and municipal wastewater, produced water from oil and gas extraction, brackish water, and other waters, should be identified and developed (see textbox, "Water extracted with the production of oil and gas"). The United States will expand technologies for enhancing reliable water supplies and will widen the range of options for delivering water to growing populations. These technologies include desalination, water treatment and reuse, and more efficient methods of water use in the agriculture, energy, buildings, and industry sectors. Federal agencies will work with others to develop these technologies and obtain objective data on costs and efficiencies of leading treatment and storage technologies. This information will include data on the extent to which these technologies remove low-level contamination (dissolved solids, metals, pharmaceuticals, pesticides, and other organic chemicals), on the energy efficiency of the technologies, and on the water efficiency of the technologies (for example, how much of the water withdrawn or stored will actually be available for use). These new technologies will not only enhance water-supply options domestically but will enhance U.S. competitiveness in the global market for new water infrastructure technology in developing nations.

Edwin Remsberg, CSREES

An extension specialist examines a purple pipe used for wastewater irrigation.

A critical factor in expanding the availability of fresh water is storage. The ability of water managers to store water during times of abundance and to recover that water during times of need will greatly improve the efficient use of available water resources. Science and technology will help us improve artificial recharge technologies and reduce their adverse impacts.

The Subcommittee on Water Availability and Quality has identified the following critical actions to provide the tools necessary to enhance reliable water supply:

- Identify and pursue appropriate Federal research opportunities for improving and expanding technologies for enhanced use of marginal or impaired water supplies. Such technologies might be applied to desalination, water treatment and reuse, or conservation in the United States and other countries.

- Develop technologies and provide scientific information to inform strategies for expanding water storage and recovery in aquifers, including improving understanding of source water and aquifer characteristics and response during cycles of injection and withdrawal.

Develop innovative water-use technologies and tools to enhance their public acceptance

Innovative technologies for expanding water supply and changing the ways in which water is used may be viewed unfavorably by the consuming public. The point has to be made that doing nothing also imposes costs, both for consumers and the economy. Water managers should rely on behavioral research that suggests the best approaches for encouraging the public, industry, and agriculture to be water-efficient and have low environmental impact. These new approaches will include adoption of low-impact landscape designs, water-efficient appliances and water reuse systems for irrigation of urban lands or for waste disposal. New agricultural practices will include irrigation that minimizes long-term water consumption per unit of crop output and innovative methods for managing nutrients, insects, weeds, and soil losses. Industrial innovations will include reuse of water and recycling of heat and chemicals. Thermoelectric generation will benefit from develop-

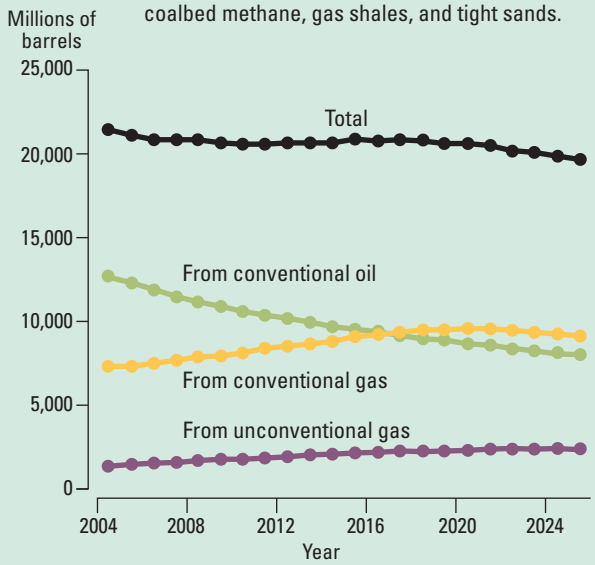
Water extracted with the production of oil and gas

Water is commonly abundant in rocks that host accumulations of oil and gas. As a consequence of this association, a significant volume of water is extracted with the production of crude oil, natural gas, and coalbed methane. This is referred to as produced water. The Department of Energy's National Energy Technology Laboratory predicts that produced waters from all sources in the contiguous 48 States will total approximately 20 billion barrels (840 billion gallons) in 2025. The quantity and quality of this "produced water" at any given location, in addition to economic and legal factors, determines whether this is a useful resource or wastewater. In general, most coalbed methane water is of better quality than water produced from conventional oil and gas wells.

Water produced with coalbed methane extraction usually contains sodium, bicarbonate, and chloride. Coalbed methane waters are relatively low in sulfate because the chemical conditions in coalbeds favor the conversion of sulfate to sulfide; sulfide is removed as a gas or precipitate. The total dissolved solids of coalbed methane water ranges from 200 milligrams per liter (mg/L) to 170,000 mg/L (for comparison, the recommended total dissolved solids limit for potable water is 500 mg/L, for irrigation, 1,000-2,000 mg/L; seawater averages 35,000 mg/L total dissolved solids).

Ongoing studies provide information on the composition and volumes of coalbed methane water in some of the Nation's most active areas of production. Researchers from the U.S. Geological Survey (USGS), Bureau of Land Management, Bureau of Indian Affairs, State agencies, and private companies are cooperating in an effort to provide a better understanding of coalbed methane resources and associated water. The Produced Waters Database (http://energy.cr.usgs.gov/prov/prodwat/), first compiled by the Department of Energy Fossil Energy Research

Forecast of produced water in the onshore 48 contiguous states. Unconventional gas sources include coalbed methane, gas shales, and tight sands.



