Envisioning the Agenda for Water Resources Research in the Twenty-First Century

Water Science and Technology Board, National Research Council

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ENVISIONING THE AGENDA FOR WATER RESOURCES RESEARCH IN THE TWENTY-FIRST CENTURY

Water Science and Technology Board
Division on Earth and Life Studies
National Research Council

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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Preface

In this new century, the United States will be challenged to provide sufficient quantities of high-quality water to its growing population. Water is a limiting resource for human well-being and social development, and projections of population growth as well as changing social values suggest that demands for this resource will increase significantly. These projections have fueled concerns among the public and water resources professionals alike about the adequacy of future water supplies, the sustainability and restoration of aquatic ecosystems, and the viability of our current water resource research programs and our institutional and physical water resource infrastructures.

With the goal of outlining a roadmap to guide policymakers, the Water Science and Technology Board (WSTB) held a series of discussions at several of its meetings in 1998–2000 about the future of the nation's water resources and the appropriate research needed to achieve their long-term sustainability. From those discussions, the board produced this report, the objectives of which are to:

- draw attention to the urgency and complexity of water resources issues facing the United States in the twenty-first century;
- broadly inform decision makers, researchers, and the public about these issues and challenges;
- identify needed knowledge and corresponding water resources research areas that should be emphasized immediately and over the long term; and
- describe ways in which the setting of the water research agenda, the conduct of water research, and investments devoted to such research should be improved in the next few decades.

This report discusses major research questions related to the critical water issues that face the nation. It lays out an interdisciplinary research portfolio for the next 20 years and recommends agenda-setting processes that can maximize the nation's ability to prioritize and conduct water resources research.

Members of the WSTB come from numerous disciplines, including en gineering, physical sciences, life sciences and ecology, and social sciences (Appendix A). Although the breadth of experience of the members is considerable, the water resources arena abuts and overlaps with many other disciplines and resource areas. Thus, in order to help assure that this report reflects a properly broad perspective, once the report was developed to WSTB members' reasonable satisfaction, we shared it with a number of other National Research Council (NRC) units for their informal evaluations and input. This proved helpful, enriching our report and heightening the resolve of WSTB regarding the report's contents. The contributions of the following NRC units are acknowledged and greatly appreciated: Committee on Human Dimensions of Global Change, Board on Atmospheric Sciences and Climate, Board on Earth Sciences and Resources, and Commission on Geosciences, Environment, and Resources.

More formally, the report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The reviews and draft manuscripts remain confidential to protect the integrity of the deliberative process. We thank the following individuals for their participation in the review of this report: Richard Gersberg, San Diego State University; Charles Howe, University of Colorado; Perry McCarty, Stanford University; David Moreau, University of North Carolina; Carolyn Olsen, Brown and Caldwell; Kenneth Potter, University of Wisconsin; Phil Singer, University of North Carolina; and James Wescoat, University of Colorado.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Stephen Berry, University of Chicago and Gilbert White, University of Colorado. Appointed by the NRC, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the Water Science and Technology Board and the NRC.

Henry J. Vaux, Jr., Chair
Water Science and Technology Board

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Executive Summary

As the United States progresses into the twenty-first century, its water resources are likely to be subjected to much greater pressures than in the past. Dramatic projections of population increases in the United States and abroad, mostly in urban areas, have fueled legitimate concerns about the nation's ability to provide sufficient quantities of high-quality water. This challenge will be increased by factors such as unpredictable economic growth in a globalizing economy, the introduction of new technologies whose potential side effects are unknown, increasing recognition of the need to preserve and enhance aquatic ecosystems, and the uncertainty related to climate variability and subsequent hydrologic predictions. The capability of the nation to successfully meet these interrelated challenges while sustainably managing its water resources will depend, in large part, on employing new knowledge gained through research.

The policies that guided water resources research and development in the twentieth century generally focused on water quantity, were uncoupled from water quality, and too often resulted in programs that focused on short-term and narrowly defined problems. They lacked coordination and sometimes failed to anticipate the emergence of critical, long-term problems. These policies are not suited to addressing the daunting water problems of the twenty-first century. Rather, the progressive intensification of water scarcity in the face of competing demands for water will necessitate proactive and innovative scientific, technological, and institutional solutions. What is needed for understanding water resources is a more holistic conceptual framework that encompasses regional-scale hydrologic systems, land–atmosphere interactions, and the biogeochemical cycles that control contaminant transport. To address this need, this report outlines an agenda for water resources research in the new century. Coordination of the water research agenda should be achieved by creating a national organization that involves state and federal governments, research institutions, users and purveyors, nonprofit organizations, and public interest groups.

Water resource problems are extremely complex and dynamic in time, necessitating that their solutions cross traditional disciplinary and societal boundaries. These sobering realizations suggest that these problems cannot be solved with the current level of investment in water resources research. A substantial commitment of new funds to support expanded programs of research, on the order of several hundred million dollars, will be essential for the protection of this increasingly scarce resource. This investment should support efforts in the following three areas:

Water Availability. Investigations of surface water and groundwater availability should focus on the development of supply-enhancing technologies, on understanding the coupled hydrologic and biogeochemical cycles that control water quality, and on developing means of preventing further declines in water quality. Data from networks of continuous ground-based and remote sensing instrumentation are critical for understanding responses to variable climates at different temporal and spatial scales. Monitoring is important not only for resource planning and regulatory activities, but also for assessing the effectiveness of water policies and management efforts.

Water Use. There is a great need to better understand the determinants of consumptive water use, the importance and scale of agricultural water use, and the nature and impact of environmental uses of water. Research on the technologies and infrastructure for water conservation and recycling will be critical to meeting future water needs.

Water Institutions. Research leading to the development of improved water management institutions should receive much more emphasis in the research agenda of the twenty-first century than it has in the past. Efforts should focus on legal and economic institutions and should involve researchers from a broad array of social science disciplines.

The 43 research issues identified in these topical areas are summarized in the following list:

Water Availability

- Develop new and innovative supply-enhancing technologies
- Improve existing supply-enhancing technologies such as wastewater treatment, desalting, and groundwater banking
- Increase safety of wastewater treated for reuse as drinking water
- Develop innovative techniques for preventing pollution
- Understand physical, chemical, and microbial contaminant fate and transport

- Control nonpoint source pollution
- Understand impact of land-use changes and best management practices on pollutant loading to waters
- Understand impact of contaminants on ecosystem services, biotic indices, and higher organisms
- Understand assimilation capacity of the environment and time course of recovery following contamination
- Improve integrity of drinking water distribution systems
- Improve scientific bases for risk assessment and risk management with regard to water quality
- Understand national hydrologic measurement needs and develop a program that will provide these measurements
- Develop new techniques for measuring water flows and water quality, including remote sensing and *in situ* techniques
- Develop data collection and distribution in near real time for improved forecasting and water resources operations
- Improve forecasting the hydrologic cycle over a range of time scales and on a regional basis
- Understand and predict the frequency and cause of severe weather (floods and droughts)
- Understand recent increases in damage from floods and droughts
- Understand global change and its hydrologic impacts

Water Use

- Understand determinants of water use in the agricultural, domestic, commercial, public, and industrial sectors
- Understand relationship of agricultural water use to climate, crop type, and water application rates
- Develop improved crops for more efficient water use and optimize the economic return for the water used
- Develop improved crop varieties for use in dryland agriculture
- Understand water-related aspects of the sustainability of irrigated agriculture
- Understand behavior of aquatic ecosystems in a broad, systematic context, including their water requirements
- Enhance and restore species diversity in aquatic ecosystems
- Improve manipulation of water-quality parameters to maintain and enhance aquatic habitats

- Understand interrelationship between aquatic and terrestrial ecosystems to support watershed management

Water Institutions

- Develop legal regimes that promote groundwater management and conjunctive use of surface water and groundwater
- Understand issues related to the governance of water where it has common pool and public good attributes
- Understand uncertainties attending to Native American water rights and other federal reserved rights
- Improve equity in existing water management laws
- Conduct comparative studies of water laws and institutions
- Develop adaptive management
- Develop new methods for estimating the value of nonmarketed attributes of water resources
- Understand use of economic institutions to protect common pool and pure public good values related to water resources
- Develop efficient markets and marketlike arrangements for water
- Understand role of prices, pricing structures, and the price elasticity of water demand
- Understand role of the private sector in achieving efficient provision of water and wastewater services
- Understand key factors that affect water-related risk communication and decision processes
- Understand user-organized institutions for water distribution, such as cooperatives, special districts, and mutual companies
- Develop different processes for obtaining stakeholder input in forming water policies and plans
- Understand cultural and ethical factors associated with water use
- Conduct *ex post* research to evaluate the strengths and weaknesses of past water policies and projects

1

Introduction

The water resources of the United States will be subjected to more intense and broader arrays of pressure in the twenty-first century than they were in the twentieth century. Projected population growth, economic growth, and the increasing recognition of the need to preserve and enhance aquatic ecosystems will combine to make managing water resources more challenging than ever before (Postel et al., 1996). Even as these pressures mount, important transitions are occurring in water management. Dams are being decommissioned and removed. Recent models hint at potential changes in the hydrologic cycle and in hydrologic variability in the future. Although observational data do not yet confirm the presence of such changes, water resource planning in the future will need to encompass the possibilities of such change (Lins and Slack, 1999). Increases in hydrologic uncertainty, the need for more water to support aquatically based ecosystems, and general disaffection with the efficacy of dams all suggest the demise of dams as the primary means of responding to increased water demands.

On the surface these changes seem to compound the problem of addressing the new realities of water management. Yet, the transition presents many new opportunities in the form of new technological breakthroughs that may allow us to manage water in new and innovative ways. Thus, for example, there is substantial potential for increasing our understanding of hydrologic and limnologic processes and for monitoring our water resources in ways that will permit the development of extremely sophisticated management systems. The fragmented policies that guided water resources research in the twentieth century will probably be inadequate to foster the development of needed water-based technologies and understandings in such an environment. While the research policies of mid-century fostered much important research, the erosion of these policies by the century's end frequently resulted in programs that focused on short-term, narrowly defined problems, lacked coordination, and sometimes failed to anticipate the emer gence of critical problems. New policies to guide water resources research and new investment in that research will be needed if the nation is to respond effectively to the water problems of the twenty-first century.

The United States entered the new century and millennium with over 270 million inhabitants, an increase of about 9 percent during the 1990s and an increase of 120 million (80 percent) since 1950. According to the U.S. Census Bureau's middle estimate, another 120 million people could be added by 2050, yielding a population of approximately 390 million. The implications of this forecast, even if not fully realized, are manifold and complex: the nation will essentially have to replicate all the housing and infrastructure built since World War II, in addition to repairing or replacing what already exists. In particular, the nation's water resources, which are already stressed in many regions, will have to be stretched and conserved to meet the water needs of a much larger U.S. population.[1] American agriculture, which is increasingly dependent upon irrigation, will be asked to meet new demands for food and fiber both domestically and abroad. At the same time, water will need to be managed to protect and restore aquatic habitats and serve instream functions such as navigation, hydropower, and recreation.

The water resource implications of twenty-first century population growth are even more dire when the regional distribution of that growth is considered. As indicates, the Northeast and Middle West, which have relatively ample water supplies (in nondrought years at least), grew by only about 5 percent in population over the past three decades. Meanwhile, the South and West, which include the nation's most water-deficient areas, each grew by about 70 percent, more than double the national rate. Most new development has occurred in quasi-urban communities dependent upon centralized providers of water and sewerage treatment. Moreover, much of that growth occurred in truly arid regions of the Southwest (e.g., Tucson, Phoenix, Las Vegas, and southern California), where new water supplies are only available through groundwater mining or imports from other regions which are increasingly unwilling to allow their own water resources to be diverted elsewhere. Perversely, water use per capita is greater in the nation's driest regions than in the more humid areas.

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[1] Few data are available on the geographic, economic, demographic, and health impacts of future water resource problems. In fact, some of the most important research areas identified by the WSTB would address these gaps in knowledge (see bulleted list in the executive summary).