[Department of Energy National Energy Technology Laboratory, http://www.netl.doe.gov/technologies/oil-gas/publications/AP/Program063.pdf]

ing advanced water-treatment technologies that would allow use of impaired water for cooling as well as from developing advanced cooling technologies.

In addition to understanding and applying the educational, regulatory, or economic measures that encourage adoption of these methods and technologies, water managers will anticipate possible resistance by water users who are accustomed to unlimited cheap water. With strong public acceptance of new methods for increasing efficiency of water use, the costs building new water-delivery, storage, and treatment systems will be reduced, and negative impacts on water resources will be minimized.

Social, behavioral, and economic science research will predict how communities, agricultural users, and industrial users will respond to the implementation of new, unconventional practices. In addition, social scientists will help water managers anticipate cultural and behavioral changes that may occur as a result of environmental changes or other broad changes arising from climate variability and change. Social sciences will provide tools for predicting how governmental incentives and market incentives might be used to influence and optimize water use.

Center and since updated by the USGS, provides the location, geologic setting, sample type, and major ion composition of produced waters.

In one study of the local effects of produced water, targeting part of the Powder River Basin in Wyoming and Montana, the USGS is cooperating with the Wyoming Department of Environmental Quality to monitor real-time water quality to determine produced water's suitability for use in irrigation. Currently, most produced water in this area is discharged to constructed reservoirs or into surface drainages, where it may infiltrate into the ground, become part of the streamflow, or evaporate. Real-time data on surface-water quality data are available at http://waterdata.usgs.gov/wy/nwis/current/?type=quality (see Powder River at Sussex, Wyoming; Crazy Woman Creek near Arvada, Wyoming; Clear Creek near Arvada, Wyoming; and Powder River at Moorhead, Montana). Readily available continuous, real-time water-quality data gives local irrigators a critical tool for decisionmaking.

Clark, M.L., and Mason, J.P., 2006, Water-quality characteristics, including sodium-adsorption ratios, for four sites in the Power River Drainage Basin, Wyoming and Montana, water years 2001-2004: U.S. Geological Survey Scientific Investigations Report 2006-5113, 22 p.

Department of Energy National Energy Technology Laboratory, Produced water from oil and natural gas operations—setting the context: (http://www.netl.doe.gov/technologies/oil-gas/publications/AP/Program063.pdf).

Rice, C.A., and Nuccio, V., 2000, Water produced with coalbed methane: U.S. Geological Survey Fact Sheet FS-156-00, 2 p.

USGS

Clear Creek in the Powder River Basin, Wyoming

USGS

Water-quality sampling at Powder River

Social, behavioral, economic, and management research will be applied to reduce conflict and better manage competing demands on our water resources and to develop ways to better incorporate scientific and technical information into risk management and water-resource decisionmaking. The social and behavioral sciences will also inform efforts to improve public awareness and education, to facilitate technology transfer, and to apply the legal and economic tools that affect water use.

Successful regulatory reform of water laws and practices associated with introducing new technologies and new analytical methods will depend on public and legislative understanding of the societal benefits to be derived from these changes.

The Subcommittee on Water Availability and Quality has identified the following critical actions for appropriate agencies to develop innovative water-use technologies and attain public acceptance of them:

- Develop innovative technologies to use water more efficiently in the agricultural, energy, buildings, and industry sectors.

- Increase and improve research in the social, behavioral, and economic sciences to provide the understanding and tools to deal with the human impacts of changing water availability and use in the United States.
- Increase investment in public education and outreach at all levels dealing with issues of water availability, water quality, and water use.

Develop collaborative tools and processes for water infrastructure solutions

Finding scientific and technical solutions to problems of water availability and quality will require extensive cooperation and collaboration among Federal, State, and local agencies, private sector water experts, stakeholders, and the public (see textbox, "Collaborating to maintain flood control and improve riverine ecosystems"). Collaboration will be particularly important in identifying and addressing infrastructure problems and needs. The Nation's water infrastructure needs and solutions will be studied and addressed in a manner integrating physical and social sciences. Federal research in both the physical and social sciences will help develop and test innovative collaborative tools and methods, including public participation/collaboration processes, decision-support computer technologies, and techniques for integrating these within various contexts. Tools may

Collaborating to maintain flood control and improve riverine ecosystems

Like all rivers, Kentucky's Green River serves multiple, sometimes competing, interests. Green River provides habitat for 151 species of fish and 71 species of fresh-water mussels. It provides base-level flow to Mammoth Cave, the world's largest known cave system. The Green River Dam provides flood protection and lake-based recreation. To balance these multiple uses, Federal scientists and engineers instituted a collaborative process to assess the needs of the various water users and to manage the infrastructure to provide win-win solutions.

In 2002 The Nature Conservancy and the U.S. Army Corps of Engineers began the Sustainable Rivers Project, a partnership to restore and preserve rivers across the country while maintaining flood control and human uses of the river system. Learning how flow regulation influences habitat is an ongoing process. The Sustainable Rivers Project is not only using the best science that is currently available to improve the habitat while meeting project mission goals, but is also helping to advance the understanding of the complex interactions of flows and water levels with biological outcomes by collecting important hydrologic and biological data and supporting a wide range of scientists who can document the effect of water management changes. In the Green River, multiple partners, including six universities, six Federal agencies, three State agencies, four counties, two cities, and six conservation/citizen groups have collaboratively developed a new management regime for the dam.

Matt Thomas

The Green River flows under a bridge near Greensburg, Kentucky, site of a U.S. Geological Survey streamgage. Water willows and mussels are common on or near gravel bars at riffles.

USACE

Bottlebrush crayfish, native to Green River, is North America's largest species at 11.5 inches.

USACE

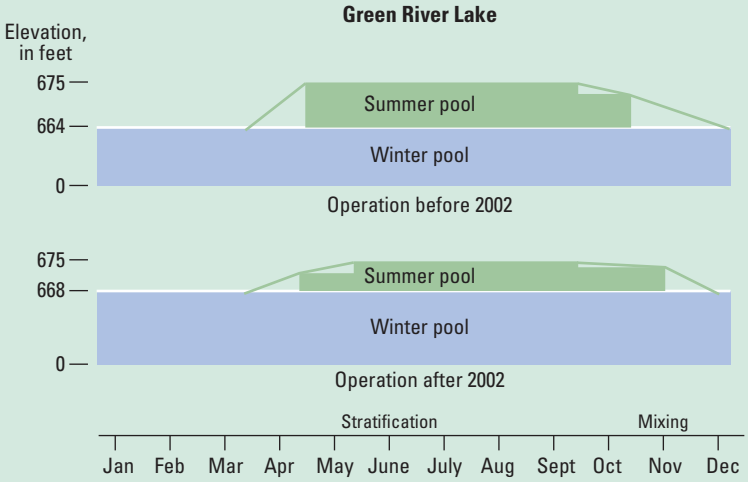
Navigation lock and dam on Allegheny River, Pennsylvania

include portable, physical/social simulation modules, software to link existing water management software, and interfaces for both collaborative model development and displaying modeling results and tradeoffs. Processes may include collaborative process design (for example, how to engage different stakeholders during different parts of the planning and decisionmaking process, meeting formats, and structures), conflict assessment and resolution techniques, and decisionmaking methods. This effort will draw on existing initiatives with Federal and non-Federal partners. Integrating traditional engineering design with ecosystems science will lead to complementary, innovative water infrastructure designs that enhance nutrient recycling, flood mitigation, aquifer recharge, and stormwater management.

The Subcommittee on Water Availability and Quality has identified the following critical actions by appropriate agencies to develop collaborative tools and processes for U.S. water solutions:

- Develop an interagency research program for collaborative decisionmaking in a wide variety of water infrastructure and use applications.

Graph showing changes in the reservoir operation rule that once only protected human life and property but now also benefits aquatic ecosystems.



This collaborative effort has improved habitat in and along the river and identified a more ecologically compatible water-release schedule from Green River Dam. The revised schedule includes delayed fall drawdown, higher winter pool, delayed spring filling, and higher releases during non-crop seasons and after floods or high water peaks have passed. Delaying fall releases until after reservoir mixing (a delay of about 45–60 days) avoids disrupting fall spawning for a number of fishes and mussels and lengthens the recreational boating season. These changes provide significant benefits to plants and animals, while maintaining the dam's primary purpose of flood control and increasing lake recreational benefits.

Collaboration regarding flood control and riverine ecosystems on the Green River has resulted in the reproduction and recruitment of three endangered species of fresh-water mussels, the near elimination of unseasonable backflows into Mammoth Cave National Park, and extension of the recreation season on Green River Lake.

Turner, W. M. and Byron, W. J., 2006, Green River Lake; pilot project for sustainable rivers, 2006: ASCE Operations Management Conference—Operating Reservoirs in Changing Conditions, Sacramento, California, August 14–16, 2006.

U.S. Army Corps of Engineers, Louisville District, March 2006, Environmental assessment and finding of no significant impact, Pool re-regulation, Green River Lake, Kentucky.

- Initiate pilot studies to integrate emerging decision tools with stakeholder input and new data sources to improve quality and ownership of water management decisions.

Improve understanding of water-related ecosystem services and ecosystem needs for water

Despite the progress that has been made in the field of ecohydrology, considerable uncertainty remains about water-related ecosystem services and water requirements to maintain these services. The science has evolved from one that simply indicated what minimum flows might be needed to maintain a particular species in a river. Today we recognize that the timing and magnitude of flow and the physical and chemical quality of water are also essential factors for maintaining productive and viable aquatic systems (see textbox: "Collaborating to maintain flood control and improve riverine ecosystems"). Furthermore, we know that ecosystems play a role in cleaning and storing water, but we have not yet quantified the water-related ecosystem services. Research needs include quantifying important processes and services provided by functioning ecosystems, such as recycling of nutrients, infiltration of stormwater, maintenance of baseflow, aquifer recharge, sediment transport, flood mitigation, and maintenance of productive aquatic and riparian habitat. Research is also needed to document ecological responses to flow variability and water quality conditions. In addition, we need to develop an array of analytical and decision-support tools so that we can describe and predict ecological and social consequences of water management decisions. We need to develop an interdisciplinary program of research to develop innovative ways to identify, characterize, and quantify societal, ecologic, and economic attributes of water management decisions, as well as the means to effectively convey these attributes to the public and to decisionmakers.

USACE

Over 200,000 acres of water provide ideal habitat for wildlife on USACE land in Tennessee and Kentucky.