TABLE 1-1 Regional Distribution of U.S. Population, 1970–2000 (thousands)

	Population (1,000s)		
Region	1970	2000	Change in population, %
Northeast	49,041	51,800	5.6
Midwest	56,572	59,600	5.3
South	62,795	96,900	71.5
West	34,804	59,400	70.6
U.S. total	203,302	267,700	31.8

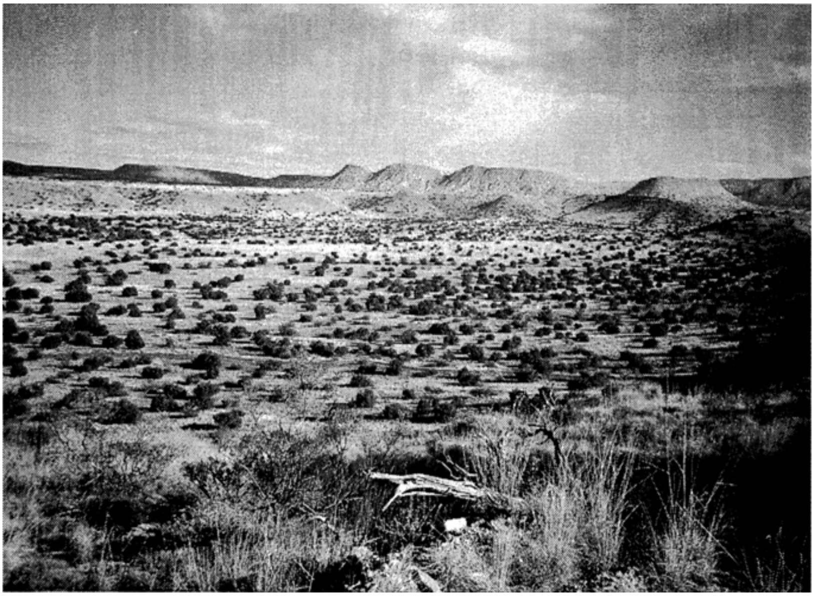
SOURCE: Adapted from U.S. Census (1999).

The prospect of significant increases in the demand for water contrasts with the circumstances that govern water availability. The supply of fresh water available for human consumption is limited. Only 0.3 percent of fresh water is found in rivers and lakes, the most accessible supplies for human use. Surface water renewal for rivers and small lakes is generally quite responsive to recent rainfall/runoff and can vary from a few days to several months. However, renewal for lakes that are large relative to their drainage basins (e.g., Lake Tahoe) can be as long as several hundred years. Groundwater accounts for roughly twice as much water as lakes and rivers in storing sustainable freshwater supplies (Gleick, 1993; Postel et al., 1996), suggesting that groundwater will be an increasingly important component of water supplies in the future. Renewable groundwater recharge, which is an important factor for coordinated management of groundwater systems, varies from tens to hundreds of years, depending upon climate, geology, and other factors (Freeze and Cherry, 1979; Wetzel, 2000). Fossil groundwater, which represents a resource that is not renewable by natural mechanisms during our lifetimes, may have been recharged several thousand years ago. If these sources are to be utilized effectively, it will be critical for water resource managers to better understand the distribution and variability of both surface water and groundwater supplies. Because stationarity (the assumption that past variability can be used to predict future variability) is likely to be abandoned as a foundation for estimating design events, new methodologies (e.g, ones based on long-term climate simulations or ones in which nonstationarity is incorporated in existing methodologies) need to be developed. Also, for short-term management and operation of water resources in the twenty-first century, more extensive real-time data to reduce the uncertainties associated with unusual events (e.g., regional or local extremes resulting from large-scale phenomena such as El Niño) will be needed.

Existing and potential threats to water quality will require careful attention. Although the United States has achieved admirable success in controlling and remediating water pollution in the last third of the twentieth century, there is little likelihood that further reductions in discharges from wastewater treatment plants and industrial sources (point sources) can achieve significant improvements. Thus, further improvements in water quality will have to be realized through the development of better technologies and techniques for controlling pollution in runoff and other diffuse (nonpoint) sources. Both the legacy of chemicals already in the ground—as exemplified by the inexorable salinization of many lands, rivers, and aquifers in the West—and future pollution of water resources must be addressed. A host of new water-quality problems may arise as synthetic chemicals are developed and advancements are made in monitoring for these compounds. The recent contamination of the nation's groundwater by the fuel additive methyltertbutylether (MTBE) is but one example of how promising technological advances can bring inadvertent environmental problems (National Science and Technology Council, 1996).

The failure of modern pollution control policies to recognize that water, land, and air are intimately related as contaminant sinks is a major problem that can be addressed through more holistic approaches. The intermittent monitoring of water-quality parameters and the piecemeal regulation of individual contaminants independent of larger-scale biogeochemical and ecosystem processes, both of which characterized the twentieth century, will be inadequate. Because the availability, fate, and transport of many critical contaminants is controlled by interactions with natural organic material in soils and sediments and in solution, a holistic and predictive understanding of water, carbon, and nutrient cycles will be required to address and manage water quality problems during this century. For example, the current regional-scale enrichment of the land surface and surface waters with nitrogen directly affects water quality (via toxicity to humans and fish) and indirectly causes ecological and biogeochemical responses (such as eutrophication) that influence the mobility of other contaminants.

The institutions devised for managing water resources in the twentieth century are not well suited to addressing the challenges of managing water resources in the twenty-first century. U.S. water rights were developed in times when water was plentiful and existing supplies were not fully allocated. Today, many eastern rivers are fully allocated and western resources require more flexible allocations to respond to changing demands. Existing institutions are inadequate for managing water as a common pool resource or in cases where water has the characteristics of a public good. In short, the fragmented and piecemeal institutional arrangements for managing the supplies and quality of water are unlikely to be sufficient to meet the water challenges of the future. Yet, knowledge about how such institutions might be modified and improved is scarce, and research on institutions occupies only a very small portion of the current water research agenda.



Much of the U.S. population growth has occurred in arid areas of the Southwest, such as New Mexico. The scarcity of water in this region is evident in the sparse vegetation found within the Sevilleta National Wildlife Refuge, 60 miles south of Albuquerque.

The structure of the water “industry” does not lend itself to the development of a systematic, integrated, and strategic water research agenda because it comprises many different types of organizations and institutions and consequently is not cohesive. There are thousands of public and private water and wastewater treatment purveyors. Municipal and state governments also play an important role in managing the nation's water resources, acting as purveyors, regulators, and planners. There are more than a dozen federal agencies with varying responsibilities for the nation's water resources. Of these parties, the federal government is responsible for most of the sustained water research.

Investment in basic science has been the foundation on which scientific advancements in the management of water resources and the attendant economic growth are built. Unfortunately, federal water research efforts are fragmented, generally reflecting the missions of each agency rather than a cohesive national perspective on water resources. Indeed, virtually every cabinet department contains one or more agencies with responsibility for some aspect of water resources management. Federal agency research agendas are largely planned and conducted independently of each other and sometimes independently of the research efforts conducted at the nation's universities. Moreover, the research agendas of operating water agencies focus almost exclusively on short-term operational problems. It is clear that the level of investment in fundamental research, which will form the basis for applied research and development a decade or so hence, is inadequate. It is not at all clear whether the fundamental research that is undertaken, largely at the nation's universities, is balanced in terms of its support of the various disciplines that are needed for water research, or how the research is used. Future research of this sort will almost certainly need to be interdisciplinary in nature, and there is scant evidence of any current effort to support effective interdisciplinary research aimed at the nation's water problems.

The Water Science and Technology Board (WSTB) perceives a need for a cohesive national water resources research vision for the twenty-first century, including agenda-setting, research coordination, and appropriate levels of public investment in water research. The research agenda presented in this report represents the consensus judgment of the Board about what research is likely to be most important in the early part of the twenty-first century. Research topics have been cast broadly in recognition that the specific focus and emphasis of the studies ought to reflect the circumstances and available knowledge at the time the work is undertaken.

The discussion that follows has been divided into three categories: water availability, water use, and water institutions. These categories are interrelated in that water availability deals with matters that affect water supply, including water quality, while water use includes factors that affect the wants and demands for water. Water institutions are treated in a separate section to highlight the importance of research in this area and to recognize that institutional questions fall within the purview of a different set of disciplines (e.g., political science, law, geography, economics) than do water availability and water use.

2

Water Availability: Quantity and Quality

In the twentieth century, there was often an unfortunate tendency to treat water-quantity and water-quality issues separately or to dismiss water-quality issues entirely. Although often done only for convenience, this artificial separation masks the importance of water quality in determining what water is available to serve what uses. Declines in water quality reduce the available water supply just as surely as does drought. Accordingly, water quality is treated here as an integral dimension of water availability in an effort to underscore the fact that water quality will have to be managed effectively to prevent water supplies from dwindling over time.

The principal water problem in the early twenty-first century will be one of inadequate and uncertain supplies, both here and abroad (Postel, 1999). Intensifying scarcity is likely to be the rule, as growing demands from nearly all water-using sectors will compete for finite levels of developed supply and remaining free-flowing water that support environmental and other instream uses. Throughout the first two-thirds of the twentieth century, scarcity was thought to apply only to developed supplies (NRC, 1992a). This scarcity was managed primarily by developing and augmenting water supplies—for example, by the building of dams and the resultant creation of reservoirs. In the latter third of the century, more attention was paid to the opportunities offered by demand management as the expense and the negative environmental consequences of traditional water-development schemes became more widely and clearly understood (Michelsen et al., 1998; NRC, 1992a). Successful management of scarcity will require more systematic, comprehensive, and coordinated approaches. All the available techniques and options will need to be regarded as alternatives, and most solutions will involve combinations of alternatives. In planning for the management of scarcity, good hydrologic (including water-quality) data will be absolutely essential.

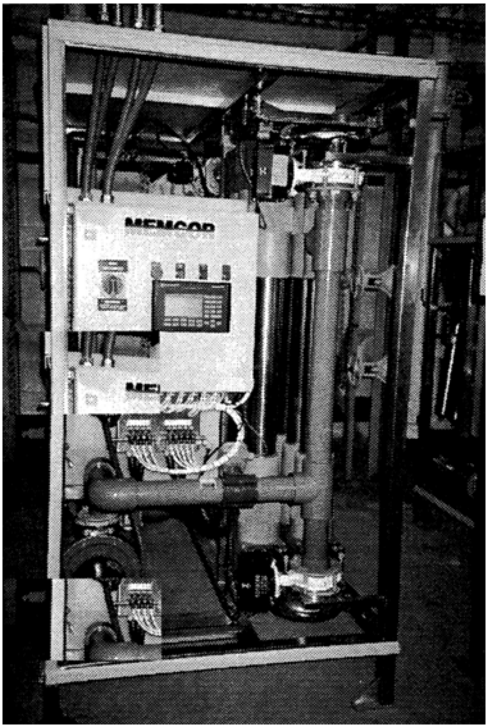
DEVELOPMENT OF SUPPLY-ENHANCING TECHNOLOGY

As scarcity continues to intensify, the search for new supplies can be enhanced by (1) the development of new supply-enhancing technology and (2) reducing the costs of some existing technologies.

There are three technologies that seem to hold considerable promise for the future. First, many of the wastewater treatment technologies that permit water to be recycled are already cost-competitive in many of the arid and semiarid regions of the West. Further reductions in cost will provide incentives for more widespread use of recycled water, thereby “expanding” the developed supply. Reductions in the capital and operating costs of such technologies will also permit municipalities and other water users to meet prevailing water quality discharge standards more inexpensively. A recent Water Science and Technology Board (WSTB) report evaluating potable reuse identified several issues that will have to be considered, including the need to improve toxicological testing of wastewater and exposure assessment methodologies to evaluate the health effects of using reclaimed wastewater for drinking (NRC, 1998). It will be necessary to improve public perception of recycled wastewater via research and educational programs in order for wastewater recycling to be successfully deployed. Research may be needed to identify other factors that influence adoption of reuse technologies, such as capital intensity and cost, reliability, and siting.