The Subcommittee on Water Availability and Quality has identified the following critical actions by appropriate agencies to address the need to improve understanding of the needs and benefits of ecosystems in U.S. water systems:

- Work with Federal and non-Federal partners to establish or expand ecosystem monitoring to address watershed or region-specific water needs as well as provisions of ecosystems.
- Expand ecosystem research programs to include hydrologic variables in ecosystems-based studies.

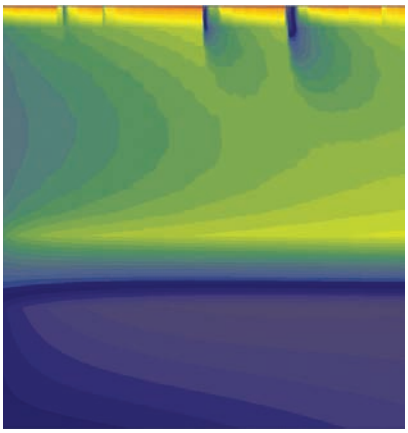
Improve predictive hydrologic models and their applications

Because water management decisions are made over a range of geographic and time scales, Federal research on hydrologic modeling must integrate across time and spatial scales. Currently, different hydrologic models are used by water-science and operational agencies to guide water managers in making hourly to seasonal decisions about water storage, water delivery, and drought and flood risk. Yet too frequently different data structures and conventions prevent inter-model comparisons and the linkage of multiple models for multidisciplinary projects and data sharing. Furthermore, water managers are calling for improved and usable forecasting and prediction models for individual watersheds.

Development of common data structures and conventions will allow for integrated, robust hydrologic forecasts while maintaining user-specific applications across different time and spatial scales. Hydrologic forecasts will also need to consider long-term water availability, combining watershed-scale hydrologic process models with regional aquifer system models and global and regional-scale atmospheric and climate models. Water managers and decisionmakers require existing and forecasted information that accounts for the roles of natural vegetation, irrigated land, ground-water development, and urban impervious sur-

faces on the long-term water budget. In addition, hydrologic models and operational forecast systems will be successful and accurate over long periods of time only if they consider the effects of climate variability and change on water availability and quality. Creating new multidisciplinary models will depend on the convergence of data and theory from the fields of hydrology, ecology, and atmospheric sciences.

To maximize the utility of hydrologic and ecologic forecasts for water management, linkages between Federal, State, and local agencies should be improved. This will be accomplished through the development of a "community hydrologic prediction system." Adoption of this community system will infuse the science of new models so that advancements will be expanded to different applications and enable the shared use of models in hydrologic forecast operations. Data sets will also be linked and shared through this community system. The private sector will be included in data collection and dissemination, forecasting simulations, and water resource management activities.



NASA

Hydrologic modeling image showing fraction soil water content in the Washita River Basin, Oklahoma

Comprehensive water models will be useful to evaluate alternative conservation measures and new technologies, innovative storage techniques, land-use practices, flood frequency, amount of base flow during dry periods, and the effects of reservoir, channel, and port sedimentation. Pilot studies of management practices, coupled with integrated models of ground water, surface water, and biological systems are needed to confirm scientific theories and to translate proposed land-use practices into estimates of resultant water quantity and quality and ecosystem health.

Elements of these are already being incorporated in the activities of a number of Federal agencies through collaborative efforts. One example is the Interagency Steering Committee on Multimedia Environmental Models, which is introducing common standards for a variety of modeling approaches.

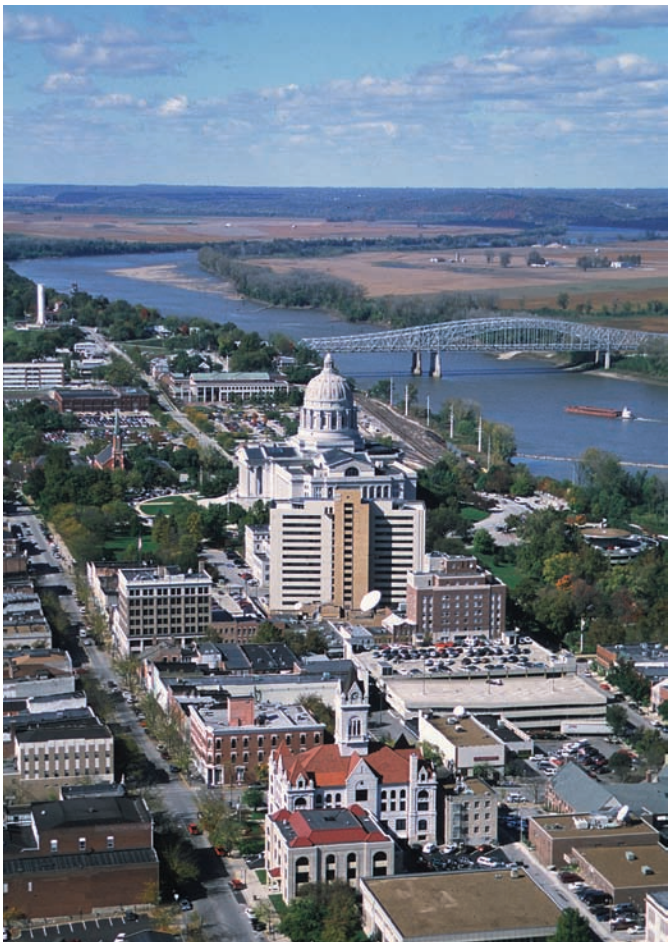
In addition to purely hydrologic modeling, institutional models and forecast services to improve water management at the watershed and subwatershed (individual field or neighborhood) scale and on a State and regional basis are also needed. These models and services will incorporate accurate representation of water rights, and thus will help water users and water managers to make the best possible long-term water-related investments. Water users will choose how to respond to changes in the available supply through new awareness and knowledge of the resource.

USGS

A researcher monitors water-level data and models ground water flow.

The Subcommittee on Water Availability and Quality has identified the following critical actions by appropriate agencies to address the need for expanding the quality and use of hydrologic models:

- Existing hydrologic models will be strengthened, integrated, and transformed into tools for making decisions on watershed and subwatershed scales.
- Hydrologic models will, to the extent possible, be linked to climate models that simulate the water cycle over broad geographic areas and long time periods.
- Hydrologic models will be coupled with institutional models to provide a full suite of physical, economic, and technological decision tools for water managers.
- Advanced hydrologic models will be transitioned to operational services through establishment of a "community hydrologic prediction system."



NRCS

The Missouri River separates agriculture from the city life as it flows past Jefferson City, Missouri.

Next Steps

The Subcommittee on Water Availability and Quality (SWAQ) has already begun follow-on planning to implement the strategic elements identified in this report. In planning implementation for these priority topics, SWAQ will emphasize topics where current or historical collaboration in science and technology has led to better outcomes as well as key areas in need of enhanced collaboration.

For a given priority implementation, SWAQ will convene a multiagency team to review the needs within these areas and benchmark skills, capabilities, and tools currently available within appropriate Federal agencies to meet these needs. The teams will recommend pathways to improve current capabilities to meet our emerging and future needs. Those pathways will be pursued through coordination of agency planning and budget processes, and through coordination with the Office of Management and Budget. This will ensure the best use of current capabilities and past investments, and ensure that future investments are efficient, coordinated, and avoid duplication.

Conclusion

The status of the Nation's water resources will continue to change with growing population, increasing urbanization, changing industrial and agricultural practices, and changing climate. Science can inform us about the status of our water resources and help us anticipate the likely effects of water-policy and management practices on those resources.

Authority to manage water resources is largely delegated to States, Tribes, and local municipalities. SWAQ is committed to productive collaboration with these water resource managers. SWAQ has identified a Federal role that emphasizes the variety of ways that water science and technology can be used to inform policies and decisions for managing water resources for the public good. The water science and technology portfolio identified by SWAQ encompasses research that produces near-term results as well as anticipating future water issues. This research includes creating and disseminating fundamental knowledge on water resources and developing new technologies to support informed choices for protecting and expanding water resource availability. This research will be carried out in collaboration with State and local governments, Tribes, the private sector, universities and other educational institutions, and other stakeholders.

In the future, water managers will need to update policies and practices to respond to changing water resource conditions and to reflect new knowledge. Our goal is to identify strategic Federal investments in water science and technology that will yield results useful for creating new and flexible management solutions. The successful stewardship of the Nation's water resources requires that science and engineering meet the needs of water managers, that water managers are able to act on new information, and that scientists, engineers, and managers work together to maintain our vital water resources.

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Appendix I

Federal Agencies' Role in the Science and Technology of Water Availability and Quality

Department of Agriculture—Agricultural Research Service (ARS)

The Agricultural Research Service (ARS) is the U.S. Department of Agriculture's principal intramural scientific research agency. The agency's research and technology transfer efforts related to water availability and quality are carried out by scientists and engineers through a coordinated system of nationally distributed Research Centers. The mission of our water-related research is to conduct fundamental and applied research on the processes that control water availability and quality for the health and economic growth of the American people, and develop new and improved technologies for managing the Nation's agricultural water resources. These advances in knowledge and technologies will provide producers, action agencies, local communities, and resource advisors with the conservation practices, tools, models, and decision support systems they need

to improve water conservation and water use efficiency in agriculture, enhance water quality, protect rural and urban communities from the ravages of droughts and floods, improve agricultural and urban watersheds, and prevent the degradation of riparian areas, wetlands, and stream corridors.

Department of Agriculture—Cooperative State Research, Education, and Extension Service (CSREES)

The Cooperative State Research, Education, and Extension Service (CSREES) Water Program provides Federal financial assistance to universities, private industries, non-profit organizations, and individuals to create and disseminate knowledge for improving or protecting water resources. CSREES funds research, education, and extension activities that help to ensure a safe and reliable source of water that meets the need for food, fiber, and energy production; human health, use, and economic growth; and to maintain and protect ecosystems. CSREES' unique niche is funding research, education, and extension programs that work to protect and improve water resources in agricultural, rural, and urbanizing watersheds, including forest lands, rangelands, and croplands. Basic research programs develop new knowledge related to water quality impairments and water supply or scarcity and new management and technology tools needed to address these issues. Integrated research, education, and extension programs create and disseminate knowledge needed to resolve stakeholder (farmer, rancher, and homeowner) identified water-resource issues at the watershed scale.