Second, further development of desalting technology appears warranted under certain circumstances. Like wastewater treatment technology, some desalting technologies are now cost-competitive where source waters are brackish. In contrast, the promise of seawater desalting has remained elusive despite substantial investments made during the last half of the twentieth century. Energy will continue to be needed to convert seawater to freshwater and to lift and transport the water to sites often remote from the ocean. The problems associated with brine disposal are also likely to continue. Nevertheless, the development of new, more effective reverse osmosis membranes and improved technologies for pretreating water have the potential to reduce the cost of desalting to affordable levels in regions where energy is relatively inexpensive, brine disposal can be managed, and demand is local. Thus, research on pretreatment technologies for membrane desalting processes and on the causes for membrane fouling in seawater could go a long way in stimulating further progress.

Third, many regions will need to augment storage to ensure adequate supplies of water during drought and dry seasons. Because surface water storage opportunities will be far less attractive than they were in the past for reasons of cost and environmental impact, there will be pressure to develop additional storage capacity by utilizing underground aquifers. Aquifer storage systems should be developed with extreme caution because water residence times in aquifers are usually longer than in surface water reservoirs. For this reason, it will be important to identify possible adverse environmental impacts and to devise management schemes to avoid or minimize those impacts. Substantive research is needed to address the practical problems of groundwater recharge and storage, such as when recharge should be done via percolation versus direct injection. Other issues include the potential for deterioration of groundwater quality because of recharge, deterioration of recharged water quality by minerals or contaminants in the aquifer, and the potential for recharge with surface water to damage the aquifer's storage capacity. The concept of aquifers as reactors and not merely as storage vessels needs to be developed to prevent problems as aquifer use increases.



New technologies for removing pathogens, such as this microfiltration unit, will be needed to help ensure that wastewater is safe for potable reuse.

The water resources research agenda for the twenty-first century should give priority to:

- developing new and innovative supply-enhancing technologies;
- improving existing technologies—particularly wastewater treatment, desalting technologies, and groundwater recharge and recovery schemes—so that both capital and operating costs will be lower; and
- assessing the safety of wastewater that has been treated for reuse as drinking water.

WATER QUALITY: FUNDAMENTAL AND APPLIED STUDIES

Future changes in land use will alter hydrologic and biogeochemical processes that control the quality of water derived from the nation's watersheds. As discussed in Chapter 1, current approaches to water-quality problems overlook important connections between local and regional hydrologic regimes. In particular, the monitoring and regulation of contaminants is currently carried out in a piecemeal manner that does not consider large-scale and long-range hydrologic and ecosystem processes or interactions between individual contaminants and major carbon and nutrient cycles. For these reasons, managing the quality of our water resources will require a holistic conceptual and modeling framework and will depend on more water-quality data and other hydrologic data acquired through *in situ* sensors and remote sensing.

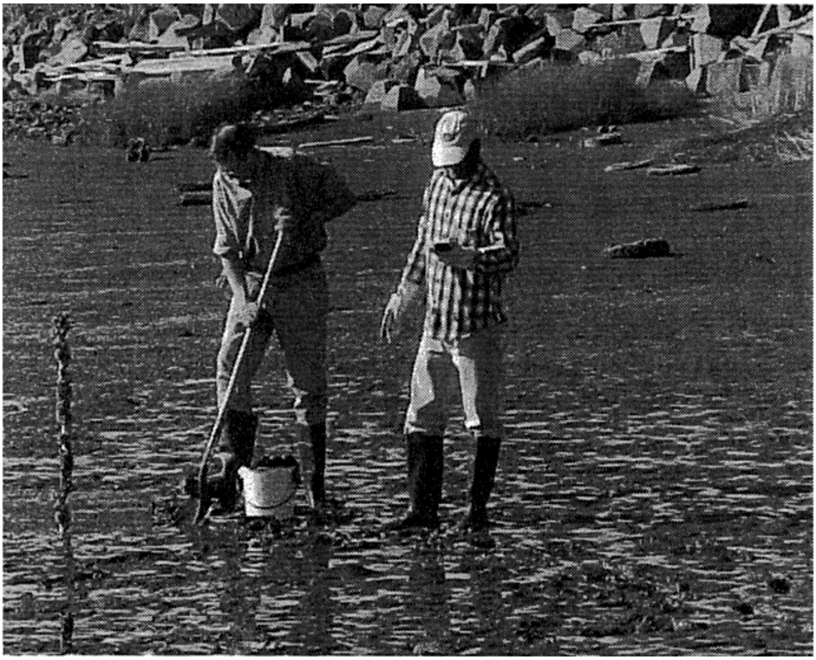
Development of this larger holistic framework will provide a means of better incorporating into water resource system management the results from several critical areas of water-quality research. It should be noted early on that preventing pollution is almost always less costly than cleaning it up after the fact. Nevertheless, the legacy of pollution that has already occurred must be addressed, in addition to the new sources of pollution that are currently going unabated. In particular, greater research is required on nonpoint source pollution, which accounts for nearly three-quarters of the contaminant loading to surface water and groundwater in the United States. Nonpoint source contaminants are delivered to waters via runoff, shallow groundwater, and atmospheric deposition. Nonpoint source pollution is a complex and spatially variable mixture of nutrients, toxic chemicals, sediment, and microorganisms from the land surface, and its transport is highly dependent upon the hydrologic regime, especially extreme events such as floods. Irrigated agriculture is a particularly troublesome nonpoint pollution source because of salinization, erosion, and release of fertilizers, pesticides, and leachable minerals such as selenium, which can create toxic conditions in receiving waters.

Controlling nonpoint source pollution requires identifying and quantifying the contributions of different land uses to pollutant loading, as well as implementing site-specific best management practices (such as forested buffers along waterways) to reduce pollutant loading. Unfortunately, identifying and quantifying nonpoint sources of pollution can be extremely difficult, especially for atmospheric deposition and other activities for which monitoring methods are inadequate. Significant efforts have been made to develop models that can predict pollutant loading from nonpoint sources given various land-use scenarios, but these models have yet to be tested thoroughly and verified for accuracy. Finally, best management practices used to reduce nonpoint source pollution are limited in their scope (what they can remove), efficiency (how much they can remove), and reliability (how well they work over time). Research is needed to improve monitoring methods and control technologies. Equally important is the development of a variety of societal approaches, including command and control regulatory regimes, voluntary and incentive-driven efforts, educational programs, landuse controls, and the control of pollution inputs to production processes. Research in these areas is typically expensive and time-consuming, but it will almost certainly be needed to undergird a workable national strategy for controlling nonpoint source pollutants. Indeed, problems of nonpoint source pollution are but one example of the need to integrate land-use and water polices.

More knowledge is needed about the susceptibility and resilience of terrestrial and aquatic environments to contaminant loadings, as the long-term impacts of contaminant accumulation may eventually undermine overall ecological function. The successful management of water quality in the twenty-first century will require a more comprehensive understanding of the ways in which the environment processes contaminants, how those processes vary, and their robustness as contaminant loads grow. Research should lead to better assessments of the resistance and resilience of ecosystems to damage by waterborne contaminants and of the extent to which different biogeochemical processes either buffer organisms from the effects of contaminants or accentuate the bioaccumulation of contaminants by organisms in higher trophic levels. Studies relevant to this general category should include characterizing the susceptibility of organisms and ecosystems to acute and chronic contaminant exposure, evaluating the recovery times of ecosystems following exposure to contaminants, and calculating residence times for pollutants.

Under conditions of water scarcity, groundwater will take on greater importance as a water resource. In the past two decades, important advances have been made in understanding the geochemical and microbial processes occurring in the subsurface that control contaminant transport. For example, the roles of iron, manganese, and humic substances as electron acceptors have been demonstrated in laboratory and field settings. Field and modeling work can now be initiated to incorporate these processes into reactive transport modeling, which can be coupled with the advanced modeling approaches now used for groundwater flow systems. The protection, mitigation, and enhancement of groundwater quality will depend on a better understanding of the rates of chemical contaminant movement, of chemical, biochemical, and physical transformations of contaminants, and of potential remediation technologies. Some emphasis should be given to studies of the long-term availability of contaminants assimilated into soil and sediment. Understanding the implications of shallow groundwater contamination for hydrologically connected surface waters and for the long-term integrity of underlying deep groundwater can be used to evaluate trade-offs between surface water and groundwater resources on regional scales.

These research needs apply not only to chemical contaminants but also to microbial pathogens. Microbial water pollution, which has always been an issue in developing nations, is a reemerging concern in the United States. Recent outbreaks of waterborne disease demonstrate the continued susceptibility of both surface water and groundwater supplies, from the *E. coli* outbreak in New York (CDC, 1999) to the *Cryptosporidium* outbreaks in Wisconsin and Nevada in which thousands were sickened, some fatally, from contaminated tap water (Smith and Rose, 1998). Microorganisms pose a particular concern in the water resources arena because of the very low tolerance exhibited for pathogens in water by humans, especially children, the elderly, and immunocompromised persons. Microbes originating from animal and human wastes are known to be present in surface source water, groundwater, and distribution systems (LeChevallier et al., 1999a,b). In a national survey, 30 percent of groundwater wells tested in the United States showed evidence of viral contamination (Abbaszadegan et al., 1999), and as much as 40 percent to 80 percent of surface waters tested contained parasites (Smith and Rose, 1998). Despite substantial advances in molecular biology (e.g., polymerase chain reaction and the promise of new techniques such as gene chip technology and bioinformatics), their application to water science and technology has been minimal. Further research on microbial detection methods, the building of occurrence databases, the development of fate and transport models, and determinations of disease risks are needed.



Contaminated sediments pose challenging problems in dealing with widespread sources that adversely affect water quality. The links between sediment biogeochemistry, contaminant availability, benthic organism feeding, and food web effects are not well understood. Thus, it is not possible to make reliable predictions, and, hence, experts disagree on management solutions.

Development of a more integrated approach that couples water quantity and quality will provide critical knowledge for improving and redesigning the nation's water resource infrastructure to meet multiple objectives under an uncertain future climate. In the twenty-first century, attention must be given to the aging of the nation's water resource infrastructure and its effect on aquatic ecosystems and water quality. In addition to the changes in the operation of reservoirs and in the discharge of treated wastewater to surface waters or groundwaters previously mentioned, changes in drinking water treatment and distribution systems will be needed. A cornerstone of the drinking water industry's effort to provide safe water has been a “multiple barrier” approach, which includes watershed protection, water treatment, and distribution system integrity. Substantial gains have been made in the development of innovative treatment technologies and, very recently, significant progress has been made in protecting some watersheds (NRC, 2000). However, improving distribution system integrity has received little attention to date. Surveys of aging infrastructure suggest that substantial investments will be required to maintain distribution systems in the coming years and to limit their vulnerability to extreme hydrologic events through in-line infiltration. Moreover, contemporary regulations on disinfection and disinfection byproducts are likely to result in fundamental changes in disinfection practices. To support these changes, research will be needed to strengthen out understanding of the microbial ecology as well as the physical and chemical properties of distribution systems.

Finally, in order for these new conceptual advances, data resources, and coupled transport models to be effectively used by decision-makers, basic research is needed to develop better risk assessment and risk management capabilities with respect to water quality. Little is known about the synergistic effects of chemical mixtures in aqueous environments or about the biological and human consequences of long-term exposure to low levels of many substances. Research efforts should be coordinated with additional research on human exposures and risk management itself. Specifically, more research is needed on methods for prioritizing risks and assessing multiple sources of risk on a relative basis. In addition, work is needed to understand the factors that affect individuals' views of water-related risks so that effective risk management and communication programs can be jointly implemented.

In the water-quality arena, the water resources research agenda for the twenty-first century should give priority to:

- identifying physical, chemical, and microbial contaminants and understanding their fate and transport;
- identifying and developing innovative technologies for preventing pollution;
- controlling nonpoint source pollution;
- improving our ability to forecast the impact of land-use changes and best management practices on contaminant loading to surface water and groundwater;
- improving our ability to predict the impact of contaminant load changes on ecosystem sercices, biotic indices, and higher food chain organisms (fish and shellfish).

- determining the role of the environment in processing and converting contaminants;
- developing better techniques and data for assessing the capacity of the environment to buffer organisms from contaminants and to recover from the effects of contamination;
- improving the integrity of drinking water distribution systems; and
- enhancing the scientific bases for risk assessment, risk management, and communication and decision-making regarding risk.

IMPROVING HYDROLOGIC FORECASTING AND PREDICTION

Because both short-term and seasonal weather play an increasing role in the nation's economy, short-term forecasting of precipitation and floods/ drought becomes important. Among other uses, forecasts are subsequently used to derive “temperature degree” days, which affect the energy market; to predict severe weather, which affects transportation and regional retail distribution centers; and to predict seasonal weather, which affects human health conditions such as West Nile encephalitis and malaria. Thus, there is substantial practical application for research aimed at improving methods of forecasting precipitation and streamflow, accurately assessing these predictions, and determining their usefulness for water management.

Improvements can be made both in the accuracy of forecasts and in the length of time for which accurate forecasts can be made. Research should also focus on improving methods of predicting runoff, streamflow, and actual evapotranspiration on a regional basis, as these parameters directly affect water management. A better understanding of historic precipitation and streamflow patterns may lead to better predictions of future patterns of precipitation and steamflow and, importantly, the variability of these patterns—especially as they relate to climate anomalies such as El Niño. Because such large-scale weather patterns can induce extreme local conditions, methods to translate predictions of variability from the regional scale to the local scale are critical to water management.

Although the average annual precipitation in the United States has not changed significantly over the last century, the incidence of heavy precipitation (and correlated high streamflow) has increased (Groisman et al., 2001), especially in the eastern portion of the country. Conversely, there is evidence of a retreat in spring snow cover extent over western regions of the country, which will affect water availability and possibly the occurrence of drought (Lettenmaier and Gan, 1990). Research that documents these changes and identifies their causes (e.g., using remote sensing and *in situ* measurement of snow hydrology) could contribute to our ability to predict severe weather and thereby manage ensuing floods and droughts more effectively. Such research is especially needed to underpin risk-based evaluation of flood and drought response policies. In addition, work aimed at understanding why damage from floods and droughts has increased over time would be useful in evaluating past flood and drought management policies. Such evaluations could contribute much to the formulation of enlightened policies in the future.

Finally, additional research to enhance our understanding of global climate change and its impacts will be needed. Changes in climate could exacerbate periodic and chronic shortfalls of water, particularly in arid and semiarid areas of the world. Such areas include many developing countries that already have limited resources with which to respond to water shortages. Climate change is leading to smaller snow packs and earlier melting (Lettenmaier and Gan, 1990), which puts at risk the water supply of semiarid regions of the western United States. For other regions, model simulations

Flooding can be catastrophic in areas where waterways are heavily developed. Photograph courtesy of Elizabeth Rogers.

of future climate change generally predict increased precipitation (Giorgi et al., 1998a), which increases the possibility of severe weather and flooding in temperate and humid regions and raises concerns about dam and levee failures, greater quantities of polluted runoff, and salinization of coastal aquifers. Global warming is likely to lead to sea level rise (on the order of a few meters) due to both thermal expansion of the oceans and melting of the Antarctic ice sheets. In the United States, an estimated 46 million people per year currently are at risk of flooding from storm surges, and climate change will exacerbate these problems, leading to potential impacts on coastal ecosystems and human coastal infrastructure (Watson et al., 1997). Finally, carbon storage in vegetation and soils is critical to global carbon cycling, and it ultimately relies on the availability of water to support vegetative growth (Tenhunen and Kabat, 1999). Disruption of this carbon storage, either by increased human water interception or altered rainfall patterns, could have serious repercussions for the global climate via carbon dioxide emissions to the atmosphere. Clearly, hydrologic issues related to global change should be included in the water resources research agenda (NRC, 1999a).

The water resources research agenda for the twenty-first century should give priority to:

- improving our capacity to accurately forecast the hydrologic cycle (precipitation, actual evapotranspiration, and streamflow) over a range of time scales (days to seasons) and on a regional basis;
- better understanding and predicting the frequency and cause of severe weather that leads to floods and droughts;
- evaluating why damage from floods and droughts has grown over time; and
- improving our understanding of global change and its hydrologic impacts.

NEED FOR ADEQUATE HYDROLOGIC DATA

Intensifying water scarcity cannot be successfully addressed in the absence of reliable data about the quantity and quality of water over time and at different locations. The end-of-century trend of investing fewer and fewer dollars in data-gathering efforts—the declining number of stream gages is but one example—will need to be reversed if availability is to be adequately characterized. It is also important to recognize that the availability of water is random in nature and that the relative extent of water scarcity will be influenced importantly by hydrologic variability.

The hydrologic measurements needed to improve short-term hydrologic forecasting and water management will be qualitatively different from the types of measurements needed for water resources planning. Historically, data collection focused on long-term river discharge data for water supply planning, flood peak discharge data for flood control design, or precipitation data for flood prediction. In the decades ahead, there will be a greater need for data collected in near real time for water systems operations. This requires merging water quality and quantity data with predictions from weather and seasonal climate models. Currently, data collection systems are within the purview of different government agencies. Inasmuch as these agencies are frequently independent of each other, compiling data into coherent sets can sometimes be difficult.

The need for adequate data is not limited to surface water. For much of the nation, too little is known about the rates of recharge to and extraction from groundwater aquifers. Groundwater supplies drinking water to approximately 50 percent of the U.S. population, and it can be critically important in the management and buffering of drought for all water using sectors. It will be crucial to understand how rates of recharge change over time, to identify the variables that influence recharge, and to determine sustainable rates of groundwater extraction (Alley et al., 1999). In addition, all groundwater aquifers are vulnerable to quality deterioration. Little is known about the rates of degradation and what they imply for the expected life of the aquifer in the absence of treatment (NRC, 1993). These rates need to be characterized and the contaminants in question and their sources identified. Such information is necessary to be able to preserve aquifers as resilient and robust components of the water supply system.

Databases from research and monitoring programs should have the capacity to connect to each other through commonly accepted linking factors, such as latitude and longitude, in order to increase their availability and maximize their value for research and public purposes. In particular, water informatics is now quite feasible, given modern water information technologies and their links to emerging monitoring, visualization, and modeling technologies. The U.S. Environmental Protection Agency (EPA) is giving considerable attention to linking factors in the National Drinking Water Contaminant Occurrence Database, primarily for chemicals, thereby strengthening the nation's ability to understand the nature and scope of these threats to public health. However, no adequate occurrence database exists for microbial contaminants.

The water resources research agenda for the twenty-first century should give priority to:

- determining the country's hydrologic measurement needs and developing a program that will provide these measurements in an effective and efficient manner;
- further developing data collection and distribution in near real time for the improvement of weather forecasting, river discharge forecasting, and water resources operations; and
- developing technically improved methods of measuring water flows and water quality, both surface and subterranean. Appropriate attention should be given to remote sensing as well as *in situ* measurement techniques. Methods for optimally merging observations from different remote sensors (e.g., satellite, radar, and rain gages) and for estimating the uncertainty of the combined products are also needed.

3

Water Use

In the twentieth century, future levels of water use were usually estimated by simply extrapolating historical per capita use rates and multiplying them by the projected growth in population. This approach is fundamentally flawed because it ignores the possibility that the social, behavioral, economic, and technological determinants of use can change over time. Although water use is clearly related to the amount of water that is available, it is also determined by a host of other factors such as price, cultural norms, landscaping preferences, and the availability and use of water-conserving technology. One reason for the failure to consider these variables in water resources planning is that the impacts of these variables on water use are not well understood. More effective water resources planning and management in the twenty-first century will require a clear understanding of the variables that determine water use. The ability to manage scarcity by economizing and "regulating" demand constitutes one important option available to the water manager.

DETERMINANTS OF CONSUMPTIVE WATER USE

In the water resources arena, the term "use" has different meanings. Consumptive uses involve changes, either in phase or quality, that render water unavailable for reuse. (Water that has been severely degraded can sometimes be treated for reuse, as discussed in Chapter 2.) For nonconsumptive uses, changes in the properties of water usually are not sufficient to bar its subsequent reuse. Diversionary uses, such as for domestic (household), commercial, public, industrial, and agricultural sectors, are frequently but not always consumptive. Instream uses (e.g., hydropower) are almost always nonconsumptive.

There is an urgent need for improved technologies that will permit water to be used more efficiently by all sectors. However, the development of such technologies is hindered by the surprising lack of information about the basic determinants of consumptive uses. Even in the agricultural arena where substantially more data are available, what is known about consumptive use is incomplete. Additional research is needed on the determinants of the levels of all these uses.

Little is known about the determinants of water use in commercial establishments or for public purposes such as cemeteries, golf courses, and parkland irrigation. Although these uses are often small when compared with domestic, industrial, and agricultural uses, they will need to be managed as part of any comprehensive scheme to address scarcity in the coming decades. Studies to identify the parameters that affect the level of commercial and public uses and the variability of those uses are especially needed.

The determinants of domestic uses have been identified for some large municipal areas and frequently form the basis of sophisticated schemes for managing water use. For other large municipalities, these determinants have not been identified with any degree of accuracy, and the determinants of domestic use have not been characterized at all for medium- and small-sized communities. It has been more than 30 years since the last comprehensive study of the determinants of domestic use (Howe and Linnaweaver, 1967), although a limited study of single-family residential indoor and outdoor water use was recently completed in 12 communities, mostly in western North America (AWWARF, 1999). Given that many medium-sized and smaller communities cannot afford to conduct their own studies of determinants, an updated comprehensive study would be of great value.

It is well understood that the level of industrial demand for additional water is extremely sensitive to pollution control laws and regulations (NRC, 1994). With the advent of the Clean Water Act, industry became much more conscious of water use, and a high percentage of water used by industry today is recycled. Studies of how industrial use levels respond to changes in pollution control laws and regulations and other variables would be helpful. Completion of such research will permit water planners and managers to estimate accurately the effect of changes in water pollution regulations on the levels of industrial consumption and use.

In general, agricultural irrigation water use is known to depend on climatic variables (e.g., temperature and humidity), crop type, and the uniformity with which water is applied. The relationship of these variables to levels of use has been characterized for some areas but not for others. Precise knowledge of these determinants and their relationship to crop yield is virtually a precondition for careful and effective agricultural water management. A comprehensive characterization of the determinants of agricul tural water use for all regions where irrigated agriculture is practiced is therefore essential.

Results from this research should permit the development of improved water demand models for each sector that uses water consumptively. Efforts should be made to generalize these models so that they can be used widely and can be applied by water managers in different regions of the country. Although improved data should lead to better models, improvements in the specification and estimation of such models should also be accorded research priority. If possible, models should be designed to account for demand management that may become necessary during short-term recurrent drought and projected long-term supply problems. Conservation-induced reductions in individual and systemwide water demand can be used to alleviate temporary water shortages, avoid increased water supply infrastructure and consumer costs, and extend the ability of existing supplies to meet current and growing demands. Research to develop more intelligent demand management methods, which are valuable for domestic, industrial, and agricultural water use, is an important dimension of the solution.

Research on the determinants of water consumption and the development of models should also encompass drought responses. It is well known that some techniques that work well in drought management, such as public appeals, are not particularly effective in helping to manage scarcity over the long run. Studies focused on the special circumstances of drought management should improve the nation's capacity to manage droughts of the future.

The water resources research agenda for the twenty-first century should give priority to:

- comprehensively characterizing the determinants of water use in the domestic, commercial, public, and industrial sectors and
- determining with greater precision the relationship of agricultural water use to such variables as climate, crop type, and water application rates for all regions where irrigated agriculture is practiced.

AGRICULTURAL WATER USE

Agriculture is of special significance because it uses most of the developed water supply in many regions of the United States and because the patterns of agricultural water use are likely to change in the future. Irrigated agriculture accounts for almost two-thirds of total developed water supply withdrawals (Figure 3-1) and over 84 percent of consumptive use (Table

3-1). In many of the semi-arid western states, agriculture uses between 75 percent and 90 percent of the developed water supply. A significant quantity of irrigation water has been made available to growers in the western United States at heavily subsidized prices. As the competition for water has intensified and reallocations have become inevitable, irrigation withdrawals have decreased about 10 percent in the last 20 years (Figure 3-1). However, population growth will likely fuel the demand for water to support irrigation (CAST, 1997; NRC, 1996a). Agricultural water use will probably continue to dominate total consumptive use even though its magnitude may be somewhat less than it was in the latter twentieth century.