Department of Agriculture—Economic Research Service (ERS)

The Economic Research Service (ERS) is the main source of economic information and research from the U.S. Department of Agriculture (USDA). ERS brings the perspective of economic analysis to critical issues confronting farmers, agribusiness, consumers, and policymakers. The agency's analysis informs public and private decisionmakers on issues of agriculture, food, the environment, and rural America. ERS research addresses how the quantity and quality of water supplies available to agriculture affect food production and profits. Survey data are used to monitor the use of water as an input to agricultural production and to assess the adoption of irrigation technologies. ERS assesses the policies and economic incentives that affect technology choices and the impact of those choices on environmental quality, including the quality of water for human and wildlife uses.

Department of Agriculture—Natural Resources Conservation Service (NRCS)

The Natural Resources Conservation Service (NRCS) is the primary Federal agency that works with private landowners to help them conserve, maintain and improve their natural resources. The agency emphasizes voluntary, science-based conservation; technical assistance; partnerships; incentive-based programs; and cooperative problem solving at the community level. Agency science and technology efforts related to water availability and quality are carried out by scientists and engineers in a variety of National Centers. Responsibilities include providing water supply forecasts, water and climate analysis, information, and services for NRCS, partners, and customers; providing emergency support to customers in response to extreme natural resource events; and operating the Snowpack Telemetry (SNOTEL) data collection system for the United States and the Soil Climate Analysis Network (SCAN). This agency also provides technical leadership, guidance, support, and expertise for water resources planning, including watershed restoration efforts. Watershed restoration encompasses watershed protection, rehabilitation, flood prevention projects, and river basin studies, including flood plain management studies and program neutral planning.

Department of Agriculture—Forest Service (FS)

The mission of the USDA Forest Service is to sustain the health, diversity, and productivity of the Nation's forests and grasslands. The agency implements water programs through the Research and Development (R&D), National Forest System, and State and Private Forestry programs to provide clean and reliable sources of water. The research focus is to understand the effects of forest and rangeland management practices and related human and natural disturbances on water quantity, quality and the sustainability of watershed functions. Forest Service R&D provides scientific understanding to distinguish healthy from degraded watersheds and to provide the technical basis for restoration to functioning, healthy, and sustainable condition. Forest Service R&D long-term experimental watershed studies are key to understanding how healthy watersheds function and what processes enhance or impair the quantity and quality of water that comes from forests. Forest Service scientists work closely with resource managers to synthesize research results, provide technology, and deliver the information to develop, adapt and evaluate management approaches.

Department of Commerce—National Oceanic and Atmospheric Administration (NOAA)

The National Oceanic and Atmospheric Administration (NOAA) delivers water information and predictions affecting all hydroclimatic conditions from floods to droughts. This includes high-resolution analyses of snow pack, precipitation, and soil conditions, and the nationally consistent production of water supply estimates, stream flow forecasts, and flood warnings that save lives and conserve America's water resources. NOAA's information products extend to climate, ecosystems, and commerce as well. Within NOAA, the National Weather Service (NWS) delivers flood watches, river and flash flood warnings, and river and lake level forecasts through 122 Weather Forecast Offices to a broad spectrum of customers, including emergency and water resource managers. Emergency managers use these forecasts for both strategic, long-term, and tactical, short-term planning. Weather Forecast Offices receive river, lake level and flash flood guidance from 13 watershed-based River Forecast Centers. These Centers also provide river forecasts to water resource managers. NOAA also supports research to improve climate prediction for hydrological applications and the use of information on climate variability and change by water resource managers. These water resource managers make critical decisions that affect flood control, water supply, water quality, river and lake transportation, irrigation, hydropower, and recreation and maintain the ecological health of the rivers.

Department of Defense—U.S. Army Corps of Engineers (USACE)

The Corps (USACE) serves the Armed Forces and the Nation by providing vital engineering services and capabilities, as a public service, across the full spectrum of operations—from peace to war—in support of national interests. USACE supports the Nation's interests by building broad-based relationships and alliances to collaboratively provide comprehensive, systems-based, sustainable and integrated solutions to national and international water-resources challenges. The Corps is proud to have the responsibility of helping to care for these important aquatic resources. Through its Civil Works program the Corps carries out a wide array of projects that provide coastal protection, flood protection, hydropower, navigable waters and ports, recreational opportunities, and water supply. The Corps' environmental mission has two major focus areas: restoration and stewardship. Efforts in both areas are guided by the Corps' environmental operating principles, which help us balance economic and environmental concerns. Sci-

ence and technology research on water availability and quality focuses on flood damage reduction, navigation, and environmental business areas.

Department of Energy—Office of Energy Efficiency and Renewable Energy, Office of Science, Office of Fossil Energy, Office of Nuclear Energy, and Office of Environmental Management

The Department of Energy has a variety of energy-water-related activities with national laboratories, universities, and industry. The Office of Fossil Energy conducts research and development on Integrated Gasification Combined Cycle technology, which reduces the water needed to generate power from coal. The Office of Nuclear Energy conducts research and development on water issues for nuclear reactors. The Office of Energy Efficiency and Renewable Energy does research and development and supports deployment of technologies to reduce the use of water in the building and industrial sectors, to reduce the amount of energy used to supply water, and to make use of renewables for water supply. The Office of Science conducts research in basic science, which can lead to breakthrough technologies such as improved membranes for purifying water. The Office of Environmental Management does extensive work in ground-water transport issues to enable better ground-water cleanup technologies.