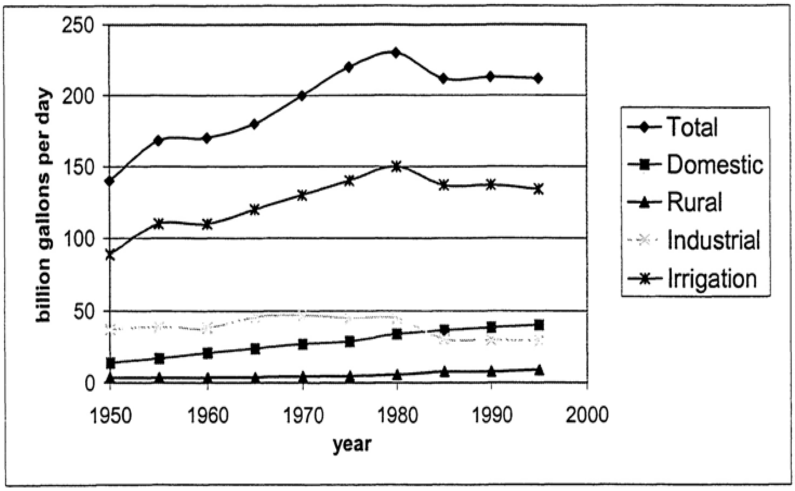


FIGURE 3-1 Trends in water withdrawal in the U.S. by sector. Total water withdrawals include irrigation, public water supplies, rural withdrawals, and industrial uses *other than* for thermoelectric and hydroelectric power generation. Note that irrigation use is nearly all consumed by evaporation in contrast to the other withdrawals, which are largely recycled. SOURCE: Solley et al. (1998).

There has been no significant increase in the availability of developed supplies of groundwater or surface water since the mid-1970s (Solley et al., 1998). Despite this and despite the decrease in withdrawals noted above, irrigated acreage has actually increased because of conservation, efficient timing, and improved water delivery, particularly east of the Mississippi River where humid conditions dominate (Solley et al., 1998). In the long run, however, it will be difficult to sustain irrigated agriculture now that the fresh water supply has been nearly completely developed. New knowledge will be needed if irrigation water is to be managed in order to avoid contamination from chemicals and salts and to prevent erosion. Salinization of both ground and surface waters continues to be a problem on many of the irrigated lands throughout the West, and many of the techniques used for the management of drainage waters ultimately fail to maintain salt balances. Research should continue on the development of more efficient water management techniques. For example, improvements in the precision of water application to crops at the appropriate time will likely increase the efficiency with which water is used. Such improvements may also result in a decrease in pollutant loading from irrigated agriculture and thus improve overall water quality.

TABLE 3-1 Consumptive Use of Water in the United States by Sector, 1995

Sector	% of Total Consumption
Domestic–Commercial	8.0
Industrial–Mining	4.1
Thermoelectric	3.3
Irrigation–Livestock	84.6

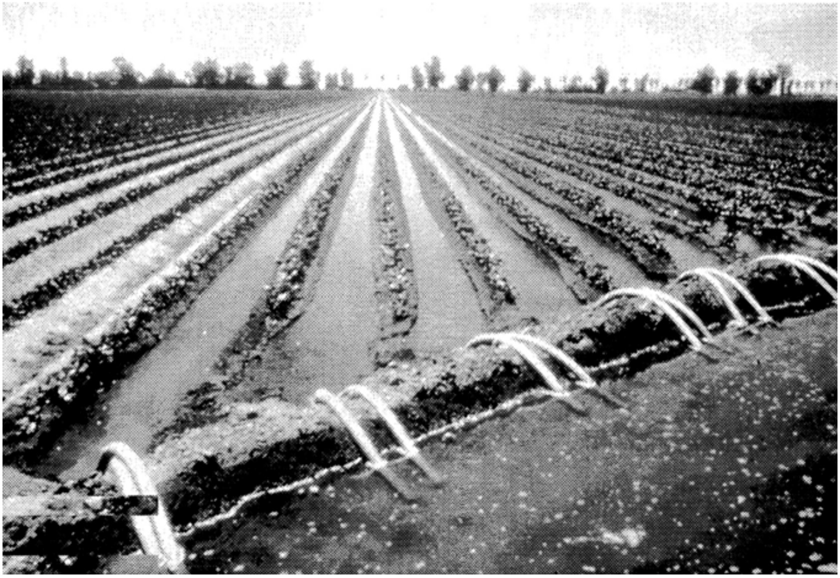
NOTE: Estimates are based on information submitted by states, tribes, and other jurisdictions that do not use identical survey methods.

SOURCE: Solley et al. (1998).

In some regions, it may be necessary to convert irrigated land to dryland farming. Some lands overlying the Ogallala aquifer, within which the groundwater has been in decline for decades, are candidates for such conversion. The Ogallala aquifer underlies a vast portion of the High Plains stretching from southern South Dakota to northwest Texas and accounts for 30 percent of all the irrigation water used in the United States. The most severe depletion has been in Texas, which had lost about 25 percent of its portion of the aquifer by 1990. Research is needed to characterize the conditions under which dryland farming can be profitable. There may also be possibilities for developing crop varieties that are specially adapted to dryland conditions and produce higher yields than would otherwise be expected. One component of a general research program should focus on the development of sustainable agricultural practices that include improved crop varieties for dryland cultivation.

Similarly, the potential of genetic alteration to improve crop water use is increasing and should be comprehensively explored. Crops using different pathways of photosynthesis have clear water use differences in the field

(Kramer and Boyer, 1995), and it may be possible to convert crops to more efficient pathways in the future. However, it is unclear whether enough genetic alteration can be achieved to accomplish such fundamental changes at this time. More fruitful approaches may be to use genetic engineering to promote deep rooting and increase the fraction of the plant devoted to grain and fruit in dry conditions. In addition, genetic control that improves crop quality may lead to a reduction in the need for weed- and pest-control chemicals, thereby resulting in greater economic return for the water used (NRC, 1996a) and improved water quality. Research should be pursued in all these areas as should research aimed at identifying potentially undesirable side effects from crop gene alteration.



Not only does agriculture consume the majority of freshwater supplies in the United States, it can also change the timing and magnitude of stream flow via drainage tiles and irrigation ditches.

Priority should be given to research on agricultural water use that focuses on:

- developing improved crop varieties for use in dryland agriculture (like those that sustain grain and fruit development in dryland conditions or are disease-resistant and drought-tolerant);

- improving the sustainability of irrigated agriculture, including more efficient management of salt balances and management of agricultural drain waters; and
- developing crops for more efficient use of water, and optimizing the economic return for the water used to irrigate them.

ENVIRONMENTAL WATER USE

Much of what is known about aquatic ecosystems and the role of water in supporting environmental services is fragmented and piecemeal. There is a critical need to understand aquatic ecosystems in a broad systems context because intensive water development has dramatically altered these systems, as manifested by extinct and endangered species, loss of wetlands and riparian areas, and loss of biological productivity (Abell et al., 2000; Dahl, 1990; Moyle and Leidy, 1992). Research is needed to help determine the water requirements of aquatic and riparian ecosystems necessary to maintain certain environmental functions, such as provision of wildlife habitat, flood control, and assimilation of contaminants. In addition, there is now much interest in the removal of dams and the restoration of original flow regimes in riverine corridors in many parts of the country. Yet, there is limited information about how the timing of certain hydrologic events controls ecosystem structure and functioning. A systematic understanding of the relationships among biological, hydrologic, and geologic factors will ultimately be needed if efforts to alter hydrologic regimes are to be successful. Systems approaches to modeling and to understanding aquatic ecology have been ongoing; however, much additional research is needed if the promise of these approaches is to be realized.

Similarly, understanding the relationship between land and water resources is essential to managing water on a watershed basis (NRC, 1999b). There has been substantial research on the relationship between land use and its effect on water quality and quantity, but much remains to be learned. The success of efforts to manage water on a watershed basis has been hindered somewhat by the tendency to study terrestrial and aquatic ecosystems independently of each other and even more so by the tendency to base studies on geographic rather than watershed-based boundaries. The scientific foundations upon which advances in watershed management will be based will need to include extensive knowledge and understanding of the relationships between terrestrial and aquatic ecosystems.

Certain flow regimes, like annual floods, are vital for maintaining the habitat of many migratory birds, such as these Sandhill cranes along the Platte River in Nebraska. These hydrologic regimes are often disrupted by dam construction. Photograph courtesy of Elizabeth Rogers.

Additional research is also needed on issues related to the protection of species diversity in aquatic habitats. It is common knowledge that the decline and extinction of aquatic species is attributable to changes in flow regimes and water quality (NRC, 1992b). Thus, a comprehensive assessment of potential limiting factors and the means of managing those limiting factors in optimal ways is needed. Research aimed at developing strategies for managing aquatic habitats for the purpose of preserving biodiversity and maintaining ecosystem health is needed as well.

Priority should be given to research aimed at developing a broad and comprehensive understanding of aquatic habitats. Such research should:

- elucidate the behavior of aquatic ecosystems in a broad, systematic context;
- describe the interrelationship between aquatic and terrestrial eco

systems to support the development of improved regimes of watershed management;

- support the enhancement and restoration of species diversity in aquatic ecosystems; and
- describe how water-quality parameters can be manipulated to maintain and enhance aquatic habitats.

4

Water Institutions

The creation of innovative water institutions and other contributions from the social sciences are critical for effective water resource management. Yet, during the late twentieth century, the amount of research on water institutions dwindled in comparison with other aspects of water resources research. Many of the institutions that we currently rely upon for the management of our water resources were devised in the nineteenth century to respond to nineteenth-century problems (Gillilan and Brown, 1997). For example, many water laws, particularly in the West, were created to address circumstances that have now largely passed. These laws as well as other institutions are not well suited to respond to the problems of the twenty-first century. The institutional issues on the research agenda are particularly urgent. This urgency and the historical underinvestment in institutional research suggest that efforts should be made to invest relatively more in institutional research than has been the case in the past.

LEGAL AND POLITICAL ISSUES

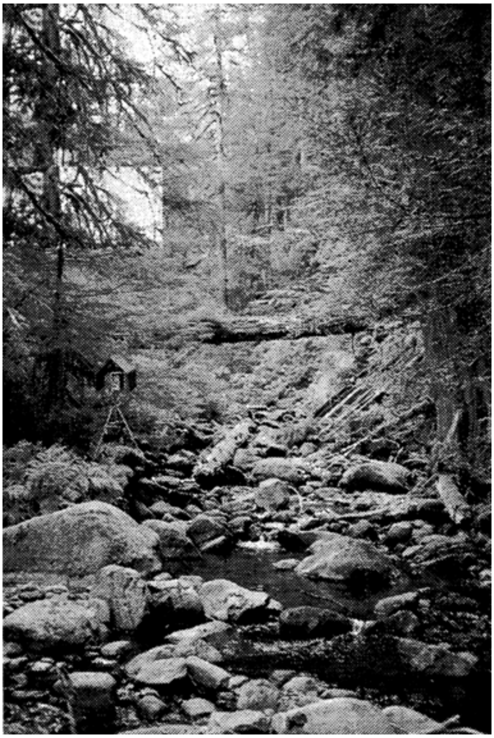
The statutes that govern U.S. water resources evolved in response to changing notions of societal needs. In the western United States, water allocation systems favored the development of water supplies, memorialized in the phrase “use it or lose it.” Many decades later, water quality was recognized as a matter of national priority, and starting with the passage of the Clean Water Act in 1972, a new set of federal and state laws was superimposed on common law water doctrines. The Endangered Species Act reflected national concern with the protection of biodiversity and, indirectly, ecosystems. Most western rivers now have federal and state protected endangered species as part of their ecosystems, as do some eastern rivers. The statutes often have conflicting objectives, with many state water laws being poorly adapted to the present era of water scarcity. In general, the legal system has failed to develop statutes that integrate the multiple goals that must govern water management in the twenty-first century. Studies of comparative law and institutions for managing water in a flexible and adaptive fashion could help in developing new state water codes where needed.