Department of Health and Human Services—Indian Health Service (IHS)

The Sanitation Facilities Construction Program is the environmental engineering component of the Indian Health Service health delivery system. The Sanitation Facilities Construction Program provides technical and financial assistance related to safe water, wastewater, and solid waste systems. In particular, the Program provides the following services:

- Develops and maintains an inventory of sanitation deficiencies in Indian communities
- Provides engineering assistance with utility master planning and sanitary surveys
- Develops multiagency-funded sanitation projects, assists with grant applications, and leverages of IHS funds
- Provides funding for water supply and waste disposal facilities
- Provides engineering design and/or construction services for water supply and waste disposal facilities
- Provides technical consultation and training for the operation and maintenance of tribally owned water supply and waste disposal systems
- Advocates for Tribes during the development of policies, regulations, and programs
- Assists Tribes with sanitation facility emergencies

Department of Health and Human Services—National Institute of Environmental Health Sciences (NIEHS)

The mission of the NIEHS is to prevent disease and improve human health by using environmental sciences to understand human biology and human disease. Reductions in the quality and availability of water for consumption and recreation is a major worldwide health concern. Research supported by NIEHS is

critical to understanding health risks associated with exposure to water contaminants such as toxins from algal blooms, metals such as mercury, and manmade compounds such as pesticides. NIEHS supports its overall mission through extramural research and training grants and contracts that fund work by scientists, environmental health professionals, and other groups worldwide; through intramural research conducted by scientists at the NIEHS facility and in partnership with scientists at universities and hospitals; through toxicological testing and test validation by the National Toxicology Program; and through outreach and communications programs that provide reliable health information to the public, medical practitioners, and public health professionals. Understanding relations between waterborne pollutants and adverse health outcomes is vitally important for addressing health risks and disease burdens in human populations faced with problems of water quality and availability.

Department of the Interior—Bureau of Reclamation

Reclamation is an agency dealing with the 17 Western States; the agency's mission is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the public. Reclamation is the Nation's largest wholesale water supplier and the second largest producer of hydroelectric power in the western United States. Because Reclamation manages such a large water infrastructure in the West, research and development efforts focus on ensuring reliable water supply and delivery under the increasing demands placed on water managers in the rapidly growing West. Reclamation's Science and Technology Program furnishes a full range of solutions for water supply and delivery to Reclamation's water and power managers and their stakeholders. Research and development efforts are typically conducted in collaboration with other Federal and non-Federal entities that have a stake in western water solutions. The program has contributed many of the tools and capabilities in use today by Reclamation and western water managers. The Science and Technology Program's primary focus includes improving water delivery reliability, improving water and power infrastructure reliability and safety, advancing water supply technologies and water efficiency solutions, and improving water operations decision support capabilities. Reclamation also funds external research in desalination technologies with emphases on inland brackish water and on lowering the cost of desalination.

Department of the Interior—U.S. Fish and Wildlife Service (USFWS)

The U.S. Fish and Wildlife Service works with others to conserve, protect, and enhance fish, wildlife, plants, and their habitats for the continuing benefit of the American people. Through its various programs and offices, the USFWS works with landowners and others to conserve threatened and endangered species associated with wetland, riparian and aquatic habitats; assesses how flow modifications or water project operations affect fish and wildlife, and recommends to regulatory agencies measures to minimize harmful effects; partners with landowners and others to restore healthy aquatic communities and their associated wetland, riparian and aquatic habitats; and manages its nearly 100 million acre National Wildlife Refuge System. USFWS has a stake as a resource manager in many aspects of Federal water resource science and technology, particularly as it relates to understanding and ensuring the ecological needs of fish and wildlife.

Department of the Interior—U.S. Geological Survey (USGS)

The USGS provides reliable, impartial information about the Nation's water resources. The information is used by decisionmakers to minimize the loss of life and property resulting from floods, droughts, and land movement; to effec-

tively manage ground-water and surface-water resources for domestic, agricultural, commercial, industrial, recreational, and ecological uses; to protect and enhance water resources for human health, aquatic health, and environmental quality; and to contribute to wise physical and economic development of the Nation's resources for the benefit of present and future generations. Many USGS activities related to water availability and quality are performed in cooperation with State and local governments, other Federal agencies, and Tribes. The USGS collects and disseminates basic hydrologic data, conducts interpretive hydrologic studies, and performs fundamental hydrologic research. For example, the USGS operates and maintains national networks of streamgages and wells; collects and maintains the Nation's water use database; measures and assesses the status and trends of our Nation's water quality; performs reconnaissance of emerging contaminants; and collaborates with other agencies to characterize changing water availability.

Department of the Interior—U.S. National Park Service (NPS)

Water is a critical resource for both ecosystems and visitors in the National Park System; therefore, a core mission of the NPS water resources program is to protect and manage water and water-related park resources. To meet this mission, the NPS needs tactical research and technical assistance to enable parks to address critical water-resource protection and management responsibilities. In partnership with parks and others, the Water Resources Division (WRD) of the National Park Service provides leadership, technical assistance, and funding support for understanding, protecting, and managing water and aquatic resources of the National Park System. The WRD provides its services directly to the parks through a broad range of programs in the areas of surface-water and ground-water hydrology and water quality, water rights, watersheds and wetlands, water-resources management planning, fisheries, aquatic ecology, and marine resources. Through the application of science in a planning, stakeholder negotiation, policy, regulatory, or administrative context, WRD's programs help units of the National Park System succeed in enhancing the overall condition of park water and aquatic resources.