Although groundwater is a significant part of the water supply and is the primary source of water for a number of municipalities, state groundwater law sometimes fails to promote the efficient use of groundwater and protect groundwater quality. In addition, groundwater law often is not well integrated with the statutes governing the use of surface waters. This leads to fractionated and inefficient water management. The development of improved legal principles and model statutes governing groundwater use to facilitate the application of conjunctive use is needed.

Existing laws also are not well suited to dealing with transboundary waters. In the opinion of the Water Science and Technology Board (WSTB), some individual arrangements such as the International Joint Commission, an institution through which Canada and the United States govern the border waters, have worked relatively well. Other transboundary arrangements have proved to be cumbersome or even unworkable. The need for effective legal arrangements (and other institutions) for the governance of transboundary waters will intensify as border populations grow. This will be particularly true of U.S./Mexico boundary waters. Comparative studies that evaluate various legal and institutional arrangements, identifying the strengths and weaknesses of each, could form the basis for the development of effective new ways of managing transboundary waters.

Existing laws and institutions often fail to address common pool or public good characteristics. In many instances, instream flows and ecological values are not adequately protected, and it appears that new laws may be needed if such protection is to be provided. The uncertainty, inefficiency, and inequity associated with the current status of federal reserved Native American water rights (as well as other federal reserved rights) need to be addressed. Similarly, laws or rules that provide nontraditional claimants with access to the nation's waters could address issues of fairness and resource uncertainty.

Legal provisions sometimes inhibit the development and implementation of innovative policies for water management. For example, adaptive management applies findings from carefully monitored experiments to the adjustment of future management and policy decisions in light of changing conditions. It aims to incorporate diverse stakeholder preferences within the context of complex ecosystems, and it underpins water management programs in several areas of the United States, such as the Florida Everglades and Glen Canyon Dam on the Colorado River (NRC, 1999c). Yet, it is unclear whether adaptive management can be incorporated into statutory water management programs that require the selection of fixed goals and specific means for reaching them. Policy- and legal-based research can improve our understanding of how water resource institutions can integrate adaptive management practices into existing management and legal regimes, while simultaneously protecting the rights of stakeholders.



The statutes that govern U.S. water resources are highly variable across the U.S. In the Pacific Northwest, such as Mac Creek, Oregon, many streams are better protected from water quality and quantity degradation by Forest Practice Acts and the Endangered Species Act than by state water laws.

The water resources research agenda for the twenty-first century should give priority to developing new legal arrangements governing diversions and consumptive use that emphasize flexibility and facilitate the management of water scarcity. Such research should:

- develop legal regimes that promote effective groundwater management and facilitate conjunctive use of surface water and groundwater;
- explore and resolve issues related to the governance of water where

it has common pool and public good attributes and arrange for the management of transboundary waters;

- resolve the uncertainties attending to Native American water rights and other federal reserved rights and incorporate considerations of equity into existing water management laws;
- conduct comparative studies of water laws and institutions with special emphasis on the dynamics of institutional change; and
- promote the wider use of adaptive management.

ECONOMIC INSTITUTIONS

During the 1980s and 1990s, increasing emphasis was placed on the possibilities of using economic institutions to manage water resources (Haddad, 2000). Economic institutions are by definition adapted to the management of scarcity, and pricing and markets have been shown to have much promise in managing water scarcity. Additional research, however, remains to be done. There are a number of critical issues related to the adequacy with which economic institutions allocate common pool resources and pure public goods. In addition, there are issues related to how to deal with third-party impacts of water markets. Additional research on economic institutions could help to resolve many of these issues and thereby facilitate the use of economic institutions in managing water scarcity.

Continuing research is needed to develop improved methods for estimating the value of water in circumstances where it is not marketed or where market-generated prices do not adequately reflect true value. Thus, for example, issues of how to value aquatic habitats and the ecological services provided by aquatic habitats remain to be resolved. Although there is need for improved methods of valuing non-marketed resources that are unrelated to water resources, there is a specific need for improved valuation techniques in the water resources arena. In addition, research is needed to evaluate and develop methods for allowing the services deriving from the common pool and public good nature of water to be allocated through markets or in association with markets. A number of efforts have been made to protect and enhance environmental resources in marketlike situations, including the imposition of taxes on the gains from trade. *Ex post* studies of the efficacy of existing methods and proposals for protecting environmental uses would be helpful. Techniques are also needed to allow appropriate entities to acquire additional water for environmental and other public purposes through markets. In the same vein, research focused on the development of economic institutions that would protect and enhance the common pool and public good attributes of water resources would be helpful.

Further research on the development of efficient markets and marketlike mechanisms for allocating water are also needed. Markets can take many forms, and there has been considerable effort to identify the forms that are best suited for water rights, storage, conveyance, and water itself in both the United States and Europe. Experiences with marketlike institutions in other sectors, such as energy, should also be evaluated (Tietenberg, 2000). In particular, studies are needed to develop innovative low-cost ways for predicting whether adverse impacts on third parties who are not directly involved in the market transactions are likely to be part of a given market transaction, and for estimating *a priori* how large these impacts will be. Methods of accounting for third-party effects that keep transaction costs low must be developed (NRC, 1992a). Studies of the benefits and costs of privatizing water and wastewater treatment services are also needed. Such studies should focus on the question of whether services can be provided more efficiently by the private sector and the related question of how the private sector is to be regulated so as to prevent monopolistic pricing practices and ensure that public resources are allocated and used fairly and efficiently.

Finally, different pricing mechanisms and their application in different management schemes should be explored. Marginal cost pricing (i.e., setting the price of water equal to the cost of providing the last increment of supply) is not always possible or appropriate. Systems that mimic marginal cost pricing (such as increasing block rate structures found in the electric power industry) but do not conform in all respects may be superior in some instances. Much controversy still surrounds estimates of the price elasticity of demand for water. [2] Empirical estimates of how water consumption for each water-using sector varies in response to different water prices would provide a useful basis for utilizing prices to manage water resources.

The water resources research agenda of the twenty-first century should give priority to:

- developing new and improved methods for estimating the value of nonmarketed attributes of water resources;
- investigating the potential use of economic institutions to protect common pool and pure public good values as they relate to water resources;

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[2] Price elasticity of demand is the percent change in the quantity demanded of a good divided by the percent change in price.

- devising and developing more efficient markets and marketlike arrangements that account appropriately for third-party impacts and in which public goods and common pool resources are accorded a "level playing field";
- elucidating the role of prices, pricing structures, and the price elasticity of demand; and
- determining the appropriate role of the private sector in achieving efficient provision of water and wastewater services. This research should also focus on efficient and effective ways of regulating private providers.

EMERGING SOCIAL SCIENCE ISSUES

There are several important social science research issues that are not clearly of legal or economic bearing but will need renewed emphasis and attention in the twenty-first century. Anthropologists, geographers, political scientists, psychologists, and sociologists have not been constantly involved in water resources research, although the importance of broader perspectives in the study of human institutions has been recognized (NRC, 1992c, 1997a). The effective management of many of our water problems will require contributions from all these disciplines. Differing value structures and cultural norms, the importance of perception, and the role of politics and political institutions are but examples of areas where contributions from the social sciences are needed.

Over the past 25 years, there has been a growing awareness that individual perceptions and social values greatly influence public decisions (Fischhoff, 1995). Perceptions of experts, stakeholders, and the public about the risks, benefits, and mitigation options affect risk management processes. Each party's knowledge, beliefs, and overall perception of the decision process can significantly change the results of that process (Fischhoff, 1995). However, management strategies are only infrequently based on a systematic assessment of the knowledge, perceptions, and beliefs of differing parties. Science-based methods such as mental modeling and value integration have received little recognition to date by the water management community as valuable approaches (Bostrom et al., 1992; Gregory et al., 2000). Applied research utilizing these and other science-based methods is needed to determine the key factors that affect water-related risk perceptions, communications, and decision processes. New knowledge about stakeholders' concerns and priorities will provide a sound foundation for designing and implementing effective, responsive water risk management and communication strate gies. The new knowledge created by this research will be crucial to designing comprehensive risk communication strategies, creating effective stakeholder dialogues, and ensuring that water research findings are disseminated appropriately to support personal and public decision-making processes.

In the last decade or so of the twentieth century, stakeholder input became very important in the formulation of water policies and water plans. A substantial amount of experience was gained from different methods for obtaining stakeholder input. Experience was also gained from situations in which stakeholder interests were relatively easy to reconcile and where the plurality of interests and intensities of interest virtually denied the possibility of achieving a consensus. There have been few systematic efforts to analyze and distill these experiences. Such research is badly needed because water managers must account for stakeholder preferences in a way that is efficient and that honors those preferences.

In many instances, user-organized institutions such as cooperatives, special districts, and mutual companies have been employed widely and successfully to develop and distribute water. Studies that identify the circumstances in which different kinds of organizations are likely to be successful and effective are needed, as well as research on new and innovative organizational arrangements for developing and distributing water. It will also be important to elucidate the links between user-organized institutions and the legal and policy environments in which they thrive (Blomquist, 1992).

Only limited attention has been devoted to the cultural, religious, and ethical facets associated with water and its use (e.g., Brown and Ingram, 1987; Espeland, 1998). Additional research is needed to identify the special attributes that will have to be accounted for as the population of the United States becomes more culturally diverse and as water scarcity intensifies. These factors critically influence the ways in which different groups have organized historically to manage their water resources. Comparative institutional studies that focus on the cultural and ethical determinants of water management organizations will be useful not only in defining the needs of different groups, but also in helping to design optimal institutions for managing water resources.

Finally, the need for studies to inform and enlighten the making of water policy will be more critical than ever. Too often, policy analysis and the development of scientific conclusions related to policy have been stymied because they have been confused with the actual making of policy. The WSTB believes that good water policy is based on good science and good analysis and urges that people not confuse efforts to develop information to support the policy-making process with policy-making itself. The specific research questions and the kinds of analysis needed will be specifically dependent on the policy issues under consideration.

Contamination of streams and estuaries from runoff and nonpoint sources results in a number of fish advisories, as indicated by this sign near a contaminated area around Hunters Point, CA. Despite being posted in three languages, this warning is frequently ignored by local residents.

The nation has accumulated over a century of experience with a variety of water policies and management modes, yet we have not learned as much as we might have from that experience. Too often water policies, experiments, and projects have been abandoned or completed without any *ex post facto* assessments as to whether they have worked well or not. Many observers have noted that current policies and policy-making efforts appear uninformed by what has gone on before (White, 1999). *Ex post* evaluations of completed water projects, of water policies, and of experience with water management regimes should be high on the research agenda of the future.

The water resources research agenda for the twenty-first century should give priority to:

- determining the key factors that affect water-related risk communication and decision processes;
- assessing the effectiveness of user-organized institutions for water distribution and identifying the legal and policy environments in which they succeed;
- analyzing the range of experience with different processes for obtaining stakeholder input in the making of water policies and water plans;
- elucidating the cultural and ethical factors associated with water use, and comparing institutions having different cultural and ethical bases;
- informing the policy-making process; and
- evaluating the strengths and weaknesses of past water policies and projects.

5

Organizing For Water Resources Research in the Twenty-first Century

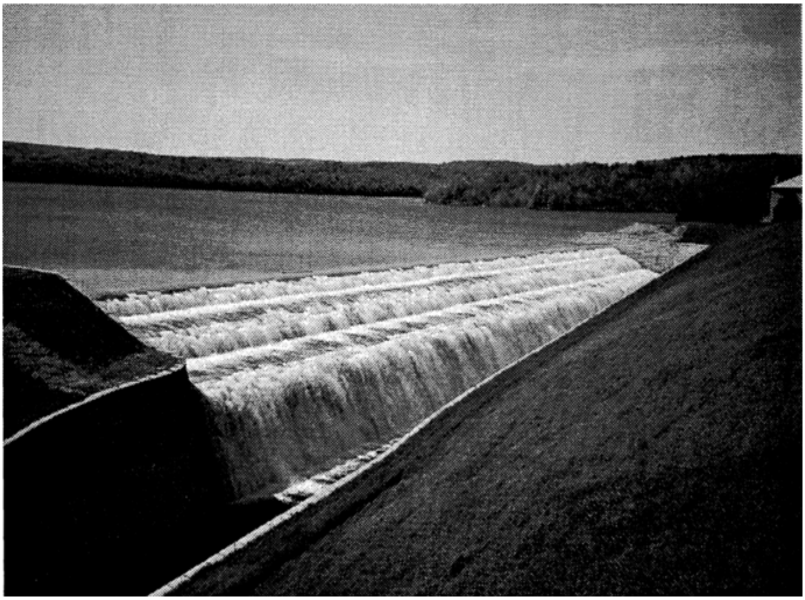
In the 1900s, the setting of water research agendas and priorities in the United States was highly decentralized. There were no processes or mechanisms, formal or informal, for identifying the nation's water research and development priorities or even for prioritizing the nation's water problems on a unified basis. More than a dozen federal agencies are involved in water research programs in addition to some state and private agencies and a few local agencies. Despite the number of federal programs for water research, there is no single catalog or description of federal funds directed to these purposes. Unfortunately, there is no commonly accepted structure for categorizing types of water research. Indeed, few of the agencies that conduct research on subjects in this report even indicate in their budgetary material activity identified as “water resources research.” Usually, such work is buried under classifications such as earth science, environmental, or among regulatory, planning, or management-related programs. Further, agencies may view activities such as monitoring or remediation as research, thereby making it difficult to decipher funds spent on research from those spent on other activities. These agencies tend to act independently, with the result that investment in research and development may be duplicative while some important research topics fall through the cracks. Significant amounts of current agency research is focused on correcting errors of the past (e.g., environmental “remediation”) or on dealing with unanticipated or unintended consequences that adequate research might have prevented in the first place. Much agency research is not forward-looking or focused on the future, but rather deals with short-term and operational problems.

There are some who would argue that the *laissez faire* approach to research agenda-setting and prioritizing serves the nation well and that what is needed is a massive infusion of research funding. The difficulty with this approach is that the competition for research dollars is far more intense now than it was at any time during the twentieth century. The same can be said for the competition for all public resources, and in an era characterized by significant constraints on public resources, it is imperative that we be more systematic and strategic in planning water research if credible arguments for more resources are to be mounted.

It would be a mistake to think that the only problem is the lack of coordination of the various federal agencies involved in water research. Rather, a coordinated research program in which researchers and agenda setters can be accountable to the public will require an alignment of state and federal governments, research universities, users and purveyors of all kinds, non-profit organizations, and public interest groups. These groups will need to ally to identify and support the research agenda of the twenty-first century. Although the notion that the research agenda should be set in a decentralized fashion may have much appeal, recent experience suggests that decentralized agenda-setting has been unduly reactive and sometimes neglectful of long-term issues. One consequence of this has been that the environmental impacts of many engineering works were unforeseen and misunderstood. Both multidisciplinary and interdisciplinary research should help to avoid a repetition of this kind of mistake.

A more viable mechanism is needed for setting and overseeing the water resources research agenda, based on the following principles:

- An effective alliance with and active participation of water resources research stakeholders is required;
- A systematic, strategic, and balanced agenda of both core and problem-driven research priorities should be set to meet short- and long-term needs;
- The core research agenda should develop (1) greater understanding of the basic processes—physical, biological, and social—that underlie environmental systems at different scales, (2) appropriate environmental monitoring programs, and (3) research tools to identify and measure structural and functional attributes of aquatic and related ecosystems (NRC, 1997a);
- The national water resources research effort should be coordinated to reduce needless duplication and to ensure that gaps do not occur;
- The research effort should be multidisciplinary and interdisciplinary;
- The research effort should be proactive and anticipate the nation's water needs and the environmental impacts of management options; and
- The research effort should be accountable to the public to assure that the water resources research investment has been appropriately utilized to meet the nation's needs.



Many water systems, such as this 50-year old reservoir in the New York City water supply system, are reaching the end of their usable lifetimes and will require new technologies and infrastructure to effectively regulate water in the twenty-first century.

PROPOSAL FOR A NATIONAL WATER RESEARCH BOARD

The Water Science and Technology Board (WSTB) recommends that Congress or the President's Office of Science and Technology Policy create a National Water Research Board that would be responsible for establishing and overseeing the national water research agenda. The Research Board should be charged with the ongoing task of developing (and keeping up-to-date) a strategic and anticipatory national water research agenda. Membership on the National Water Research Board should include stakeholders from the public and private sectors as well as academic representatives—the people who best understand water problems in their areas. Board composition should reflect the recognition that water resources research transcends media boundaries and is closely linked to terrestrial and atmospheric processes. Thus, this Research Board should help to ensure that there is adequate balance among disciplinary, multidisciplinary, and interdisciplinary research.

The WSTB recognizes that there are a variety of institutional mechanisms that could be employed to implement and administer the research agenda, such as an *ad hoc* interagency organization, a body within an existing agency, or an independent agency, each of which has its advantages and disadvantages. The WSTB believes that the appropriate mechanism for implementation should be identified through customary policy-making processes after careful consideration of the available alternatives.

A National Water Research Board would provide a relatively simple, centralized system of setting research priorities. The appropriate implementation of those priorities could provide the necessary assurances and accountability for additional investments in water resources research. Because existing water research is so fragmented and obfuscated under a variety of rubrics, as previously discussed, even approximate estimates of the total annual investment in such research are difficult to formulate. Indeed, one of the first tasks the National Water Research Board should undertake would be to determine the current level of investment and the additional investment needed. Available estimates suggest that the real value of dollars currently invested in water research is significantly less than the levels of investment that prevailed in the 1950s, 1960s, and 1970s. A strong case can be made that substantial increases in water research investment, on the order of several hundred million dollars, are called for if the nation is to address successfully the daunting array of water problems it will confront in the twenty-first century.

CONCLUSIONS

The progressive intensification of water scarcity in the early decades of the twenty-first century will necessitate innovative scientific, technological, and institutional solutions. Because the needed solutions to the problems described in this report are not currently available, appropriate water resources research in the new century is critical to human and ecosystem welfare.

The WSTB has concluded that water resources research in this new century must be planned and prioritized in a coordinated and systematic way. The United States cannot afford to continue the fragmented and uncoordinated execution of water resources research typified during the past century. The WSTB suggests that coordination of the water research agenda can be achieved by creating a National Water Research Board that involves state and federal governments, research institutions, users and purveyors, nonprofit organizations, and public interest groups. The Research Board should be patterned after similar boards such as the National Science Board. Effective implementation and administration of a strategic and proactive research agenda to be developed by the Research Board should provide the justification and accountability for augmented levels of investment in water resources research.

Water resources problems are extremely complex, necessitating that their solutions cross-traditional disciplinary and societal boundaries. This sobering reality strongly suggests that these problems cannot be solved with the current level of investment in water research. Rather, a substantive commitment of significant new funds will be essential if we are to attain effective stewardship of this increasingly scarce resource.

Finally, the WSTB has identified three broad areas that should be included in the water resources research agenda for the twenty-first century:

1. Studies of water availability should focus on the development of supply-enhancing technologies, on understanding the threats to water quality, on developing means for preventing further declines in water quality, and on developing ways of enhancing water quality. In consort with these investigations, data need to be available in near real time and should characterize

Multidisciplinary and interdisciplinary research will be needed to anticipate the nation's water needs and their environmental impacts.

water quantity and quality for both surface and subsurface waters. The monitoring of water quantity and water quality will also be important in assessing whether water policies and management efforts are working and for identifying and understanding causes of emerging water problems.

2. Studies of water use should focus on developing a better understanding of the determinants of consumptive use, the importance and scale of agricultural use, and the nature and impact of environmental uses. Research on the technologies and infrastructure for water recycling will be critical to meeting future water needs.
3. Studies leading to the development of improved water management institutions should receive much more emphasis in the research agenda of the twenty-first century than they have previously received. Studies should focus on legal and economic institutions, and researchers from other social science disciplines in water resources research should be involved.

The specific research issues identified in these three areas are summarized in the list below, which represents a 20-year interdisciplinary research portfolio for the water resources field.

Water Availability

- Develop new and innovative supply-enhancing technologies
- Improve existing supply-enhancing technologies such as wastewater treatment, desalting, and groundwater banking
- Increase safety of wastewater treated for reuse as drinking water
- Develop innovative techniques for preventing pollution
- Understand physical, chemical, and microbial contaminant fate and transport
- Control nonpoint source pollution
- Understand impact of land-use changes and best management practices on pollutant loading to waters
- Understand impact of contaminants on ecosystem services, biotic indices, and higher organisms
- Understand assimilation capacity of the environment and time course of recovery following contamination
- Improve integrity of drinking water distribution systems
- Improve scientific bases for risk assessment and risk management with regard to water quality
- Understand national hydrologic measurement needs and develop a program that will provide these measurements

- Develop new techniques for measuring water flows and water quality, including remote sensing and *in situ* techniques
- Develop data collection and distribution in near real time for improved forecasting and water resources operations
- Improve forecasting the hydrologic cycle over a range of time scales and on a regional basis
- Understand and predict the frequency and cause of severe weather (floods and droughts)
- Understand recent increases in damage from floods and droughts
- Understand global change and its hydrologic impacts

Water Use

- Understand determinants of water use in the agricultural, domestic, commercial, public, and industrial sectors
- Understand relationship of agricultural water use to climate, crop type, and water application rates
- Develop improved crops for more efficient water use and optimize the economic return for the water used
- Develop improved crop varieties for use in dryland agriculture
- Understand water-related aspects of the sustainability of irrigated agriculture
- Understand behavior of aquatic ecosystems in a broad, systematic context, including their water requirements
- Enhance and restore species diversity in aquatic ecosystems
- Improve manipulation of water-quality parameters to maintain and enhance aquatic habitats
- Understand interrelationship between aquatic and terrestrial ecosystems to support watershed management

Water Institutions

- Develop legal regimes that promote groundwater management and conjunctive use of surface water and groundwater
- Understand issues related to the governance of water where it has common pool and public good attributes
- Understand uncertainties attending to Native American water rights and other federal reserved rights
- Improve equity in existing water management laws

- Conduct comparative studies of water laws and institutions
- Develop adaptive management
- Develop new methods for estimating the value of nonmarketed attributes of water resources
- Understand use of economic institutions to protect common pool and pure public good values related to water resources
- Develop efficient markets and marketlike arrangements for water
- Understand role of prices, pricing structures, and the price elasticity of water demand
- Understand role of the private sector in achieving efficient provision of water and wastewater services
- Understand key factors that affect water-related risk communication and decision processes
- Understand user-organized institutions for water distribution, such as cooperatives, special districts, and mutual companies
- Develop different processes for obtaining stakeholder input in forming water policies and plans
- Understand cultural and ethical factors associated with water use
- Conduct *ex post* research to evaluate the strengths and weaknesses of past water policies and projects

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APPENDIX A

Water Science and Technology Board Members' Biographical Sketches

HENRY J. VAUX, JR. (Chair) is a professor of resource economics at the University of California, Riverside. He currently serves as Associate Vice President for the Agricultural and Natural Resource Programs for the University of California system. He previously served as Director of the University of California Water Resource Center. His principal research interests are the economics of water use and water quality. Prior to joining the University of California, he worked at the Office of Management and Budget and served on the staff of the National Water Commission. He received a Ph.D. in economics from the University of Michigan.

CAROL A. JOHNSTON (Vice-chair through June 2000) is a senior research associate at the Natural Resources Research Institute of the University of Minnesota, Duluth. Her research in landscape ecology, geographic information systems, and the biogeochemistry of wetlands and watersheds has been funded by the National Science Foundation, the Environmental Protection Agency, Sea Grant, NASA, and other organizations. Her professional experience includes positions at Cornell University, the Wisconsin Department of Natural Resources, and the Environmental Protection Agency. She received M.S. and Ph.D. degrees in soil science from the University of Wisconsin–Madison.