Environmental Protection Agency (EPA)

EPA is responsible for ensuring that drinking water is safe and that watersheds, coastal oceans, and their aquatic ecosystems are protected and restored to provide healthy habitat for fish, plants, and wildlife; to support economic and recreational activities; and to ensure a healthy environment for people. Safe Drinking Water Act programs protect human health through the protection and regulation of water supplies, including compliance activities and financial assistance to municipal water-treatment facilities. Clean Water Act programs protect and restore fresh and coastal waters by setting protective criteria and reducing pollutant loads to water bodies. Additional programs target increases in acreage and functions of wetlands; recreational uses of coastal and freshwater beaches; and reduction of pollution leading to fish consumption advisories. EPA's Global Change Research Program (GCRP) assesses the potential impacts of global change on water quality as precipitation and hydrologic regimes are altered. The primary global change stressors studied are climate change, climate variability, and land use change. EPA's GCRP focuses on both human uses (such as impacts to drinking water and wastewater systems) and on impacts to aquatic plant and animal life. Understanding the relation between natural systems and the uses of water is critical to implementing these diverse programs. To that end, EPA conducts and promotes research, both in-house and extramurally, to support these monitoring, planning, and conservation activities and to support sound rule-making.

National Aeronautics and Space Administration (NASA)

NASA's mission is to pioneer the future in space exploration, scientific discovery, and aeronautics research. In the realm of scientific discovery, one of NASA's goals is to study the Earth from space to advance scientific understanding and meet societal needs. Specifically with regards to water resources, NASA develops remote sensing systems to measure aspects of the global water cycle, such as precipitation, soil moisture, snow cover, river discharge, ground water, evaporation, water quality, and many others. NASA engages in research activities to infuse these observations into modeling systems, either directly or through data assimilation, to improve our ability to assess the current state of the environment as well as enable enhanced weather forecasting and climate prediction capability. As part of these activities, NASA is improving our understanding of how aspects of the water cycle affect climate change, and how in turn climate change might alter the water cycle, both globally and regionally. Through partnerships with other agencies, NASA seeks to extend the benefits of its science results into management, regulatory, and policymaking systems and practices.

National Science Foundation (NSF)

NSF's overall mission is to promote the progress of science, to advance the national health, prosperity, and welfare; and to secure the national defense. NSF supports fundamental research and education across all fields of science and engineering, except medical sciences. Support is provided to scientists and engineers through limited-term awards, primarily to universities and colleges. Water-related research spans basic studies of water across terrestrial, aquatic, atmospheric, and subsurface systems and processes from watershed to global scales. It includes studies of aquatic ecosystem function and health in natural and built domains as well as investigations into new processes for wastewater treatment and techniques to deal with contaminated surface and ground waters. NSF also supports studies of coupling between human and natural systems, the development of new sensors and sensor networks, and the creation of new cyberinfrastructure tools in support of research.

Tennessee Valley Authority (TVA)

The mission of TVA is to develop and operate the Tennessee River system to improve navigation, minimize flood damage, provide electric power, and promote economic development in the Tennessee Valley region. TVA's ongoing research and technology development efforts are in direct support of energy and environmental issues related to TVA's statutory responsibilities for river, land management and power generation. These include, among others, generation and transmission technologies, environmental impacts and control, renewable resources, and other emerging technologies. Emergency response focuses on natural disasters such as flood and drought events, power system emergencies, hazardous material emergencies, protection of water supplies, and homeland security.

APPENDIX II

Interface of Water Availability with Disaster Reduction

Floods and droughts define the extremes of water availability. Too much water or too little water is devastating to life and property. Flooding is the most frequent of natural disasters. One in three Federal disaster declarations is because of flooding; damages reach $2 billion per year. Drought, on the other hand, affects more people than any other natural disaster; damages to property because of drought average $6-8 billion per year.

To address the science and technology needs for disaster reduction, the National Science and Technology Council's Committee on Environment and Natural Resources has established a sister subcommittee to the Subcommittee on Water Availability and Quality (SWAQ) called the Subcommittee on Disaster Reduction (SDR). The SDR includes many of the same Federal agencies as SWAQ and explicitly considers floods and droughts. The SDR recently prepared a document that identified six Grand Challenges for disaster reduction (note that in the SDR document, the terms disasters and hazards encompass events with both natural and technological origins):

- Provide hazard and disaster information where and when it is needed.
- Understand the natural processes that produce hazards.
- Develop hazard mitigation strategies and technologies.
- Recognize and reduce vulnerability of interdependent critical infrastructure.
- Assess disaster resilience using standard methods.
- Promote risk-wise behavior.

SWAQ recognizes that many of the efforts identified in the present Grand Challenges report for Water Availability and Quality will do double duty to reduce the impact of floods and droughts. Indeed, Federal research under SWAQ's purview is to "understand the processes that control water availability and quality, and to collect and make available the data needed to ensure an adequate water supply for the Nation's future." Many SWAQ actions, therefore, will help meet some of the Grand Challenges identified by the SDR. Accordingly, Federal agencies will view many of the recommendations for research priorities of the two subcommittees as mutually reinforcing, albeit with slightly different focus. Ultimately, most of the activities and research identified by SWAQ will serve to reduce the vulnerability of the Nation to the extremes of the hydrologic cycle and thus reduce impacts of hydrologic-induced disasters.

NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

COMMITTEE ON ENVIRONMENT AND NATURAL RESOURCES

Subcommittee on Water Availability and Quality