RICHARD G. LUTHY (Vice-chair) is the Silas H. Palmer Professor of Civil and Environmental Engineering at Stanford University. He received his B.S. in chemical engineering and M.S. and Ph.D. in environmental engineering from the University of California at Berkeley. Dr. Luthy was previously on the faculty at Carnegie Mellon University and former head of the Department of Civil and Environmental Engineering. His area of teaching and research is physicochemical processes and water quality. His research includes interdisciplinary approaches to understand phase partitioning and availability of organic contaminants and the application to water quality engineering and environmental quality criteria. He has served on several NRC committees on hazardous materials. Dr. Luthy is a member of the

National Academy of Engineering.

RICHELLE M. ALLEN -KING is an Associate Professor in the Department of Geology at Washington State University. She received a B.A. in chemistry from the University of California, San Diego and a Ph.D. in Earth Sciences (hydrogeology) from the University of Waterloo, Ontario, Canada. Her research focuses on organic pollutants in the hydrologic cycle. She has particular expertise in studying the biogeochemical processes affecting pollutant fate and transport in groundwater. She is currently a member of the Committee on the Bioavailability of Contaminants in Soils and Sediments, and the Science Advisory Board for the Washington State Department of Ecology's Toxic Cleanup Program.

GREGORY B. BAECHER is professor and chair of the civil engineering program at the University of Maryland. Prior to joining the faculty at Maryland in 1995, Dr. Baecher served on the faculty of civil engineering at the Massachusetts Institute of Technology from 1976 to 1988, and served as the CEO and founder of ConSolve Incorporated, Lexington, Massachusetts, from 1988 to 1995. His fields of expertise include risk analysis, water resources engineering, and statistical methods. Dr. Baecher received a B.S. in civil engineering from the University of California-Berkeley and his M.S. and Ph.D. degrees in civil engineering from the Massachusetts Institute of Technology.

JOHN S. BOYER (member through June 2000) received an A.B. in biology from Swarthmore College, an M.S. in plant physiology from the University of Wisconsin; and a Ph.D. in plant physiology from Duke University. His research interests are metabolic mechanisms of losses in plant growth under dehydrating or saline conditions. His research explores photosynthesis, cell enlargement, and reproduction beginning at the level of the whole plant but using methods in biophysics, biochemistry, and molecular biology. Experimental material includes agronomic species and marine plants in an effort to extend findings to practical applications. Since 1987, Dr. Boyer has been the DuPont Professor of Marine Biochemistry/ Biophysics, College of Marine Studies, University of Delaware. Dr. Boyer is a member of the National Academy of Sciences.

JOHN BRISCOE received his B.Sc. in civil engineering from the University of Cape Town. He received his M.S. and Ph.D. in environmental engineering from Harvard University. He has been with the World Bank since 1986, where he was a senior economist in the Brazil Department, then chief of the Water and Sanitation Division. He is currently the Bank's senior water advisor, with oversight responsibility for the World Bank's work on water resources management, hydropower, irrigation, and water and sanitation. Previously, he was associate professor at the School of Public Health with the University of North Carolina at Chapel Hill, where he did research on water supply and water resources management. He previously worked in the water management offices of the governments of South Africa and Mozambique and as a research scientist at the International Centre for Diarrheal Disease Research in Bangladesh.

EFI FOUFOULA -GEORGIOU is a professor of civil engineering and the director of the St. Anthony Falls Laboratory, University of Minnesota. Her research focuses on understanding and modeling the complex spatio-temporal organization and interactions of hydrologic processes, including precipitation and landforms. Dr. Foufoula-Georgiou obtained her diploma in civil engineering from the National Technical University of Athens, Greece, and her Ph.D. degree in environmental engineering from the University of Florida. She has chaired and served on many national and international committees and government advisory panels and has served on the editorial boards of several journals. She is a fellow of the American Geophysical Union.

DENISE FORT (member through June 2000) is a member of the faculty of the University of New Mexico's School of Law. She has been a member of the New Mexico Bar since 1976. Professor Fort has extensive experience in environmental and natural resources law and policy. She served as chair of the Western Water Policy Review Advisory Commission, a Presidential commission that prepared a report on western water policy concerns. In earlier positions, she served as director of New Mexico's Environmental Improvement Division, as a staff representative to the National Governors Association, as an environmental attorney, and in other capacities concerned with environmental and natural resource matters. She received her B.A. from St. John's College (Annapolis and Santa Fe, New Mexico) and her J.D. from the Catholic University of America's School of Law.

STEVEN P. GLOSS is a professor of zoology and physiology and a member of the faculty in the Institute and School of Environment and Natural Resources at the University of Wyoming. Dr. Gloss is the former director of the Wyoming Water Resources Center and the Spatial Data and Visualization Center at the University of Wyoming. He served two terms as president of the National Institute for Water Resources. His research interests include water resource policy and management, water quality, fisheries science and limnology, aquatic ecology and toxicology, general ecology, and adaptive management. Dr. Gloss received his Ph.D. in biology from the University of New Mexico working on an interdisciplinary NSF-RANN project focusing on the Colorado Plateau. Dr. Gloss was a member of the Committee on

Grand Canyon Monitoring and Research and chairs the Committee on Missouri River Ecosystem Science.

WILLIAM A. JURY is a professor of soil physics and chair of the Department of Soil and Environmental Sciences at the University of California-Riverside. He received his Ph.D. in physics from the University of Wisconsin. Dr. Jury's principal research interests are the measurement and modeling of organic and inorganic chemical movement and reactions in field soils; development and testing of organic chemical screening models; spatial variability of soil physical and chemical properties; and assessing volatilization losses of organic compounds. Dr. Jury is a member of the National Academy of Sciences.

GARY S. LOGSDON is director of water treatment research for Black & Veatch. Previously, he served for more than 25 years with the U.S. Public Health Service and the U.S. Environmental Protection Agency. In his current position, he directs design of pilot drinking water treatment plant testing programs and works with water utilities to optimize their operations. He has a wide range of experience in water treatment technology development; he has conducted research on water filtration for removal of *Giardia* cysts, bacteria, and turbidity, and on the modification of water quality for corrosion control. He holds B.S. and M.S. degrees in civil and sanitary engineering from the University of Missouri at Columbia and a D.Sc. from Washington University.

DIANE M. MC KNIGHT is a professor in the Department of Civil, Environmental, and Architectural Engineering and a fellow of the Institute of Arctic and Alpine Research at the University of Colorado. She received a B.S. in mechanical engineering, an M.S. in civil engineering, and a Ph.D. in environmental engineering from the Massachusetts Institute of Technology. Dr. McKnight was a research scientist at the USGS Water Resources Division. She studies biogeochemical processes, aquatic ecology, and reactive solute transport in streams and lakes in the Rocky Mountains and in polar desert areas of Antarctica. Dr. McKnight is the acting president of the Biogeosciences section of AGU. Currently, she is a member on USGCRP and IPCC committees on climate change and water resources. Her major research interest is in limnology and biogeochemical processes in natural waters.

GEN . JOHN W. MORRIS (Lt. Gen. U.S. Army Ret.) is president, J.W. Morris Ltd., and professor of construction management at the University of Maryland. He was formerly an engineer advisor to Zork, Rissetto, Weaver & Rosen, and Chief of Engineers, U.S. Army Corps of Engineers. Gen. Morris also served as Executive Director for International Operations for

Royal Volker Stevin N.V. and Chair/CEO of the Planning Research Corp Engineer Group. He earned a B.S. in civil engineering from the U.S. Military Academy and an M.S. from the University of Iowa. General Morris is a member of the National Academy of Engineering.

Philip A. Palmer is a recently retired senior environmental fellow in the DuPont Chemicals Core Resources Section of the Corporate Remediation Group. He has over 15 years of experience in the field of remediation technology development. Mr. Palmer oversaw development and pilot testing of new technologies on DuPont sites and assessment of the company's remediation technology needs. He holds a B.S. and M.S. in chemical engineering from Cornell University and an M.S. in environmental engineering from Drexel University.

Rebecca T. Parkin received her A.B. in sociology from Cornell University and her M.P.H. in environmental health and her Ph.D. in epidemiology from Yale University. She is an associate research professor in the Department of Environmental and Occupational Health in the School of Public Health and Health Services at The George Washington University. She is also president of Beccam where she provides epidemiologic reviews, analyses of testimony and exhibits, and programmatic assistance for government, academia, and the private sector. Previously Dr. Parkin was director of Scientific, Professional and Section Affairs at the American Public Health Association and the assistant commissioner of the Division of Occupational and Environmental Health at the New Jersey Department of Health. Dr. Parkin's areas of expertise include environmental epidemiology, public health policy, and risk assessment and communication.

Rutherford H. Platt is a professor of geography and planning law at the University of Massachusetts at Amherst. He received his Ph.D. in geography from the University of Chicago and also holds a J.D. from the University of Chicago Law School. He served as assistant director and staff attorney for the Open Lands Project, Inc., Chicago, and is a member of the Illinois bar. He has served on several NRC committees, including the Committee to Review the New York City Watershed Management Strategy, the Committee on Flood Insurance Studies, the Committee on Water Resources Research Review, the Committee on a Levee Policy for the National Flood Insurance Program, and the Committee on Managing Coastal Erosion. He chaired the NRC Committees on Options to Preserve the Cape Hatteras Lighthouse and the Flood Control Alternatives in the American River Basin.

Joan B. Rose is a professor in the Marine Science Department at the University of South Florida. Her research interests include methods for detection of pathogens in wastewater and the environment, water treatment for removal of pathogens, wastewater reuse, and occurrence of viruses and parasites in wastewater sludge. She received a B.S. in microbiology from the University of Arizona and her M.S. in microbiology from the University of Wyoming. Dr. Rose received her Ph.D. in microbiology from the University of Arizona.

Jerald L. Schnoor is a University of Iowa Foundation Distinguished Professor of Environmental Engineering and co-directs the Center for Global and Regional Environmental Research. He is a member of the National Academy of Engineering. He received his Ph.D. in environmental health engineering from the University of Texas. His research interests are in mathematical modeling of water quality, aquatic chemistry, and impact of carbon emissions on global change. He has research projects in aquatic-effects modeling of acid precipitation, global change and biogeochemistry, groundwater and hazardous wastes, and exposure risk assessment modeling. He is the editor of four books and the author of *Environmental Modeling.* Dr. Schnoor is also the associate editor of *Environmental Science & Technology.*

R. Rhodes Trussell is the lead drinking water technologist and director for corporate development at Montgomery Watson, Inc. Dr. Trussell received his B.S. in civil engineering and his M.S. and Ph.D. in sanitary engineering from the University of California, Berkeley. He is a member of the National Academy of Engineering.

Eric F. Wood (member through June 2000) is Professor of Civil and Environmental Engineering at Princeton University, where he has taught since 1976. He received his Sc.D. in civil engineering from the Massachusetts Institute of Technology. His research areas include hydroclimatology with an emphasis on land-atmospheric interaction, hydrological remote sensing, modeling the terrestrial water and energy budgets over a range of scales and hydrologic impact of climate change. He is a past member of the NRC's Water Science and Technology Board, a member of the NRC's Board of Atmospheric Science and Climate (BASC), the Committee on Hydrological Sciences, and BASC's Climate Research Committee.

Laura J. Ehlers is a senior staff officer for the Water Science and Technology Board. Since joining the NRC in 1997, she has served as study director for seven committees, including the Committee to Review the New York City Watershed Management Strategy, the Committee on Riparian Zone Functioning and Strategies for Management, and the Committee on Bioavailability of Contaminants in Soils and Sediment. She received her B.S. from the California Institute of Technology in biology and engineering and applied science. She earned both an M.S.E. and a Ph.D. in environ mental engineering at Johns Hopkins University.

ELLEN A. DE GUZMAN is a senior project assistant at the National Research Council's Water Science and Technology Board. She received her B.A. degree from the University of the Philippines. She is the associate editor of the WSTB newsletter and has worked on a number of studies including *Risk Analysis and Uncertainty in Flood Damage Reduction Studies, Watershed Management for Potable Water Supply, Issues in Potable Reuse, Valuing Ground Water, New Directions in Water Resources Planning for the U.S. Army Corps of Engineers, and Improving American River Flood Frequency Analyses.*